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MESSENGER'S MANEUVERS TO REDUCE ORBITAL PERIOD DURING THE EXTENDED MISSION: ENSURING MAXIMUM USE OF THE BI-PROPELLANT PROPULSION SYSTEM

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Two orbit-correction maneuvers (OCMs) were required during MESSENGER's extended mission to reduce the orbital period from 11.6 to 8 hours. The OCMs were designed as a pair to maximize use of the bi-propellant propulsion system. The first maneuver was designed to be flexible to a range of values for the amount of oxidizer remaining in the system. A special autonomy scheme was necessary to respond to oxidizer depletion and continue the maneuver without interruption using only monopropellant thrusters. The second maneuver executed four days later and was designed on the basis of the performance of the first maneuver.

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. 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[1]. Following the success of MESSENGER's primary mission, an extended mission began on 18 March 2012. The extended mission introduced a new set of science questions that were raised by discoveries from the first year of orbital operations. In order to answer a subset of these questions, a shorter orbital period that would provide more observing time at low altitudes was desired. Two orbit-correction maneuvers (OCMs) were executed four days apart in April 2012 to reduce MESSENGER's orbital period from 11.6 to 8 hours. The maneuvers were designed as a pair to ensure that the desired orbital period would be achieved while also maximizing use of the bi-propellant propulsion system.

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The MESSENGER spacecraft is 3-axis stabilized and uses reaction wheels as the primary means of maintaining attitude control.[2] In addition, the guidance and control (G&C) system's actuator suite includes thrusters, which are used for angular momentum management and for trajectory control and can also be used as a backup for attitude control in the event of multiple wheel failures. The sensor suite is comprised of star trackers, digital Sun sensors, and an inertial measurement unit, which contains four accelerometers 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 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 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.

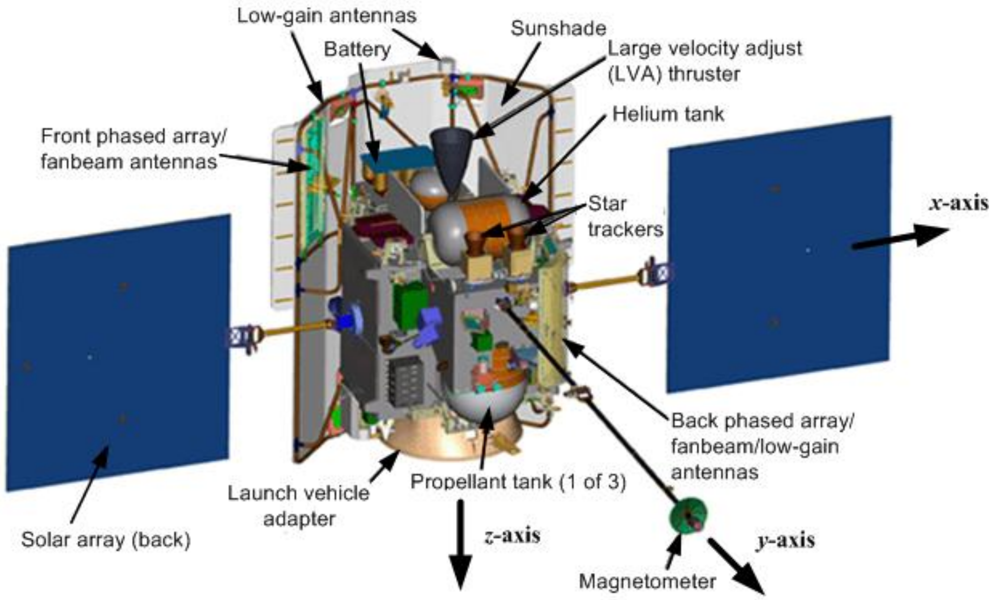

Figure 1. MESSENGER Spacecraft Components and Body-Axis Convention.

The MESSENGER propulsion system (MPS), shown in Figure 2, was designed and built by Aerojet and consists of four propellant tanks and 17 thrusters.[3] The MPS includes one bipropellant engine, the large velocity adjust (LVA) thruster, which provides about 680 N of thrust, and two sets of monopropellant thrusters, including 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 because of 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.

