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MESSENGER MANEUVER PERFORMANCE DURING THE LOW-ALTITUDE HOVER CAMPAIGN

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Helium gas pressurant from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft's near-empty main fuel tanks was used as a propellant to delay the spacecraft's surface impact onto Mercury until late April 2015 and enabled a one-month "hover" campaign with periapsis altitudes as low as 5 km. The final eight maneuvers of the mission had special challenges, including repurposing helium pressurant as a propellant, firing thrusters that had not been used in more than eight years, and executing multiple maneuvers within a short time frame that, if unsuccessful, would have led to impact times as little as 30 hours later.

INTRODUCTION

As part of NASA's Discovery Program, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft became the first 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 as a result of 50% more passes.[3] A second extended mission began on 18 March 2013 for additional scientific observations of Mercury. During the second extended mission, a series of OCMs were executed to delay Mercury surface impact while also providing occasions for low-altitude flyover observations as close as 15 km to Mercury's surface.[4] A slight extension to the second extended mission was granted in 2014 to attempt further observations at altitudes as low as 5 km over a one-month time frame by using five

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planned OCMs to maintain the low periapsis altitude. This additional month, termed the "hover" campaign, was made possible through the use of helium gas (GHe) as a propellant for the mission's final two planned OCMs. The MESSENGER propulsion system (MPS) carried helium as a pressurant for the main fuel tanks; it was not intended to provide thrust for the spacecraft. There is no combustion when expelling the helium, effectively turning the chemical MPS into a cold-gas propulsion system. In preparation for the challenging hover campaign maneuvers, OCM-12 was designed to use both hydrazine (N_2H_4) and GHe as propellants. Helium was intentionally used as a propellant before the hydrazine was exhausted to help maintain sufficient hydrazine levels for later burns. The maneuver also provided an opportunity to characterize the thruster performance and spacecraft attitude control during cold-gas maneuvers. The hover campaign maneuvers exhausted the remaining hydrazine through OCM-15. The last four maneuvers were executed solely on helium gas, two of which were unplanned additions to the nominal hover maneuver sequence.

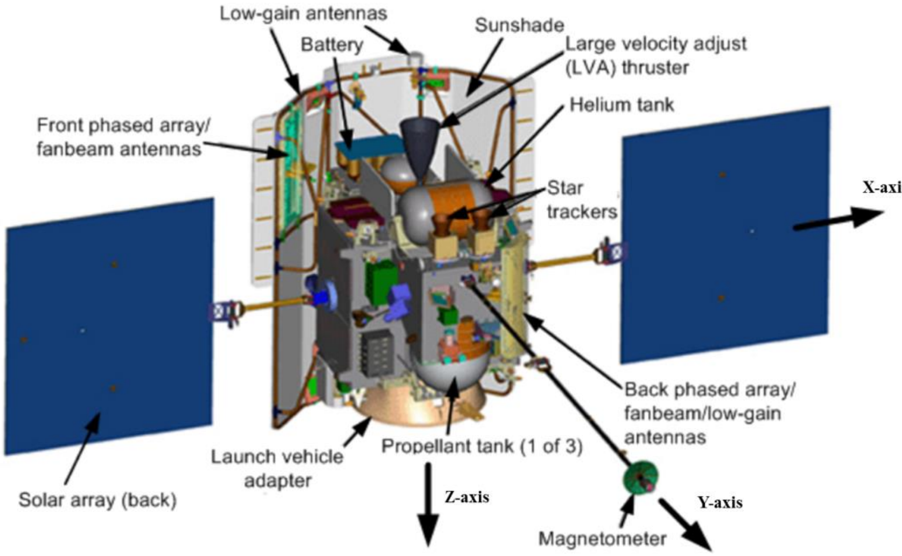

Figure 1. MESSENGER Spacecraft Components and Body-Axis Convention.

The MESSENGER spacecraft, shown in Figure 1, is three-axis stabilized and uses reaction wheels as the primary means of maintaining attitude control.[5] The actuator suite includes thrusters, which are used for angular momentum management and trajectory control and 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 MPS, shown in Figure 2, was designed and built by Aerojet-General Corporation (now Aerojet Rocketdyne) and consists of four propellant tanks and 17 thrusters.[6] The MPS includes one ~680-N rated bipropellant engine, and two sets of monopropellant thrusters comprised of 12 4.4-N rated thrusters (A1–A4, B1–B4, S1–S2, and P1–P2) and 4 22-N rated 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. When the helium tank valve is open, gas flows into main fuel tank 1 (FT1) and main fuel tank 2 (FT2) to maintain the desired pressure. As hydrazine is expelled from the main tanks and the pressure drops below a defined value, the pressure regulator opens to allow helium to flow into the tanks. The helium gas ensures a stable pressure in the tank, thereby providing steady performance of the thrusters. The fourth tank, the refillable auxiliary tank, contains a diaphragm but is not pressure regulated. The MPS was used to successfully execute a total of 19 OCMs during the orbital phase of the MESSENGER mission. The oxidizer tank and FT1 were depleted of fuel during the April 2012 OCMs, and FT2 was depleted during OCM-10 in September 2014. All remaining hydrazine in the auxiliary tank, residual hydrazine in FT1 and FT2, and MPS helium gas pressurant were used as propellant during the hover campaign.

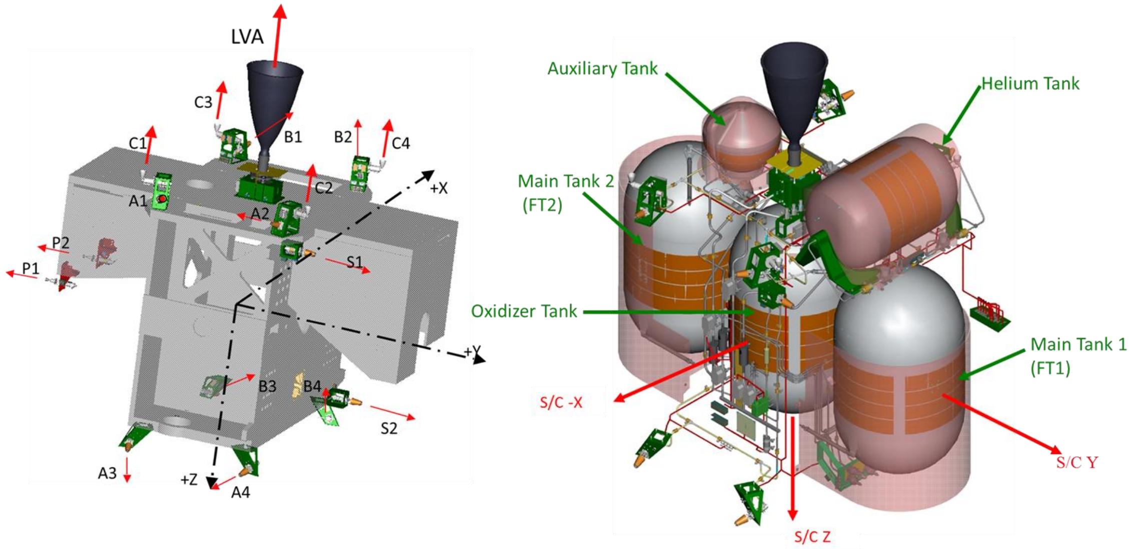

Figure 2. MESSENGER Propulsion System (MPS) Thruster Locations, Thrust Directions, and Tank Layout in the Spacecraft (S/C) Body Frame.

THE HOVER CAMPAIGN

The final OCMs of the MESSENGER mission, OCM-13 through OCM-18, were executed between 12 March and 28 April 2015 to maintain spacecraft minimum periapsis altitude between 5 and 35 km above the planet surface. The cadence and periapsis altitude of the hover campaign maneuvers are shown in Figure 3. These OCMs were scheduled on the basis of several constraints. Designing for high maneuver and fuel efficiency imposed schedule and pointing limits on the maneuvers. Each maneuver also required an opportunity for a contingency burn within three orbits of the nominal burn. Additionally, a solar conjunction made attempting maneuvers unfavorable for several days in mid-April. Table 1 lists the maneuver dates, velocity change (ΔV) thruster selection, fuel source, and execution results of the OCMs discussed in detail in later sections of this paper. The variations in design parameters made each of the hover campaign maneuvers unique in planning and execution.

Table 1. Summary of Design Details for OCM-12 through OCM-18. Auxiliary Tank is Abbreviated as "Aux."

OCM #	Date (2015)	ΔV Thrusters	Propellant	Fuel Source	Post-OCM Altitude (km)	Periapsis Altitude Increase (km)	Duration (s)	Total ΔV (m/s)
12	21 Jan	22-N Cs	N_2H_4 & GHe	Aux, FT1&2	104.3	79.0	109.14	9.63
13	18 March	22-N Cs	N_2H_4	Aux	34.4	22.7	32.96	3.07
14	2 April	4.4-N Ps	N_2H_4	Aux	28.3	22.8	401.24	2.96
15	6 April	4.4-N Ps	N_2H_4 & GHe	Aux, FT1&2	25.6	12.5	600*	1.73
15A	8 April	22-N Cs	GHe	All	28.3	10.8	303*	1.92
16	14 April	22-N Cs	GHe	All	13.3	6.8	201.92	0.99
17	24 April	22-N Cs	GHe	All	18.3	9.8	469.22	1.53
18	28 April	22-N Cs	GHe	All	6.3	1.0	181.02	0.45

*OCM-15 and OCM-15A autonomously terminated because of a maximum burn duration timeout.

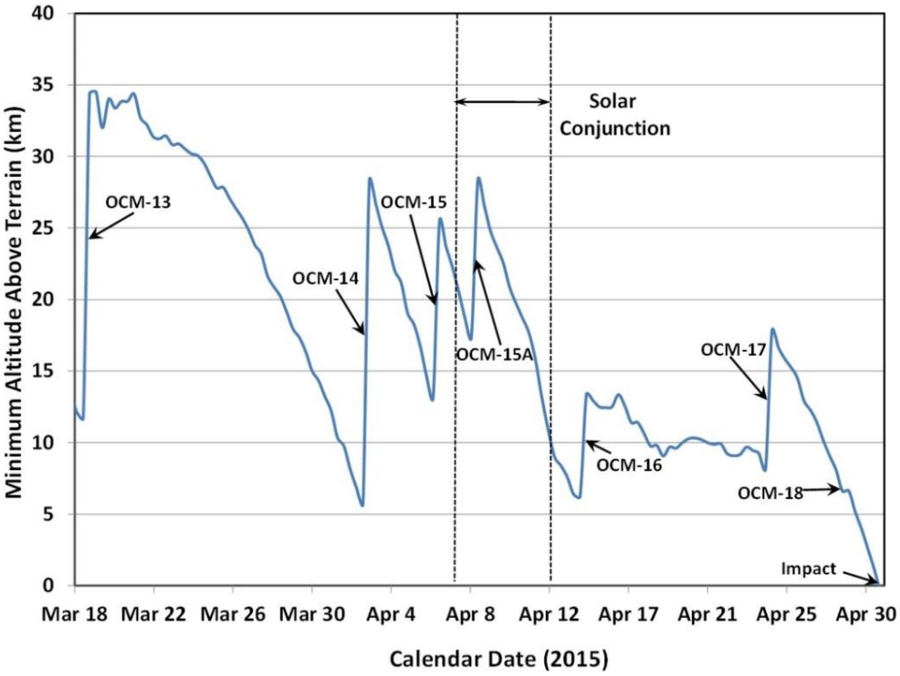

Figure 3. Spacecraft Periapsis Altitude Relative to Mercury Terrain during the Hover Campaign.

Because the main fuel tanks were previously depleted of "usable" propellant (e.g., propellant that could be credibly extracted from the main fuel tanks), the hover OCMs relied on the remaining hydrazine in the auxiliary tank, an unknown amount of residual hydrazine in the main fuel tanks that was previously deemed unusable, and the GHe used to pressurize the main tanks. Sun-to-spacecraft geometry constraints required that OCM-14 and OCM-15 use two 4.4-N thrusters, P1 and P2, to complete the maneuvers. Thrusters P1 and P2 had not been used in more than eight years and, because they protrude from the front of the sunshade, were exposed to extreme heat and radiation during that time, causing some concern about their performance. The final four maneuvers included the challenges of using helium as a propellant. All remaining accessible hydrazine onboard the spacecraft was consumed in OCM-13 through OCM-15, with final depletion mid-burn in OCM-15. OCM-15 completed the burn on helium but reached only 50% of the desired ΔV magnitude. To maintain a safe minimum altitude before OCM-16, OCM-15A was planned and executed in 2 days to boost the spacecraft back into the planned orbital trajectory. OCM-15A was successfully executed as the first maneuver designed to use helium as the sole propellant for achieving ΔV. OCM-16 and OCM-17 also successfully used helium to reach the desired altitude changes. A final maneuver was added after OCM-17 to ensure that the spacecraft would impact on the desired orbit, one with scheduled coverage by a Deep Space Network (DSN) 70-m antenna, enabling substantial data downlink before impact. The final maneuver of the MESSENGER mission, OCM-18, effectively delayed impact until the desired orbit on 30 April 2015.

OCM-12: PRE-HOVER CAMPAIGN HELIUM TEST

Ahead of the hover campaign, OCM-12 was executed on 21 January 2015 to perform the final planned periapsis-raising maneuver of the second extended mission. This maneuver provided a unique opportunity to realize some additional risk by attempting to characterize the use of GHe as a propellant and to access and quantify any remaining fuel in FT1 and FT2. Both main fuel tanks were previously treated as though they were depleted of all hydrazine, but less conservative analysis of the tank conditions suggested that it was probable that residual fuel remained accessible. Fuel tank switches among FT1, FT2, and the auxiliary tank were strategically included in the design of OCM-12 to reduce risk of a partial burn or burn abort while still achieving the desired periapsis altitude raise. The five maneuver segment durations and fuel sources are listed in Table 2. OCM-12 began by drawing hydrazine from the auxiliary tank and then switched to FT1 to access any remaining usable hydrazine and the GHe. FT2 was then opened to access GHe from both main tanks and to confirm hydrazine depletion of FT2. The burn completed after a sequenced switch to the auxiliary tank, which restored the flow of hydrazine to the thrusters and provided the remaining ΔV. Completing the burn on the auxiliary tank ensured that there would be sufficient thrust at the end of the burn to maintain a steady attitude, thereby reducing the risk of losing spacecraft control in case of zero thrust from the helium. The tweak segment, used as a terminal segment for all maneuvers, is one in which the spacecraft continues to use the thrusters for attitude control following completion of the targeted velocity change, ensuring a quiescent spacecraft dynamic state prior to returning attitude control to the reaction wheels. Only the A- and B-thrusters fire during the tweak segment to stabilize the spacecraft at the desired attitude.

Table 2. OCM-12 Maneuver Segment Durations and Fuel Sources.

Segment	ΔV Thrusters	Duration (s)	Propellant	Fuel Source
1 – Settle	C1–C4	20	N_2H_4	Auxiliary Tank
2 – Main 1	C1–C4	12	N_2H_4 & GHe	FT1
3 – Main 2	C1–C4	18	GHe	FT1 & FT2
4 – Trim	C1–C4	59.14	N_2H_4	Auxiliary Tank
5 – Tweak	n/a	30	N_2H_4	Auxiliary Tank

In all MESSENGER OCMs, the maneuver and propulsion system performance was monitored by guidance and control (G&C) autonomy for several maneuver health and safety conditions, in addition to the normal spacecraft-level fault protection functions. The monitored burn parameters include burn direction and magnitude error, fuel-feed pressure (PFF) conditions, latch valve health status, and spacecraft attitude. Nominal spacecraft autonomy monitored for attitude pointing violations outside the Sun keep-in (SKI) zone as well as the health of the spacecraft hardware through battery, thermal, and processor checks. The SKI zone defines orientation limits to keep the sunshade pointed sunward to protect the bus and payload from extreme temperatures. Violations of specific conditions could result in premature termination of the burn and demote the spacecraft to safe-mode. The PFF check would abort the burn if the fuel line pressure drops below a specified level. Because the goal of the hover OCMs was to deplete all remaining hydrazine, the pressure was expected to drop below normal levels; therefore, the PFF check was disabled for OCM-12 through OCM-18. The hover OCMs also carried a higher risk than previous burns because of the unknown amount of propellant and the limited recovery time for a contingency burn if the OCM was aborted. These OCMs were designed to avoid a burn abort or safing event except in extreme circumstances. To prevent a noncritical burn abort, select autonomy rules were disabled for all burns to defer responses that would end the burn. If one of the deferred rules fired, the response would execute after completion of the burn. Serious faults that could impact the burn would be detected by the G&C propulsion checks, which would then terminate the burn without fault protection system intervention.

Because of the unknown results of using helium as a propellant, custom autonomy was enabled for OCM-12 to limit gas ingestion into the auxiliary tank and prevent loss of attitude control in case of unexpected thrust levels during the GHe segments of the burn. Autonomy monitored for the “tweak” state, which identified a completed or aborted burn, and checked for critically low pressure in FT1 and FT2. Either state would trigger the system to open the auxiliary tank and close the FT1 and FT2 tank valves. If the autonomy rule fired to open the auxiliary tank during the Main 1 segment, an additional autonomy rule would close FT2 shortly after it was opened in the Main 2 segment.