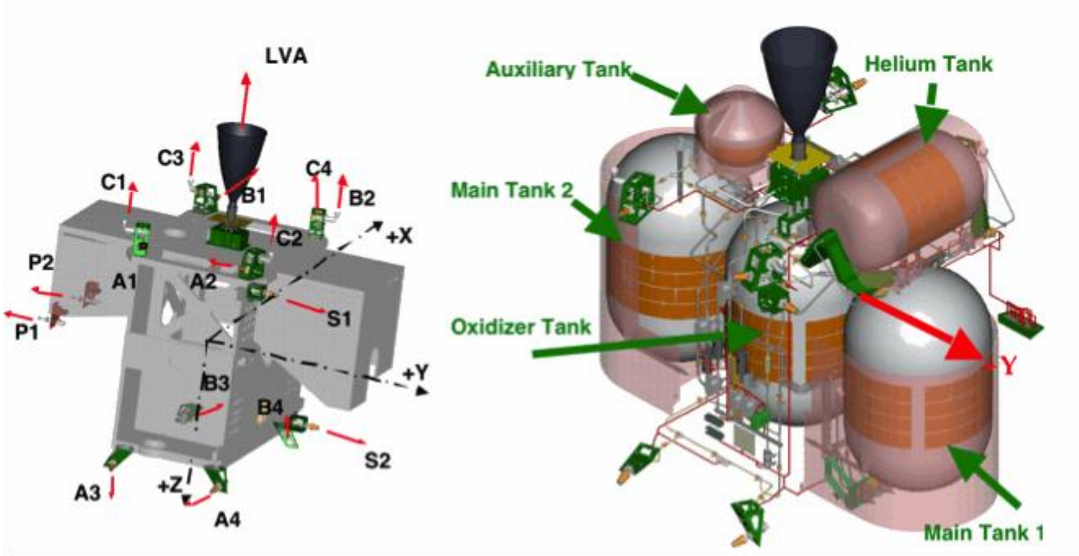

Figure 2. MESSENGER Propulsion System (MPS) Thruster Locations, Thruster Directions, and Tank Layout.

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 selected 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 employed 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, but the auxiliary tank is refilled in a separate segment in a mode-3 maneuver. A separate refill segment is required because during the main segment the main fuel tanks would not be able to support the flow rate required to fire simultaneously the LVA and 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.

EXTENDED MISSION ORBIT-CORRECTION MANEUVERS

To date the MPS has been used to execute successfully a total of eight OCMs. The first six OCMs were performed during the primary mission and kept the orbital periapsis near 200-km altitude and the orbital period near 12 hours.[4, 5] The sixth OCM was added to the primary mission trajectory plan in preparation for the extended mission. OCM-6, which was executed as a mode-2 maneuver on 3 March 2012, lowered periapsis altitude to 200 km. According to the primary mission OCM cadence of odd-numbered OCMs to lower periapsis altitude and even-numbered OCMs to reduce orbital period, the sixth OCM would have been used to reduce orbital period. However, because a very large ΔV was needed to reduce the orbital period to 8 hours in the extended mission, any additional orbital period modification was postponed until the extended mission. Rather than wasting a maneuver opportunity in March 2012, OCM-6 was used to lower periapsis altitude, which was beneficial for some observing instruments.

MPS Operational Guidelines

For all primary mission OCMs a complex set of MPS operational guidelines, developed by Donald E. Jaekle of PMD Technology (North Andover, Mass.), was followed to minimize the amount of propellant trapped on the tank baffles and the chance of gas ingestion.[6] At very low fill fractions care is needed when operating the system since the fuel and oxidizer tanks do not contain propellant management devices. The two OCMs designed to lower the orbital period early in the extended mission required a more complex set of MPS operational guidelines than those used during the primary mission, partially due to lower propellant fill fractions and the desire to deplete the remaining usable oxidizer.

On the basis of the estimated remaining usable propellant at the beginning of the extended mission, as shown in Table 1, the bi-propellant propulsion system could supply a 29-s maximum LVA thruster firing with the remaining 3.115 kg of usable oxidizer (a best-case estimate). Except for the usable oxidizer estimate, the usable propellant estimates in Table 1 are all worst-case numbers. Adoption of the best-case usable oxidizer estimate allowed the MESSENGER team to maximize performance of the final bi-propellant maneuver.

The uncertainty in the best-case remaining usable oxidizer estimate dictated that any mode-3 maneuver in the extended mission be flexible to a range of values for the amount of oxidizer remaining in the system. More specifically, the mission's final mode-3 maneuver would need to complete the desired maneuver ΔV using an unknown integral value for LVA thruster firing between 0 and 29 s. Since LVA thruster firing produces a greater thrust level than monopropellant operation alone by nearly a factor of eight, a variation in LVA thruster firing time would introduce additional variation in the total maneuver duration and the consumption of fuel. Therefore, completing the total orbital period change in a single mode-3 maneuver would require exceptional complexity and would unduly increase mission risk. In order to keep mission risk to a minimum, the total orbital period reduction was split between two separate OCMs that were designed as a pair; OCM-7 was designed to impart about 62.8% of the desired ΔV, and OCM-8 to impart the remaining 37.2%.

Table 1. Extended Mission Maneuver Planning Mass Tracking Summary. Commanded Momentum Dumps (CMDs) are Mode-1 Maneuvers for Off-Loading Angular Momentum.

	Auxiliary Tank (kg)	Main Fuel Tank 1 (kg)	Main Fuel Tank 2 (kg)	Oxidizer Tank (kg)
OCM-6 Starting Mass	10.329	11.268	16.230	4.891
Mass Added/Consumed for OCM-6	0.197	-2.597	-2.762	0.000
Mass Expended for CMDs 43-47	-0.042	0.000	0.000	0.000
OCM-7 Starting Mass	10.484	8.671	13.468	4.891
Unusable Propellant Estimated for OCM-7 Planning	-0.931	-3.561	-3.561	-1.776
OCM-7 Usable Mass	9.553	5.110	9.907	3.115

Given the amount of usable propellant remaining in the MPS, Mr. Jaekle performed low-gravity fluid dynamics analyses to determine a set of guidelines for operating the MPS during a pair of maneuvers, the first a mode-3 maneuver and the second a mode-2 maneuver. The fuel tank switching scheme implemented at OCM-6 was crucial in enabling another mode-3 maneuver. Operating the LVA thruster without turn-on transients due to gas ingestion requires at least 7.35 kg of usable propellant in the main fuel tank that is being accessed at LVA thruster ignition. Since main fuel tank 2 contained at least 7.35 kg of usable fuel following OCM-6, a final mode-3 maneuver was possible.

The OCM-7 mode-3 maneuver sequence guidelines, shown in Table 2, were developed under the assumption that oxidizer depletion was possible during the main segment and that OCM-7 would be the final mode-3 maneuver. The settle segment in Table 2 is no different from that in the primary mission MPS operational guidelines for mode-3 maneuvers and draws liquid below the tank baffles into a pool at the tank outlets. To further stabilize the small pool of oxidizer and to reduce the likelihood of oxidizer gas ingestion, the refill segment minimum duration was increased from 35 s to 70 s for the extended mission. Since the oxidizer tank would never be accessed again following OCM-7, the trim segment minimum duration could be reduced to 20 s, which is about three times less than was required during the primary mission (the properties of liquid oxidizer make it more difficult to settle than fuel). During the main segment, all four C-thrusters must be used for ΔV in addition to the LVA thruster to minimize the effects of thrust reduction in the case of earlier-than-expected (<29 s) oxidizer depletion. Since all four C-thrusters are used during the main segment, the trim segment can also utilize the full set.

Table 2. OCM-7 Mode-3 Maneuver Sequence MPS Operational Guidelines.

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	70	Main Tanks
3	Main	LVA, C1, C2, C3, C4	N/A	Main Tanks, Oxidizer Tank
4	Trim	C1, C2, C3, C4	20	Main Tanks

The OCM-8 mode-2 maneuver sequence guidelines, shown in Table 3, were developed from estimates for the range of usable fuel that would remain in the system after OCM-7. In all cases the remaining usable propellant in both of the main fuel tanks would be below the 7.35 kg threshold. Below this level the tanks would require an additional settle segment of firing two C-thrusters for at least 35 s in order to reduce the risk of gas ingestion from the main fuel tanks during the main segment. The second settle segment added complexity to the OCM-8 maneuver design, because the G&C software does not recognize a second settle segment; in order to execute a second settle segment, a mid-maneuver parameter block load must be implemented. Since the best-case values for fuel available at OCM-8 could enable an additional mode-2 maneuver sometime in the future, the OCM-8 main segment required a minimum duration of 41 s. The main segment minimum duration would maximize the remaining usable propellant by preventing a propellant geyser from forming that would deposit onto the main fuel tank baffles.

Table 3. OCM-8 Mode-2 Maneuver Sequence MPS Operational Guidelines.