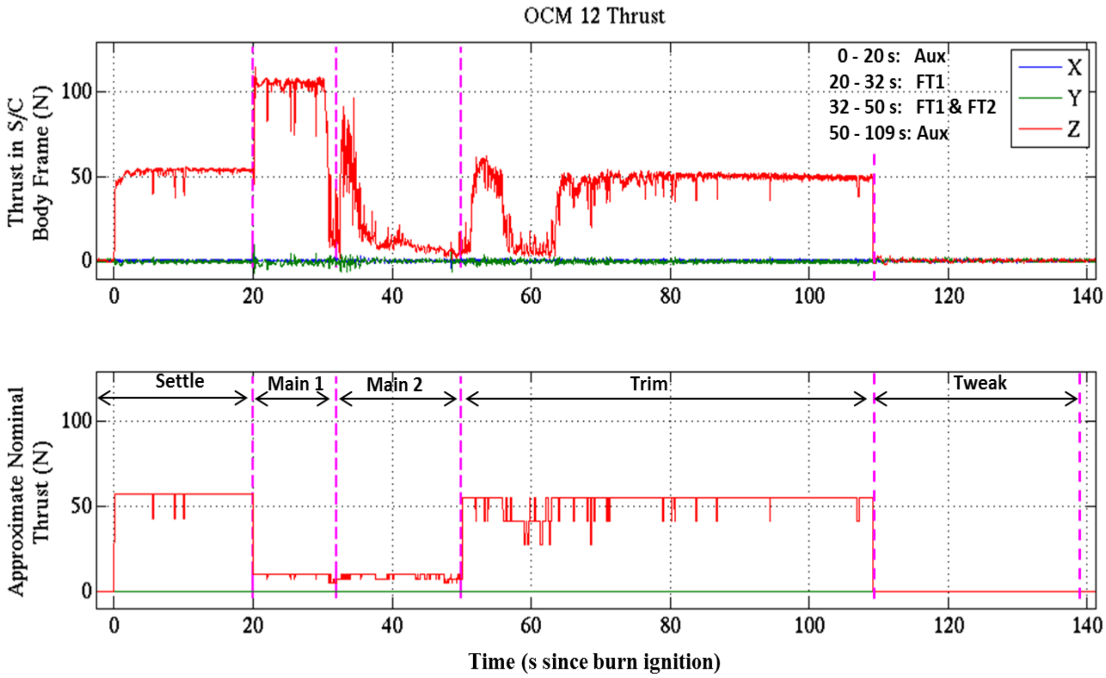

Figure 4. OCM-12 Actual (Top) and Nominal (Bottom) Thrust in the Spacecraft (S/C) Body Frame. The Vertical Dashed Lines Delineate Maneuver Segments.

Thrust levels from OCM-12 in Figure 4 show the substantial difference between the observed flight data in the upper plot and the nominal expected thrust in the lower plot. In flight, thrust was steady with a constant supply of hydrazine throughout the auxiliary tank segment for the first 20 s as anticipated. The thrust then doubled when FT1 was opened and an additional 0.462 kg of hydrazine was extracted from the tank, allowing the full C-thrust for ~10 s before fully depleting the tank and expelling GHe. FT2 was opened at 32 s, and a second, shorter burst of hydrazine is evident on the basis of the increased thrust in the plot just after the tank opened at the beginning of the second main segment. Following the depletion of hydrazine from FT2, the thrust rapidly dropped as the system transitioned to sustained GHe flow from the main fuel tanks. Once FT1 and FT2 were closed and the auxiliary tank was reopened for the trim segment 50 s into the burn, the thrust returned to the expected level initially, but was interrupted by a drop in the thrust for several seconds, which suggests that a gas bubble was present in the auxiliary tank. Once the gas bubble was purged, the thrust returned to a nominal level for the remainder of the burn, but with inconstancy not seen in previous burns. Although the test at OCM-12 was unsuccessful at fully characterizing the system performance (e.g., thrust and specific impulse) when using GHe as a propellant due to the limited time on gas alone, the maneuver did uncover an additional 0.591 kg of usable hydrazine and helped to provide confidence that the hover campaign maneuvers requiring GHe would yield sufficient thrust to keep the spacecraft orbiting Mercury until the end of April.

HOVER CAMPAIGN MANEUVERS: OCM-13 THROUGH OCM-18

The hover campaign maneuvers differed from previous maneuvers in multiple ways. The cadence of maneuvers during the hover campaign (seven maneuvers in seven weeks) made it impossible to plan, simulate, test, build, and upload commands to the spacecraft following the same rigorous process used in prior maneuvers. Before OCM-13, planning for maneuvers took one to two months, and the detailed design for any subsequent maneuver started after the previous maneuver was complete. This schedule allowed a thorough review of the maneuver results and a full trajectory re-optimization, including contributions from any deviations in the execution of the last maneuver. Instead, for the hover campaign, a series of commands were developed with a reduced set of changeable parameters to enable quicker build, test, and upload times. Using this framework, the number of detailed reviews and simulations required for each maneuver was substantially reduced with minimal increase in risk. Four of the OCMs were fully designed before the hover maneuver campaign began. As a result, later OCMs required a quick turnaround update on the basis of the results of the previous maneuver.

Due to geometry constraints and a desire to maximize efficiency, many of the hover campaign OCMs were executed with the spacecraft attitude just a few degrees from the edge of the SKI limit. The SKI limit constrains spacecraft pointing to keep the sunshade aligned within 10° azimuth and 12° elevation of direct Sun pointing at all times. Drifting outside the SKI limits for an extended duration would cause the spacecraft to demote to safe mode. To maintain low direction errors in maneuver execution during the burn, the attitude control system can use burn guidance to actively adjust the spacecraft pointing during the burn. The attitude control system actively minimizes the maneuver-execution pointing error when burn guidance is enabled, but it can point the spacecraft close to the SKI limits and relies heavily on attitude control pulsing to minimize maneuver-execution pointing error. To reduce the risk of a demotion due to a SKI violation and to increase maneuver efficiency, the hover OCMs were executed with the burn guidance disabled, so that any steering conducted was solely to ensure that attitude and rate errors stayed within the control deadbands. Increased maneuver-execution pointing error was accepted to improve maneuver fuel efficiency without increasing the risk of safing the spacecraft. Because the science conducted during the hover campaign was designed to be compatible with a wide range of achieved trajectories (i.e., periapsis altitudes), maneuver-execution pointing error was less important during the hover campaign compared with past OCMs.

The commanding used in the hover campaign OCMs simplified certain elements of the maneuver design process but also added constraints that limited the flexibility of each maneuver design. First, all hover sequence burns were designed as single-segment burns using only one set of thrusters and no tank changes, except when opened or closed by autonomy rules. Changes were also made to the attitude thruster control parameters. Before the hover campaign, the attitude control deadbands for the spacecraft were chosen for each specific burn type to optimize burn performance. P-thruster, C-thruster, and commanded momentum desaturation burns all used different parameters. For the hover campaign, limitations on command space required that the attitude control deadbands provide acceptable limits for all maneuver and commanded momentum desaturation configurations. The single set of parameters also had to provide acceptable performance across varying thrust scenarios of hydrazine, gas, or some combination of the two. Creating a default set of universal thruster control parameters introduced slightly more error than was seen previously but within the tolerance of the burn design. Typical burns had pointing errors <1° for the resultant ΔV, whereas the hover OCMs were expected to have pointing errors up to ~4°. The updated parameters were also chosen to reduce the on-time of the A- and B-thrusters, which are less efficient than the C-thrusters. Forcing the control system to maintain attitude control primarily using the C-thrusters would help save propellant, because the C-thrusters are pointed such that their pulsing contributes to the desired ΔV, whereas the A- and B-thrusters are approximately orthogonal to the desired ΔV. A summary of the hover campaign maneuver execution errors and performance is shown in Table 3. With the exception of OCM-15, the control system maintained low magnitude and pointing errors despite variations in active thrusters, fuel source, and fuel availability.

Table 3. Maneuver Execution Performance for OCM-13 through OCM-18.

OCM #	ΔV Thrusters	Duration (s)	Total ΔV (m/s)	ΔV Magnitude Error** (%)	Burn Pointing Error** (°)	Average Thruster Duty Cycles	
						Attitude Control[§]	Main ΔV
13	22-N C1-C4	32.96	3.07	0.412	0.627	0.38 %	99.5 %
14	4.4-N P1-P2	401.24	2.96	-0.015	3.978	18.76 % A2,A4,B2,B4	96.3 %
15	4.4-N P1-P2	600.00*	1.73	-50.67	2.760	11.53 % A2,A4,B2,B4	94.6 %
15A	22-N C1-C4	303.00*	1.92	-0.132	1.248	0.26 %	97.8 %
16	22-N C1-C4	201.92	0.99	0.020	0.695	0.08 %	99.5 %
17	22-N C1-C4	469.22	1.53	0.167	0.751	0.06 %	98.9 %
18	22-N C1-C4	181.02	0.45	0.176	1.295	0.00 %	96.2 %

* OCM-15 and OCM-15A terminated due to a maximum burn duration timeout.