Segment Order	Segment Type	Thrusters	Minimum Duration (s)	Propellant Source
1	Settle 1	A1, A2, B1, B2	60	Auxiliary Tank
2	Settle 2	C1 and C4 or C2 and C3	35	Auxiliary Tank
3	Main	C1, C2, C3, C4	41	Main Tanks

OCM-7 Fault Protection

The fault protection scheme developed specifically for OCM-7 was instrumental in maximizing efficiency of the bi-propellant propulsion system. Without the special autonomy rule and macro that were designed to detect oxidizer depletion, a mode-3 maneuver that was flexible to a range of values for the amount of oxidizer remaining in the system would not have been possible. A maneuver designed to deplete the best-case estimate for oxidizer remaining in the MPS using nominal fault protection and a nominal mode-3 maneuver sequence would have significantly increased mission risk, since oxidizer depletion would either abort the burn, resulting in a significant under-burn, or, if internal G&C autonomy was disabled to allow the burn to continue past oxidizer depletion, gas ingestion could cause potentially non-recoverable controllability issues. Given that a non-recoverable spacecraft is an unacceptable risk, the team would have been forced to either accept the possibility of significant under-burn at OCM-7, which would jeopardize the amount of time that could be dedicated to science, or, not attempt a final mode-3 maneuver, decreasing the mission's remaining ΔV capability.

The OCM-7-specific autonomy rule and macro were designed to disable the bi-propellant thruster upon detection of oxidizer depletion, thereby forcing the system to complete the remainder of the maneuver using the monopropellant thrusters. In particular, the maneuver and special fault protection were designed so that the maneuver would continue uninterrupted without tripping any internal G&C system performance checks that would abort the burn. The fault protection scheme relied on the ability of the main processor (MP) to monitor the value for the "low-thrust flag," which is asserted by the G&C software during mode-3 maneuvers. The G&C "low-thrust flag" is not directly stored in the MP's data collection buffer (DCB). Therefore, in order for the MP to monitor the value for the "low-thrust flag," a memory dwell configured to monitor the physical address in memory where the flag is stored must be used. The result of the memory dwell is then reported to the MP DCB once per second.

The custom autonomy rule monitors the "low-thrust flag," and if the value is set to "1" for two consecutive seconds, the rule initiates a macro that disables bi-propellant operation; a "low-thrust flag" value of "1" indicates that the thrust level calculated by the G&C software has fallen below a parameterized value, the value representing oxidizer depletion. The response macro disables bi-propellant operation by commanding the G&C software to mask the LVA thruster as being available for use and sends commands to close the LVA thruster fuel and oxidizer latch valves. In the case that the LVA thruster fires for the maximum 29 s, the autonomy rule will fire, since the transition to C-thruster use only will be flagged as having low thrust. However, it is a no-harm case because it will reassert the desired state; at this time in the maneuver sequence, the commands sent are identical to the oxidizer depletion response macro. The redundant commanding was included for added conservatism in the case that the autonomy rule failed to respond as expected.

Nominal performance of the specific OCM-7 fault protection relied on careful selection of two parameters, the duration over which the "low-thrust flag" is raised that will elicit a macro response (the autonomy rule "persistence"), and the thrust value chosen to represent oxidizer depletion. The autonomy rule persistence was chosen to be 2 s to balance the risk of falsely tripping the autonomy rule when gas ingestion is intermittent and the risk of wasting fuel after oxidizer depletion; about 1.7 s was estimated to be the longest duration of intermittent gas ingestion due to inboard-outboard propellant slosh as estimated by Mr. Jaekle. The combination of the 2 s autonomy rule persistence and the latencies involved in reporting the value of the "low-thrust flag" to the MP DCB result in an effective LVA shutdown latency that is closer to 5-6 s.

The low-thrust threshold was set to be 50% of the desired thrust from the LVA plus 60 N; 60 N corresponds to the minimum duty cycle that was expected for the C1-4 thrusters operating alongside the LVA thruster, off-pulsed for control, during the main maneuver segment. The LVA thrust value of 50% was estimated to be the upper limit for thrust in the presence of intermittent gas ingestion. Additionally, an LVA thrust value of about 45% was thought to be the thrust level produced in a post-oxidizer-depletion fuel-only flow scenario. Since this scenario would introduce an untested and potentially harmful engine operating condition, the low-thrust limit was chosen to be higher than the 45% LVA thrust value plus 60 N. Prior to its use at OCM-7, the fault protection scheme was qualified via a simulation that used data from the intermittent gas ingestion that was seen at OCM-3, with a fictional fuel-only flow scenario, and with a range of nominal performance scenarios; in all cases the fault protection scheme performed nominally.

Maneuver Planning Strategy

To ensure that the desired orbital period change would be achieved with a pair of OCMs early in MESSENGER's extended mission, the possible range of outcomes associated with variable LVA thruster firing at OCM-7 had to be well understood. First, the OCM-7 maneuver sequence had to be compatible with the variations that could be expected during the maneuver execution; even in the presence of variation the maneuver should continue until the desired ΔV is achieved. Secondly, the effect on OCM-8 starting conditions had to be incorporated into the maneuver planning strategy and schedule.

From the G&C and propulsion system viewpoints, a variable LVA thruster firing has the largest effect on maneuver duration, fuel tank usage, and propulsion system states, all of which must be explicitly included in a maneuver sequence. For instance, within a maneuver sequence the limit on maneuver duration (the "time-out" duration) must be set so that the G&C software can abort an off-nominal burn that is taking too long to complete. Since nominal LVA thruster operation delivers more ΔV in the same amount of time as a monopropellant operation, the time-out duration for OCM-7 had to be set for the 0-s LVA thruster firing case, which would have required the longest maneuver duration in order to achieve the desired ΔV. Otherwise, cases with longer LVA thruster firing times could be cut off too early. Related to maneuver duration is the fuel tank usage scheme. All maneuver sequence designs must include a fuel tank usage scheme that dictates which tanks will provide fuel during each maneuver segment, and how long they should be accessed. Variation entered into the OCM-7 fuel tank usage scheme due to maneuver segment duration and the difference in mass flow rate between bi-propellant and monopropellant operation. Finally, the propulsion system states, such as tank pressures, are dependent on how long propellant tanks are accessed and what their current fill fractions are. Tank pressure, for instance, affects the thrust and specific impulse that can be expected from each thruster, which consequently influences the achieved trajectory change.

To understand the difference in the variation of achieved trajectory that was possible following OCM-7, and to understand how that variation might affect the design of OCM-8, the mission design team analyzed three cases for the duration of LVA thruster firing: the 0-s case, the 14-s case, and the 29-s case. Each LVA thruster firing duration case would result in a different post-OCM-7 achieved orbital period, optimal OCM-8 start time, and desired OCM-8 ΔV, indicating that a universal OCM-8 maneuver sequence was not possible. Although the MESSENGER team could not create an OCM-8 maneuver sequence that was compatible with all nominal OCM-7 outcomes, the team could pre-design for one of the OCM-8 initial conditions cases and prepare to turn around within a short period of time an optimized OCM-8 maneuver sequence designed on the basis of the performance of the first maneuver.

To maintain consistency with the stated goal of maximizing use of the MPS, the OCM-7 maneuver sequence was developed using a desired ΔV and maneuver start time that were based on the best-case scenario of the LVA thruster firing for 29 s. For the OCM-8 maneuver sequence developed prior to OCM-7, however, the maneuver design was based on the case of 14 s of LVA thruster firing during OCM-7, since the 14-s case was considered the most likely. Basing the OCM-8 maneuver design on the 14-s OCM-7 case provided some conservatism in the team's ability to execute a second maneuver four days later on 20 April 2012. Under the assumption that the 14-s OCM-7 case was the most likely outcome, the chances of having to re-design OCM-8 were thought to be reduced. Additionally, if the team were unable to upload a new OCM-8 maneuver sequence due to Deep Space Network (DSN) problems, for instance, an OCM-8 maneuver sequence would already be onboard and would be able to provide most of the desired trajectory change under a variety of initial conditions. In addition to including a pre-OCM-7 OCM-8 maneuver design in the maneuver planning strategy, the planning schedule accounted for a re-design of OCM-8 within 24 hours on the basis of the performance of OCM-7.