**Errors estimated by initial ground processing of inertial measurement unit accelerometer data.

[§] C-thruster burn attitude control thrusters are A1-A4 and B1-B4 fired in coupled pairs.

OCM-13 Design and Results

Executed on 18 March 2015, OCM-13 was the simplest of the seven hover-sequence OCMs. The maneuver used hydrazine propellant from the auxiliary tank, with four C-thrusters firing to increase the minimum altitude by 22.7 km. OCM-13 targeted a 5.7-km minimum altitude above terrain on 2 April 2015, just before OCM-14. Because of concerns about gas ingestion from the main tanks into the auxiliary tank during the previous burn, the burn duration timeout, which cuts off the burn regardless of achieved ΔV, was set to 55 s, nearly twice the expected maneuver duration of 30 s, to prevent a premature burn termination should the auxiliary tank contain additional GHe bubbles. This timeout value was chosen on the basis of Monte Carlo simulations in which the thrust level was dropped to near zero in the middle of the burn, simulating a gas bubble (similar to what was seen in the final segment of OCM-12). A maximum duration of 55 seconds provided a 30% margin on the mean burn duration seen in the gas bubble simulations.

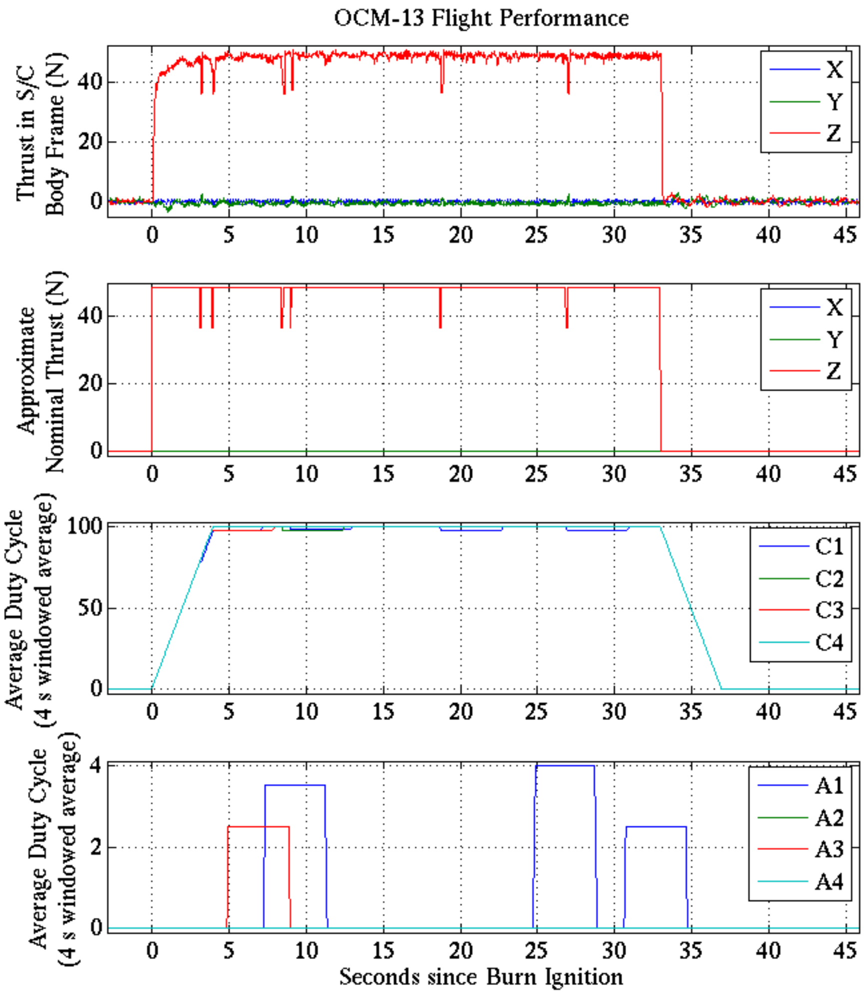

Figure 5. OCM-13 Flight Performance: (Top to Bottom) Thrust in the Spacecraft Body Frame, Approximate Nominal Thrust Given Constant Pressure and Thruster Duty Cycling, and Moving Averages of C-Thruster and A-Thruster Duty Cycles.

In line with expected performance, OCM-13 imparted a total ΔV of 3.07 m/s (0.412% overburn and 0.627° pointing error), which raised the periapsis altitude to 34.4 km and used 0.725 kg of hydrazine. The burn completed after 32.96 s when the desired ΔV was reached as measured by the onboard accelerometers. Post-burn reconstruction showed a slight overburn but was well within expectations. Thrust was nearly constant through the burn as shown in the top plot of Figure 5 with a slight ramp up during the first 2 s of the burn, which could be indicative of helium being purged from the system. The updated attitude control deadbands worked as expected as evidenced by the reduction in A- and B-thruster on-times. OCM-13 C- and A-thruster duty cycles are shown in the bottom plots of Figure 5. (B-thruster duty cycles are not shown because they can be inferred from the A-thruster duty cycles; when the A- and B-thrusters are used for attitude control in C-thruster burns, they fire in coupled pairs to reduce residual ΔV.) With a total ΔV of 3.1 m/s and total duration of 33 s, the first maneuver of the hover sequence had both the largest magnitude change and shortest duration of the hover OCMs.

OCM-14 Design and Results

Attitude constraints imposed by the spacecraft-to-Sun geometry at OCM-14 required this burn to use the P-thrusters, two of the 4.4-N rated thrusters that protrude through the front of the sunshade. The pre-burn periapsis altitude above terrain prior to OCM-14 was only 5.53 km, leaving 30 hours before the spacecraft would impact the planet surface if OCM-14 failed to execute as designed. Because of the low thrust from the P-thrusters, the burn duration increased to >400 s, compared with 33 s at OCM-13 for a similar ΔV magnitude. To improve efficiency in the P-thruster burns, only four of the eight attitude-control thrusters were enabled (A2, A4, B2, and B4). When fired for attitude control, these four thrusters contribute a ΔV component in the desired direction, whereas the disabled thrusters would have contributed in the opposing direction, working against thrust from the P-thrusters. However, any A2, A4, B2, and B4 on-pulsing for attitude control contributes to maneuver-execution direction errors because of their 15° offset angle and the fact that they were not paired with their oppositely offset counterparts.

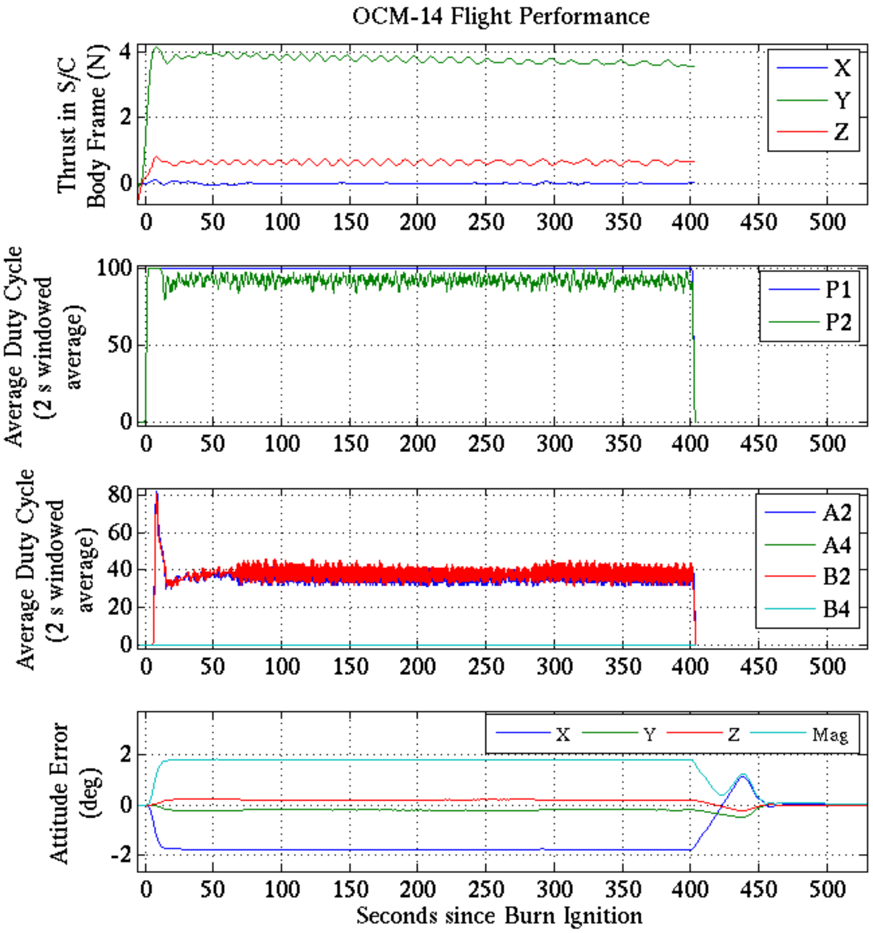

Figure 6. OCM-14 Flight Performance: (Top to Bottom) Thrust in the Spacecraft Body Frame, Average P-Thruster and A- and B-Thruster Duty Cycles, and Attitude Error during the Burn.

OCM-14, executed on 2 April 2015, successfully raised MESSENGER's periapsis altitude by 22.77 km in 401.2 s with a total ΔV of 2.96 m/s (0.015% under-burn and 3.978° direction error) using 0.926 kg of hydrazine from the auxiliary tank. The thrust for OCM-14 is shown in Figure 6. Although low, the thrust remained fairly level through the 6-minute burn, indicating a steady flow of hydrazine and nominally functioning thrusters as expected. The almost 2° attitude error shown in the bottom plot of Figure 6 was a result of the universal thruster control deadbands used for all hover OCMs. By design, once the attitude error reaches the deadbands, the attitude error is held steady near the limit to minimize attitude control thruster on-pulsing. Final maneuver execution pointing error includes an additional ~2° of error due to the uncoupled torques and imperfect ΔV contribution of the A2- and B2-thrusters. Because of the center of mass location during OCM-14, neither the A4- nor the B4-thrusters were needed for attitude control during the ΔV portion of the maneuver.

OCM-14 showed the resiliency of the MESSENGER thrusters and the attitude control system by successfully executing a maneuver using thrusters that had been idle for years and maintaining control of the vehicle during the first of several low-thrust maneuvers.

OCM-15 and OCM-15A Design and Results

Although the P-thrusters were confirmed to be functioning well in OCM-14, OCM-15 had two further challenges. First, it was questionable whether the remaining hydrazine in the auxiliary tank would be depleted during OCM-15. Post-OCM-14 tank pressures suggested that adequate propellant was available to execute the entire burn on hydrazine, but there was still some uncertainty. If the hydrazine was fully depleted from the auxiliary tank mid-burn, the thrust could drop to zero when the tank diaphragm reached the outlet. This drop in thrust could cause a loss of attitude control unless the propellant source was switched over to the main fuel tanks to use helium. To maintain a nearly constant fuel source, special autonomy was put in place to detect a critically low PFF of <50 psi (345 kPa). These low pressures would indicate a depletion of the auxiliary tank, and therefore the MPS would open FT1, FT2, and the helium tank to allow helium and any residual propellant to flow to the thrusters. The helium would enable the spacecraft to retain attitude control; however, it would be highly inefficient for achieving the desired ΔV through the already low-thrust P-thrusters.

The second challenge was that one day after OCM-15, the spacecraft would enter solar conjunction, which spanned 7–12 April 2015, where the Sun–Earth–probe (SEP) angle is <3° and communication with the spacecraft is limited and degraded. The lack of high-quality tracking data during conjunction makes it difficult for the navigation team to fully reconstruct maneuver performance and predict the new orbit trajectory. An unsuccessful or substantial under-burn before conjunction could result in impact before OCM-16 if a solid communications link could not be established and an emergency correction maneuver implemented.

OCM-15 was executed on 6 April 2015 at 16:14:06.9 UTC. As shown in Figure 7, the initial thrust was similar to the thrust level seen at OCM-14, but approximately 150 s into the burn the thrust began to slowly decline as the pressure in the auxiliary tank decreased. Custom autonomy opened FT1 and FT2 at 215 s into the burn, as designed, when the PFF dropped to <50 psi (345 kPa). Once the main tanks were opened, residual hydrazine from the tanks and fuel lines produced a brief increase in thrust, seen in the top plot of Figure 7. At 226 s, the propulsion system had established a steady-state gas flow, resulting in ~0.15 N thrust per P-thruster, just 8% of the nominal thrust. Helium gas did not provide enough thrust to complete the ΔV, as was anticipated, and the maneuver terminated upon reaching the maximum allowable duration of 600 s. The total

ΔV achieved was 1.7267 m/s, a 50.67% under-burn. If no further action had been taken, the spacecraft would have impacted the surface of Mercury before OCM-16, cutting the hover campaign short by more than 2 weeks.

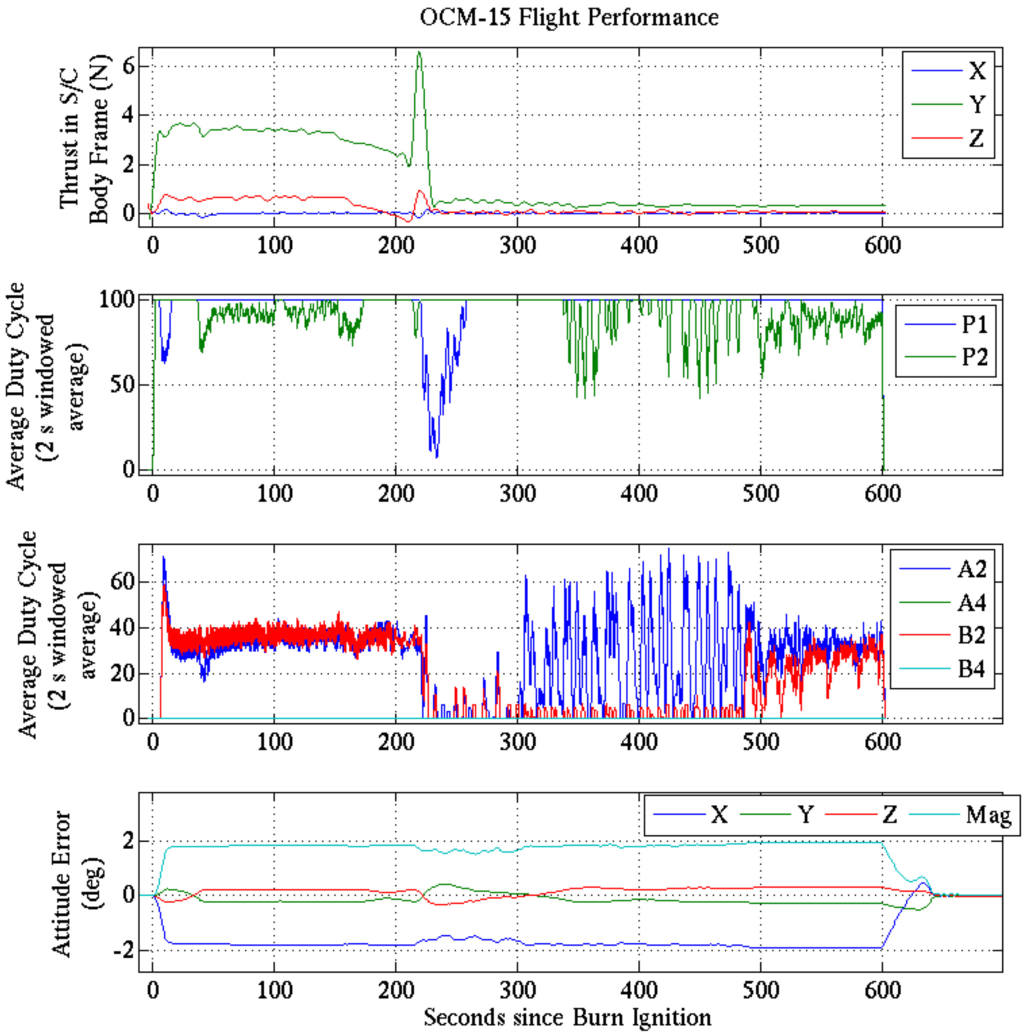

Figure 7. OCM-15 Flight Performance: (Top to Bottom) Thrust in the Spacecraft Body Frame, Average P-Thruster and A- and B-Thruster Duty Cycles, and Attitude Error during the Burn.