OCM-7 Design and Results

Once the extended mission MPS operational guidelines, specialized fault protection scheme, and maneuver planning strategy were developed, the OCM-7 fuel tank usage scheme could be designed. The fuel tank usage scheme was the final critical design element that would enable a mode-3 maneuver that was flexible to a range of values for the amount of oxidizer remaining in the system. The fuel tank usage scheme is outlined in Table 4, along with the maneuver segment durations and thruster selections, all of which are consistent with the OCM-7 MPS operational guidelines in Table 2. As is typical, the settle segment draws fuel from the auxiliary tank. During the refill segment, fuel tank 2 (FT2) is the first main fuel tank to be accessed, since it was estimated to contain more than 7.35 kg of usable fuel and contained more usable fuel than fuel tank 1 (FT1), as shown in Table 1. The magnitude of the difference between the amounts of usable fuel in the main fuel tanks was sufficiently high that the entire main segment would draw fuel from FT2, even with the possible variation in the duration of LVA thruster firing. Once transitioning to the trim segment, FT2 would remain the fuel tank being accessed for a maximum of 59 s. At this time, if the maneuver had not yet completed, FT1 would be become the active fuel tank. The duration of 59 s is specific to the point in the maneuver, given a maximum LVA thruster firing duration, for which FT2 would be depleted to about 1.5 kg above the minimum usable fuel estimate (the worst-case FT2 fuel expenditure). After 92 s on FT1, which is specific to the duration required to deplete FT1 down to its minimum usable fuel estimate given no LVA thruster operation (the worst-case FT1 expenditure), FT1 would be closed and fuel would be accessed from the auxiliary tank for the remainder of the maneuver. The G&C software handles the aforementioned tank transitions internally on the basis of settable parameters, except for the transition from FT1 to the auxiliary tank during the trim segment. Within the maneuver sequence, a special time-tagged command was added to force the transition from FT1 to the auxiliary tank 151 s into the trim segment. In case the maneuver has already transitioned to using the auxiliary tank or the maneuver has completed, the time-tagged commanding harmlessly re-iterates the current state. The remainder of the trim segment (if necessary) and the tweak segment continue with the use of the auxiliary tank until the desired ΔV has been achieved or the maneuver has been terminated at the time-out duration.

Table 4. OCM-7 Maneuver Sequence. Attitude Control Thrusters Are Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks [Designed Duration (s)]
Settle	60	60	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Auxiliary Tank
Refill	70	70	C1, C4 (off-pulsed for control)	A1-4, B1-4	Fuel Tank 2
Main	≤ 29	29	LVA (continuous), C1-4 (off-pulsed for control)	A1-4, B1-4	Fuel Tank 2 [≤ 29]
Trim	≤ 280	28.76 with Fuel Tank 2	C1-4 (off-pulsed for control)	A1-4, B1-4	Fuel Tank 2 [≤ 59] Fuel Tank 1 [≤ 92] Auxiliary Tank [≤ 129]
Tweak	30	30	None	A1-4, B1-4	Auxiliary Tank

OCM-7 was successfully executed on 16 April 2012, imparting a total ΔV of 53.26 m/s, which decreased the orbital period from 11.6 to 9.08 hours (3.43 s below target) with negligible change to the orbital periapsis altitude. The G&C system performed very well, resulting in a ΔV magnitude error of 0.0451% and a ΔV pointing error of 0.0063°, both of which were within the expected errors for a mode-3 maneuver. As can be seen in Table 4, the LVA thruster fired for the maximum 29 s, which enabled the maneuver to be completed in the minimum amount of time and provided the mission with the best-case scenario for remaining ΔV capability. Since the LVA thruster fired for the maximum 29 s, the special autonomy rule never responded to apparent oxidizer depletion; it responded only to the transition between the main and trim segments, as expected in the case of 29 s of LVA thruster firing. After a significant amount of the desired ΔV was imparted during the main segment, the trim segment was required to last only 28.76 s and used fuel from FT2 only.

At the completion of OCM-7, 11.148 kg of propellant had been consumed, of which 8.176 kg was hydrazine and 2.972 kg was oxidizer. All of the consumed hydrazine was accessed from the auxiliary tank and FT2; FT1 was never accessed, indicating that a sizable amount of fuel was available in FT1 to be used for OCM-8. From the best-case unusable oxidizer estimate of 1.776 kg (see Table 1), OCM-7 left 0.143 kg of usable mass in the oxidizer tank, indicating that OCM-7 was very successful in maximizing the efficiency of the MPS.