The introduction of helium into the auxiliary tank during OCM-10 and OCM-12 proved to have a longer-lasting impact than originally expected. In the final segment of OCM-12 through OCM-14 more than 1.6 kg of hydrazine was consumed from the auxiliary tank without any evidence of helium bubbles, suggesting that any helium in the auxiliary tank had been exhausted prior to OCM-15. While the depletion of hydrazine during OCM-15 was a recognized possibility, the expectation was that the cessation of propellant flow would be abrupt with the line pressure dropping to the ~1 psi (6.9 kPa) vapor pressure of N_2H_4. However, instead of a sudden decline, the blowdown and thrust curves shown in Figure 8 were observed, signifying a gradual decline in PFF. As the pressure declined, thrust magnitude decayed as well, indicating that propellant flowed continuously to the thrusters until the switch to FT1 and FT2. These data suggest that the helium introduced into the auxiliary tank was not fully expelled in the prior maneuvers, but remained as a hydrazine froth or foam that was slowly expelled as the diaphragm lowered. This helium resulted in an overestimation of remaining propellant by ~0.7 kg. Once the latch valves to FT1 and FT2 were opened for the remainder of the maneuver, the auxiliary tank was fully pressurized with helium. Based on the available thrust data, the hydrazine foam was not seen for the remainder of the mission.

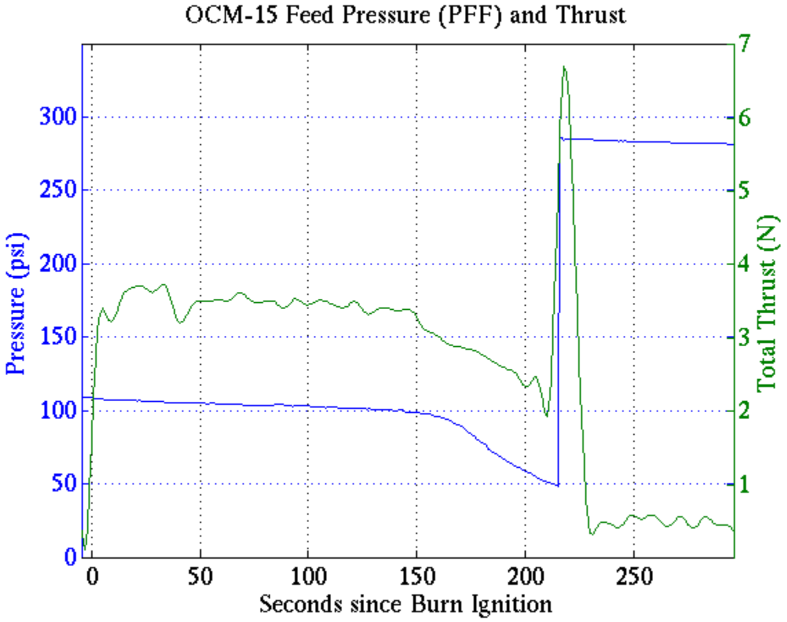

Figure 8. OCM-15 Feed Pressure and Thrust before Switch to FT1/FT2. Gradual decline suggests that hydrazine was suffused with helium bubbles, forming a foam or froth that slowly evacuated.

The team quickly executed a clean-up maneuver, OCM-15A, to complete the designed OCM-15 periapsis altitude raise. Because of the impending superior solar conjunction, this maneuver was designed, tested, loaded to the spacecraft, and executed in less than 48 hours. All three fuel tanks were opened, and OCM-15A used four C-thrusters and helium gas to impart the remaining ΔV to put the spacecraft back on the desired trajectory. This maneuver successfully reached a ΔV of 1.917 m/s in 303 s (0.132% under-burn, 1.248° pointing error), but because of lower than expected thrust levels the burn terminated after reaching the maximum allowable maneuver duration. As shown in Figure 9, after an initial burst of thrust from hydrazine in the thruster lines, the average total thrust through the burn was ~3 N with four C-thrusters, far less than the 10 N that was seen in the helium test performed during OCM-12. It is hypothesized that during OCM-12 the gas segment expelled a mixture of helium and hydrazine droplets that provided additional thrust.

After each OCM, the maneuver data file is downlinked with high priority to confirm that the burn executed as desired. In addition to the challenge of developing a maneuver on an extremely compressed schedule, OCM-15A was executed at a SEP angle of <1.9°, at which command uplink and telemetry downlink were severely degraded. Because of the low data rates and minimal tracking data, only part of the burn data file was immediately downlinked, which impacted the team's ability to accurately reconstruct the burn. A partial reconstruction was completed in the hours after the burn using limited data. The complete reconstruction was performed the next day after the full data file was downlinked. This was the only MESSENGER OCM executed during a solar conjunction.

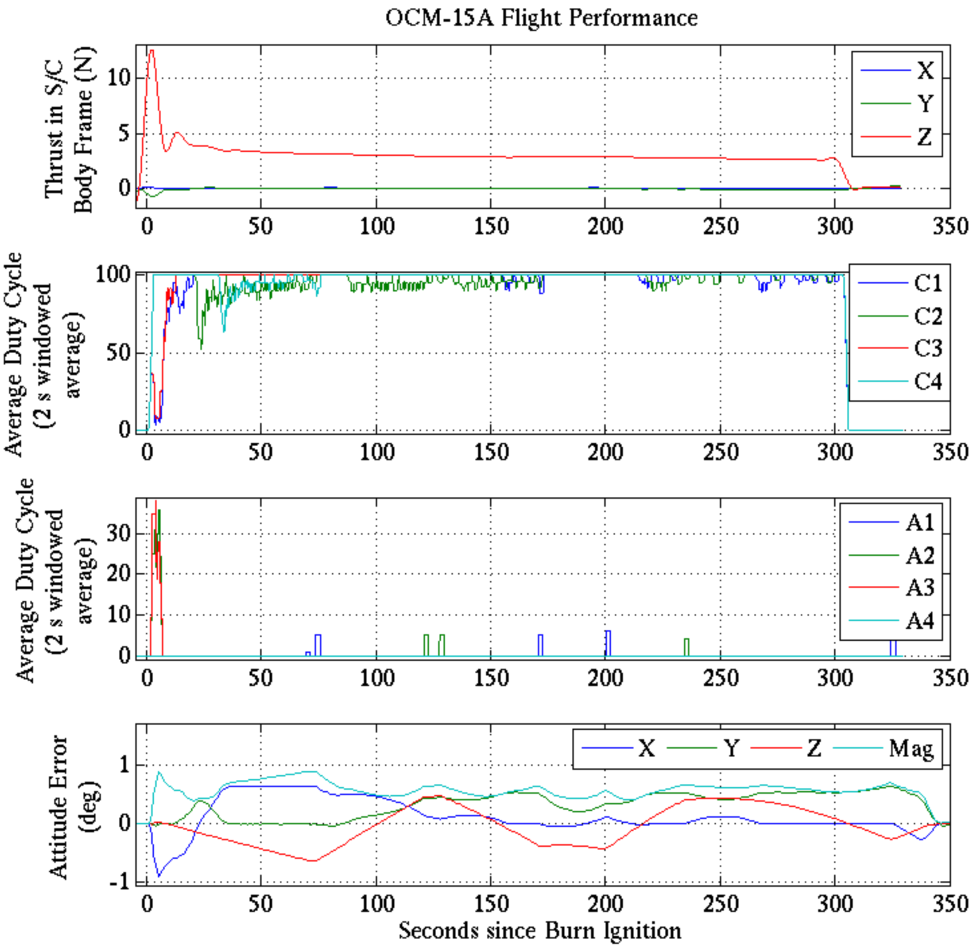

Figure 9. OCM-15A Flight Performance: (Top to Bottom) Thrust in the Spacecraft Body Frame, Average C-Thruster and A-Thruster Duty Cycles, and Attitude Error through the Burn.

Although the remaining burns executed entirely on helium through the C-thrusters, it appeared that there was still hydrazine in the A- and B-thruster feed lines. The attitude error shown in the bottom plot of Figure 9 has a scalloped pattern, with the peaks lined up with on-pulsing of the A- and B-thrusters. As the spacecraft reached the edge of the deadband, the thrusters fired to minimize the attitude control errors, but with more force than would be the case if GHe was used as the propellant. The P- and C-thrusters were clearly exhausting GHe at OCM-15 and OCM-15A, respectively, but the limited pulsing of A- and B-thrusters was insufficient to purge their lines of hydrazine. This elevated thrust for A- and B-thrusters persisted throughout the remainder of the mission.

OCM-15A placed MESSENGER back on the desired trajectory and showed that use of helium as a propellant could successfully impart ΔV. Perhaps more importantly, following OCM-15A, the spacecraft was on a trajectory ensuring that communication would be reestablished following the superior solar conjunction, thereby allowing additional, important science data to be collected as originally planned.

OCM-16 Design and Results

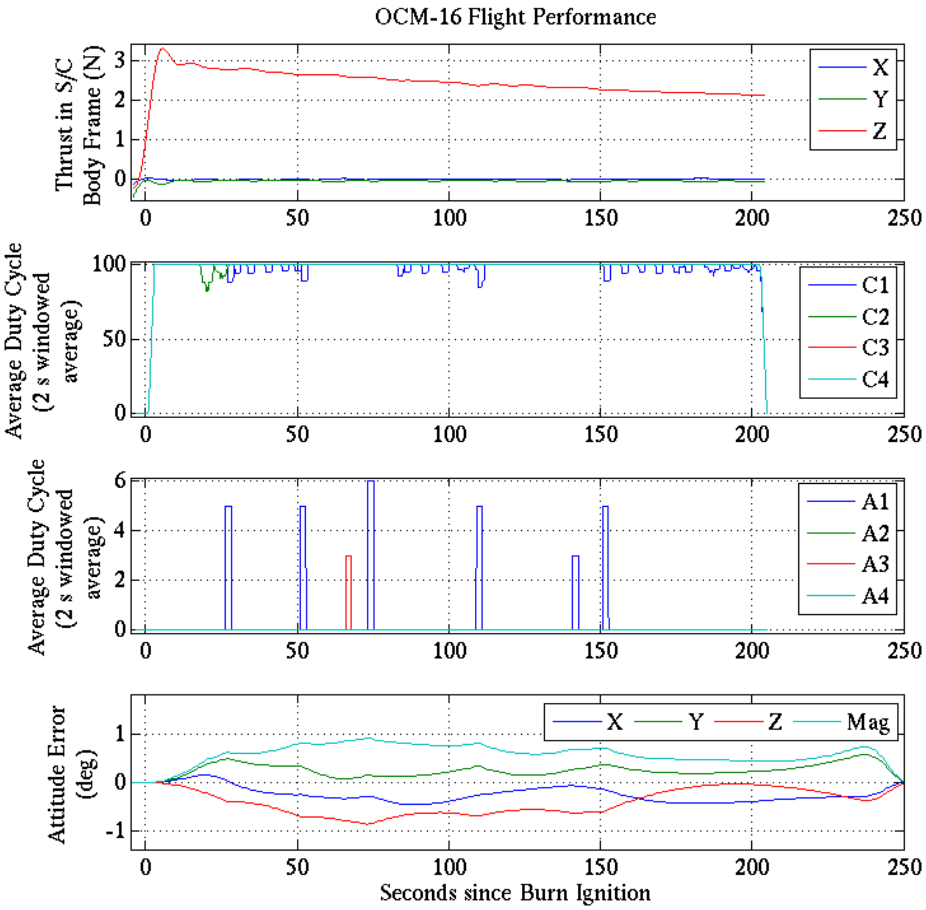

Figure 10. OCM-16 Flight Performance: (Top to Bottom) Thrust in the Spacecraft Body Frame, Average C-Thruster and A-Thruster Duty Cycles, and Attitude Error through the Burn.

As previously mentioned, the rapid sequence of maneuvers during the hover campaign required the team to design most of the maneuvers before the execution of OCM-13. OCM-16 was updated after OCM-15A, when the resulting thrust of helium through the C-thrusters was seen to be only one-third of the expected value. The OCM-16 burn timeout was substantially increased from the original design to account for the lower thrust, and the mid-burn momentum desaturation was changed to allow the wheels to passively spin down rather than actively targeting zero spacecraft momentum. The change in momentum desaturation implementation arose out of concerns that the reaction wheels (which introduce a disturbance torque to the vehicle during a momentum desaturation) could overwhelm the control torque supplied by the thrusters at the compromised thrust levels, leading to a loss of attitude control. A passive spin down provides a reduction in spacecraft momentum without imparting additional torque to the vehicle.

OCM-16 was similar to OCM-15A, with FT1, FT2, and the auxiliary tank open to allow helium to flow through the four C-thrusters. It was executed 2 days after the spacecraft exited solar conjunction on 14 April 2015, successfully raising the periapsis altitude by 6.85 km to a post-burn periapsis altitude of 13.3 km. The total ΔV of 0.985 m/s (0.020% magnitude error and 0.695° pointing error) was imparted in 201.9 s with an average thrust of ~2 N. As shown in Figure 10, the thrust dropped steadily through the maneuver as helium was expelled and the PFF dropped. Despite the thrust decline, the spacecraft continued to maintain attitude control as seen in the limited off and on pulsing of the C- and A-thrusters, respectively, as well as the relatively consistent attitude errors during the burn. The passive momentum desaturation strategy worked as hoped, resulting in a total momentum drop from 2.45 to 1.04 Nms during the burn. However, the momentum was not quite low enough to maintain acceptable momentum levels (< 3 Nms) through OCM-17, which would execute 10 days later. A final stand-alone commanded momentum desaturation was executed on 17 April 2015, and it targeted a safe momentum level that could carry the spacecraft through OCM-17.

OCM-17 Design and Results

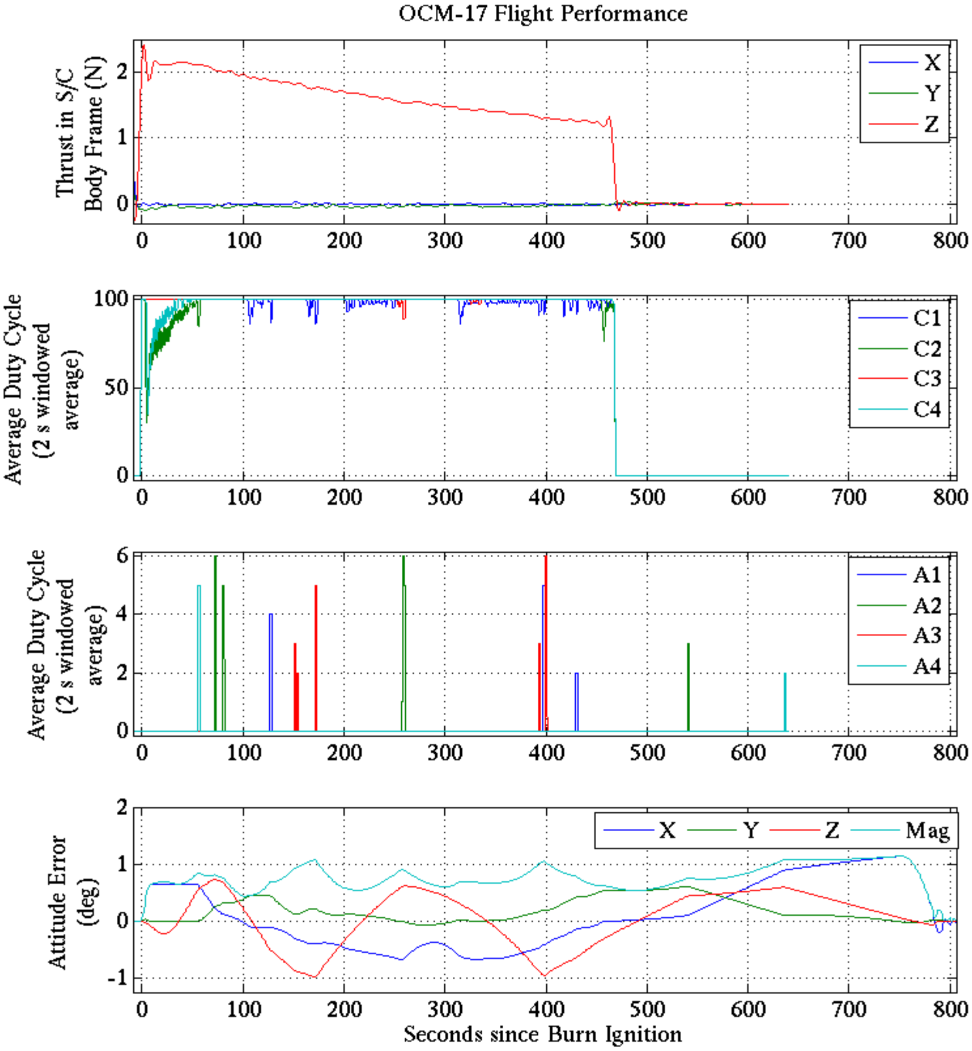

Figure 11. OCM-17 Flight Performance: (Top to Bottom) Thrust in the Spacecraft Body Frame, Average C-Thruster and A-Thruster Duty Cycles, and Attitude Error during the Burn.

OCM-17, like OCM-15A and OCM-16, used the four C-thrusters to impart ΔV, helium from the MPS as the propellant, and reaction wheels originally configured to passively spin down.

There was an obvious decrease in thrust during the two previous OCMs (see Figure 9 and Figure 10) as fuel tank pressure dropped; therefore, the team made two changes to the initially chosen burn parameters in anticipation of still lower thrust than previously observed. Because OCM-17 was the last scheduled maneuver with no need to conserve helium, the burn timeout was set to the maximum value allowable within the streamlined commanding framework (753 s) to provide the best chance for a successful burn even if the thrust was substantially lower than expected. The low thrust also created a concern that the spacecraft would no longer be able to effectively dump momentum in a nominal stand-alone commanded momentum desaturation, which uses only the 4.4-N-rated A- and B-thrusters. A passive spin down, as was used in OCM-15A and OCM-16, would not provide a sufficient decrease in momentum for the spacecraft to remain safe until impact; therefore, OCM-17 was changed to target a biased momentum level during the burn that would keep the momentum at <3 Nms for the remainder of the mission.