OCM-8 Design and Results

The OCM-8 maneuver sequence that was developed prior to OCM-7 is shown in Table 5, and follows the extended mission MPS operational guidelines in Table 3. In this maneuver sequence, which assumes that the LVA thruster fired for 14 s during OCM-7, the main segment would draw fuel from FT2 for the first 14 s, and then transition to the auxiliary tank for the remainder of the maneuver. However, on the basis of the outcome of OCM-7, if the pre-built OCM-8 maneuver sequence had been executed on the spacecraft without modification, there would likely have been insufficient fuel in FT2 for the first 14 s of the main segment. In such a case, insufficient fuel in FT2 could result in a burn abort due to sustained gas ingestion, since it would likely trip the internal G&C autonomy that monitors attitude stability. Additionally, the achieved thrust during gas ingestion would be less than expected, increasing the chances that the maneuver would not complete before reaching the time-out duration. The chance of aborting the burn due to low feed pressure values (a propulsion system state monitored by the G&C software during maneuvers) is also increased if the pre-built OCM-8 were to be executed post-OCM-7.

Table 5. Pre-OCM-7 OCM-8 Maneuver Sequence. Design Is Predicated on a 14-s LVA Thruster Firing Duration at OCM-7. Attitude Control Thrusters Are Pulsed as Needed.

Maneuver Segment	**Designed Duration (s)**	ΔV **Thrusters**	**Attitude Control Thrusters**	**Fuel Tanks [Designed Duration (s)]**
Settle 1	60	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Auxiliary Tank
Settle 2	35	C1, C4 (off-pulsed for control)	A1-4, B1-4	Auxiliary Tank
Main	≤ 255	C1-4 (off-pulsed for control)	A1-4, B1-4	Fuel Tank 2 [14] Auxiliary Tank [≤241]
Tweak	30	None	A1-4, B1-4	Auxiliary Tank

Following OCM-7 there were no issues with DSN communications, so the MESSENGER team was able to analyze post-OCM-7 telemetry quickly. In addition, all necessary personnel were ready and available to re-design OCM-8 within 24 hours, given the performance of OCM-7. The post-OCM-7 OCM-8 maneuver sequence is shown in Table 6. The main differences between the two OCM-8 maneuver sequences are the target ΔV, maximum main segment duration, and the fuel tank usage scheme. In the revised OCM-8 maneuver sequence thrust would be supplied for a longer period of time using thrusters drawing fuel from pressure-regulated tanks (the main fuel tanks), rather than thrusters drawing fuel from the auxiliary tank in blow-down mode, so the main segment duration in the revised OCM-8 maneuver sequence was expected to be shorter. Additionally, since OCM-7 resulted in a best-case scenario for total mass remaining in the main fuel tanks, the main segment could draw fuel from the main fuel tanks for a longer period of time before switching to the auxiliary tank. The target ΔV differed to account for the 29 s LVA thruster firing and the fact that the mission design team cannot perfectly predict the achieved thrust levels at every moment in the maneuver during their planning.

Table 6. Post-OCM-7 OCM-8 Maneuver Sequence. Attitude Control Thrusters Are Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks [Designed Duration (s)]
Settle 1	60	60	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Auxiliary Tank
Settle 2	35	35	C1, C4 (off-pulsed for control)	A1-4, B1-4	Auxiliary Tank
Main	≤ 195	145.18 with Fuel Tank 1	C1-4 (off-pulsed for control)	A1-4, B1-4	Fuel Tank 1 [89] Fuel Tank 2 [≤ 57] Auxiliary Tank [≤ 49]
Tweak	30	30	None	A1-4, B1-4	Auxiliary Tank

The updated OCM-8 fuel tank usage scheme was intended to deplete FT1 to a revised worst-case estimate for remaining fuel in FT1, which would nominally occur after 85 s of drawing fuel from FT1. This revision included a reduction in the unusable propellant margin, taking advantage of the fact that usable propellant estimates were proven to be conservative at OCM-7. In the maneuver design, the time on FT1 was intentionally extended 4 s past the time of FT1 depletion, since it was estimated that the thrust reduction that would occur during the 4 s of gas ingestion would not uncover FT2’s outlet, and 4 s of gas ingestion did not present appreciable risk. After 89 s of drawing fuel from FT1, the G&C software was supposed to switch to FT2 for a maximum of 57 s, which was believed to be the maximum duration that FT2 could provide fuel based on the revised usable propellant estimates. If the maneuver had not completed after 57 s of drawing fuel from FT2 a time-tagged command would perform the transition to the auxiliary tank. Otherwise, the G&C software would perform the switch when the target ΔV was achieved to begin the tweak segment.