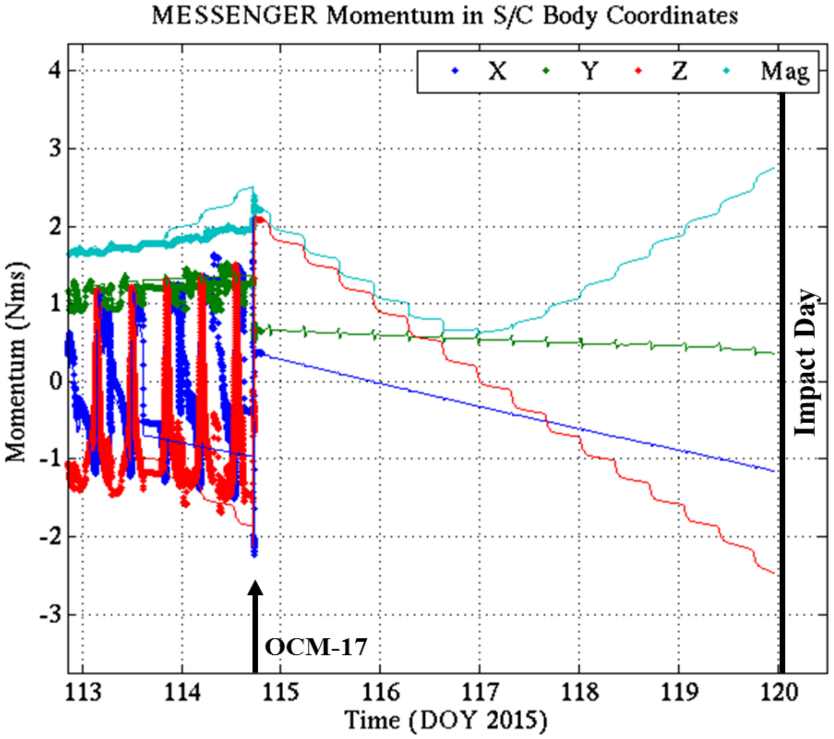

Figure 12. Flight Data and Predicted MESSENGER Momentum in Spacecraft Body Coordinates after OCM-17 for the Last Week of the Mission. DOY, Day of Year.

The last planned burn of the MESSENGER mission executed on 24 April 2015 at 17:22:49 UTC and imparted a total ΔV of 1.53 m/s by expelling ~430 g of helium over 469.22 s (0.167% magnitude error, 0.751° direction error). As shown in Figure 11, total thrust started at near 2 N but dropped steadily, with an ending force of 1.2 N. Varying thrust resulted in increased off-pulsing of thrusters C2 and C4 during the first ~50 s of the maneuver, and OCM-17 attitude error data suggest that there continued to be hydrazine in the A- and B-thruster fuel lines on the basis of the scalloped profile also seen in OCM-15A and OCM-16. The targeted momentum desaturation successfully increased the angular momentum to the desired state in <70 s and maintained that level for the remainder of the burn as designed. The momentum state before and after OCM-17, and the predicted momentum from OCM-17 to impact are shown in Figure 12.

OCM-18 Design and Results

Orbit propagations after OCM-17 indicated that the spacecraft altitude was decreasing more quickly than initially anticipated, which would result in surface impact occurring one orbit earlier than the targeted end of mission. The planned final orbit included a 70-m DSN contact that would provide the opportunity to downlink an additional 137 MB of science data. To increase the likelihood that MESSENGER would not impact the surface until the desired orbit, OCM-18 was designed, tested, uploaded, and executed in under two days, as the need for the maneuver was not identified until 27 April.

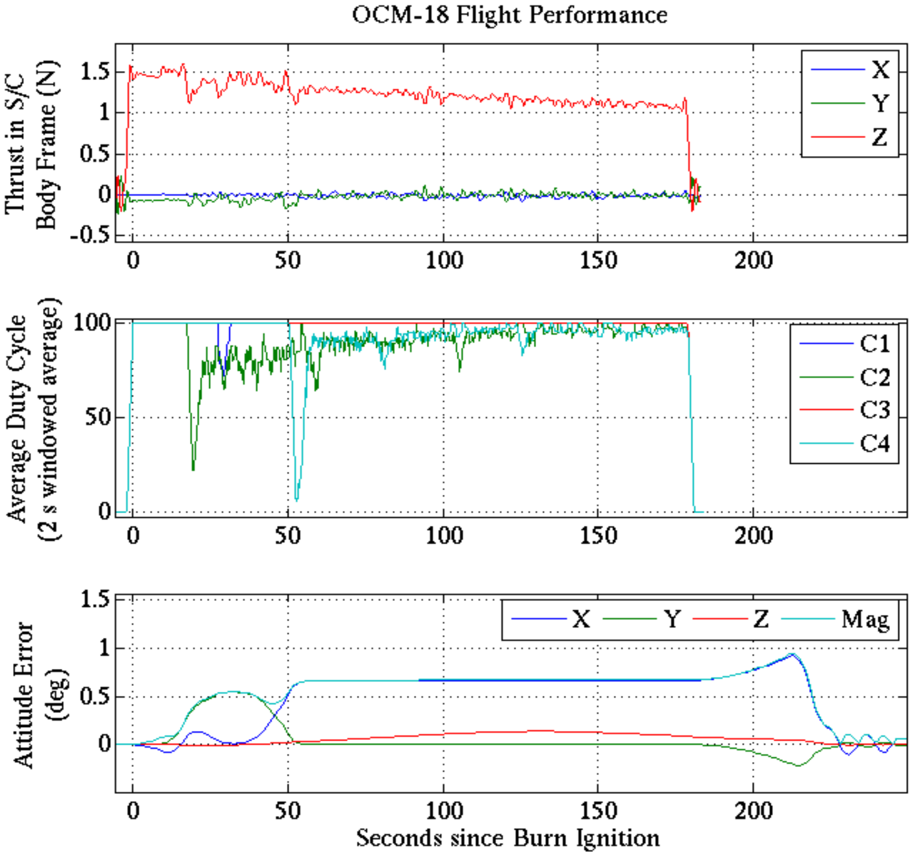

Figure 13. OCM-18 Flight Performance: (Top to Bottom) Thrust in the Spacecraft Body Frame, Average C-Thruster Duty Cycles, and Attitude Error through the Burn.

The final maneuver of the MESSENGER mission used 0.114 kg of helium to increase the periapsis altitude by 1.08 km with a total ΔV of 0.44 m/s over 181.02 s (0.176% magnitude error, 1.295° pointing error). The starting PFF was 120.2 psi (829 kPa), providing a maximum of 1.5 N of thrust at the start of the burn. In OCM-18, only the C-thrusters were fired; none of the A/B attitude control thrusters fired during the burn or during the tweak segment after the main burn. The low thrust level minimally affected the spacecraft attitude, resulting in only the C-thrusters maintaining attitude control during the maneuver. At 20 and 65 s (Figure 13), flight data show that C2 and C4 began firing less to compensate for shifts in attitude during the burn. Because of the limited time before impact and safe momentum levels, the wheels were again set to passively spin down during the burn. The momentum dropped by only 0.125 Nms, which was more than sufficient to maintain low spacecraft momentum in the final days of the mission. OCM-18 successfully delayed surface impact for one final orbit, ensuring utilization of the final planned 70-m DSN contact.

CONCLUSIONS

MESSENGER's final months in orbit at Mercury involved several maneuvers executed in ways not previously envisioned during the vehicle design, or attempted in the preceding 10 years of flight. OCM-12 was successfully executed in January 2015 despite variations in thrust, setting the stage for the hover sequence maneuvers. The unexpected hydrazine discovered in FT1 at OCM-12 provided a much-needed fuel margin for the hover maneuvers. Although the thrust level varied substantially in sometimes unexpected ways throughout the hover campaign, the spacecraft attitude control system maintained low errors in thrust magnitude and direction during the burns. The execution of OCM-13 through OCM-18 brought several challenges that were overcome with a dedicated and flexible team and robust maneuver implementation strategies, allowing an important extension to the MESSENGER mission more than a month past the originally projected impact date. This final portion of the mission afforded the science team an unprecedented view of Mercury, enabling a more detailed spatial resolution of the surface and near-surface environment. MESSENGER impacted the surface of Mercury on 30 April 2015 at 19:26 UTC after more than four years and 4104 orbits around the planet and nearly eleven years in space.

ACKNOWLEDGMENTS

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