The OCM-8 maneuver on 20 April 2012 successfully imparted a total ΔV of 31.42 m/s, which decreased the orbital period from 9.08 to 8.0 hours (1.89 s above target) with negligible change to the orbital periapsis altitude. The G&C system performed very well, resulting in a ΔV magnitude error of 0.0521% and a ΔV pointing error of 0.0477°, both of which were within the expected errors for a mode-2 maneuver.

The execution of OCM-8, however, contained some operational surprises in regard to the observed fuel tank switching commands. As can be seen in the achieved duration column in Table 6, the G&C software failed to send the command to switch from FT1 to FT2 at 89 s into the main segment. Instead, the entire main segment completed using FT1 only. Diagnosis of the main fuel tank swap failure revealed that for any mode-2 or mode-3 maneuver that follows a prior mode-2 or mode-3 maneuver and has exactly one tank swap (as controlled by the G&C software; time-tagged commands within the maneuver sequence are not involved), the subsequent tank swap command will not be sent. The maneuvers must be of the same mode, but they need not immediately follow one another. The only maneuver that shares these characteristics with OCM-8 was OCM-6, because OCM-6 was a mode-2 maneuver and contained only one main fuel tank swap. The value that initiates a tank swap was “stuck” across the OCM-6 and OCM-8 maneuvers, resulting in the first main fuel tank swap during OCM-8 (FT1 to FT2) being skipped, since the logic caused the G&C software to believe that the desired tank swap had already occurred. If subsequent tank swaps were to be commanded by the G&C software, the subsequent tank swaps would have occurred; only the first tank swap is affected by the hole in the logic.

Although the main segment accessed FT1 for longer than designed, high-rate accelerometer data from OCM-8 showed no evidence of gas ingestion and the desired ΔV was still achieved, indicating that the usable propellant estimate for FT1 was very conservative. Without the extra conservatism in the usable propellant estimates that were used to plan the extended mission OCMs, the tank switch failure at OCM-8 could have resulted in an under-burn at OCM-8. In fact, the substantial amount of work that was required to develop the usable propellant estimates was essential to success of both OCM-7 and OCM-8.

Following OCM-8 the usable propellant estimates were revised on the basis of the performance of OCM-7 and OCM-8, as shown in Table 7. The usable propellant in FT1 is effectively zero following OCM-8, since 0.576 kg cannot be reliably settled at the tank outlet. The amount of usable oxidizer that remains is also inaccessible. Therefore, MESSENGER's remaining ΔV capability depends on the amount of usable fuel remaining in FT2 and the auxiliary tank, estimated to be a total of 12.477 kg after OCM-8. Options for future OCMs are currently being studied and benefit greatly from the extra 2.683 kg believed to be accessible in FT2, which the team was not expecting to be available at this point in MESSENGER's mission. Even with the amount of fuel needed for regularly scheduled commanded momentum dumps (about 10 g per CMD, about 40 CMDs per Earth year), the amount of fuel that remain on the spacecraft has the potential to postpone Mercury surface impact until March or April 2015, presenting significant opportunity for additional scientific data collection.

Table 7. OCM-8 Mass Tracking Summary.

	Auxiliary Tank (kg)	**Main Fuel Tank 1 (kg)**	**Main Fuel Tank 2 (kg)**	**Oxidizer Tank (kg)**
OCM-8 Starting Mass	10.572	8.671	5.200	1.919
Mass Added/Consumed for OCM-8	0.154	-8.095	0.000	0.000
OCM-8 Ending Total Mass	10.725	0.576	5.200	1.919
Unusable Propellant Estimated for OCM-8 Planning	-0.931	-3.411	-2.516	-1.776
OCM-8 Ending Usable Mass	9.794	0.000	2.683	0.143

CONCLUSION

After careful design and consideration of impacts to mission risk, the two OCMs of MESSENGER's extended mission successfully reduced the orbital period to 8 hours. The first maneuver in the pair executed on 16 April 2012 and depleted the usable oxidizer as planned with no maneuver interruptions or other anomalies. From the velocity change on 16 April, the follow-up monopropellant maneuver was re-designed within 24 hours and executed on 20 April. The second maneuver completed the final orbital period adjustment from 9.1 to 8 hours. Conservatism in the usable propellant budget and in the maneuver design ensured that the desired orbital period change would be achieved and that the use of the bi-propellant propulsion system would be maximized. Consequently MESSENGER's remaining ΔV capability has the potential to postpone

Mercury surface impact until March or April 2015, presenting significant opportunity for additional scientific observations.

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