MESSENGER's Mercury Orbit Insertion Maneuver: Design Chronology, Contingency Preparedness, and Final Results

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Abstract. On March 18, 2011, MESSENGER became the first spacecraft to orbit the planet Mercury. The successful Mercury orbit insertion (MOI) maneuver was preceded by many years of design trades and contingency preparations. The design history for this maneuver includes such improvements as a cost-saving, risk-reducing simplification from two maneuvers to one. Contingency preparedness analyses for MOI, one of the most thorough ever completed for an orbiter mission, revealed new insights into maneuver design and trajectory optimization that preserved the potential for full recovery from about 82% of all MOI under-burn scenarios. In addition, the final design objectives and results of MOI offer an opportunity for objective evaluation of the maneuver's success.

Keywords: MESSENGER, Mercury, orbiter, contingency.

1. Introduction

Designed and operated by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in Laurel, Maryland, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is led by the Carnegie Institution of Washington with key flight and science operation contributions from KinetX, Inc., NASA's Jet Propulsion Laboratory (JPL) and Goddard Space Flight Center, and numerous universities, research institutions, and subcontractors. This seventh mission in NASA's Discovery Program launched from Cape Canaveral, Florida, aboard a Delta II 7925H-9.5 launch vehicle on 3 August 2004. Seven years after launch the spacecraft has completed five large deep-space maneuvers (DSMs), one Earth flyby, two Venus flybys, three Mercury flybys, Mercury orbit insertion (MOI), and one orbit-correction maneuver. The mission's core science objectives[1] are being addressed during a one-year Mercury orbital phase that began after MOI.

The design of the MOI maneuver for the March 2011 arrival at Mercury, first identified in 1998[2], underwent a number of improvements, refinements, and tests until days before orbit insertion. These improvements included a cost-saving simplification from a two-part MOI to a single MOI maneuver, improvements in maneuver ΔV optimization, and accuracy enhancements to the maneuver model determined from in-flight performance. Two in-flight maneuver tests boosted the MESSENGER flight team's confidence to implement the variable thrust direction needed for MOI. Another aspect of the MOI design chronology comes from variations in the launch opportunities, resulting in different planetary gravity-assist flyby options, Mercury arrival dates, and Mercury arrival velocities.

To meet science requirements and engineering safety constraints, the spacecraft's planned initial orbit included a 200-km (125 km to 225 km) periapsis altitude, 12-hour (± 10 minute) orbit period, and 60º N (56ºN to 62ºN) periapsis latitude. An 82.5º (± 1º) initial inclination requirement prevents end-of-mission inclination from exceeding 85.0º relative to Mercury's equator. The Mercury orbit-insertion strategy uses one maneuver, minimizing the time and propellant required to deliver the spacecraft into the science orbit. The maneuver's timing and time-varying thrust vector orientation were designed to minimize propellant usage. The MOI maneuver slowed the spacecraft's Mercury-relative velocity by orienting the thrust vector nearly opposite to the instantaneous spacecraft velocity vector. The initial thrust time for MOI gave the best possible simultaneous link margin during MOI using antennas at Deep Space Network locations in Goldstone, California, and Canberra, Australia. Final reconstruction of the MOI maneuver indicated successful placement of the spacecraft into the science orbit well within allowable tolerances. Preparation for MOI led to the development of multiple contingency strategies. Recovery options from an anomalous or missed MOI were identified, designed, documented, reviewed, and practiced using ground software and flight team interfaces. For MOI ΔV completion < 70%, the spacecraft would enter a new orbit around the Sun. For MOI ΔV completion > 70%, the spacecraft would enter orbit around Mercury. Each contingency recovery plan required up to two deterministic maneuvers to insert the spacecraft into the Mercury science orbit, but recovery from heliocentric orbit required 2-4 extra Mercury flybys. If

52% of MOI ΔV were completed, the recovery strategy delayed the timing of the first of two recovery maneuvers until nearly three months after the missed or anomalous MOI. Additional strategies were designed for recovery from a number of problems that would place the spacecraft in a Mercury-centered orbit that did not meet primary science orbit requirements.

2. Mercury Orbit Insertion Design Chronology before MESSENGER Launch

The history of Mercury orbit insertion maneuver design for low-cost ballistic Mercury orbiters spans a quarter century from the 1985 identification of the heliocentric trajectory class used by MESSENGER to the 2010 final MOI design. In 1985 Yen[3] documented a new method with improved performance for ballistic Mercury orbiter missions. This method lowered launch energy and post-launch ΔV by using two Venus gravity assists, trajectory-correction maneuvers (TCMs) if necessary for Earth-to-Venus and Venus-to-Mercury transfer phasing, followed by up to three Mercury gravity assists with subsequent ΔV near aphelion. The Venus flybys lower the spacecraft orbit's perihelion and aphelion as well as perform much of the 7° plane change from Earth orbit to Mercury orbit. Each Mercury flyby and subsequent ΔV lower the spacecraft orbit's aphelion and rotates the orbit line of apsides closer to Mercury's line of apsides, thereby minimizing the orbit insertion ΔV.

The requirements for MESSENGER's MOI maneuver originated with early mission concept studies at JHU/APL in the spring of 1996 and concluded with a change in the orbit period tolerance early in 2010. Prior to MESSENGER's July 1999 formal selection by NASA, the initial science orbit requirements at Mercury matched the parameters given in the Introduction, except for an 80° orbit inclination and a tighter ± 1 minute orbit period tolerance. In March 1998, Venus-Venus-Mercury-Mercury gravity assist (VVMMGA) and VVMMMGA heliocentric trajectories with August 2005 launch periods were designed, and the latter option was modified to become an early MESSENGER backup launch option. In April 2000, the addition of a one-year Earth-Earth transfer prior to the August 2005 launch brought a new EVVMMMGA backup launch option into the allowable launch period under current Discovery Program guidelines. This early backup launch option eventually became the opportunity utilized by MESSENGER on its 3 August 2004 launch. April 2000 also brought initial designs of a March 2004 launch VVMMGA trajectory with 5 April 2009 MOI and a backup May 2004 launch VVVMMGA trajectory with 2 July 2009 MOI[4]. The final baseline and backup launch options in 2004 appear as key-event timelines in Figure 1. The ΔV for MOI depends on arrival velocity relative to Mercury and on the sub-spacecraft Mercury periapsis latitude, which corresponds to the Mercury arrival argument of periapsis. For trajectories with only two Mercury flybys, MOI ΔV was about 1.6 km/s including finite-burn costs. For these trajectories, high MOI ΔV ruled out a deterministic TCM prior to the first Mercury-TCM-Mercury leg. Analytical support for the MESSENGER navigation and mission design teams was provided by JPL from 1997 until late 2002 and KinetX, Inc., from May 2003 until the end of the mission.

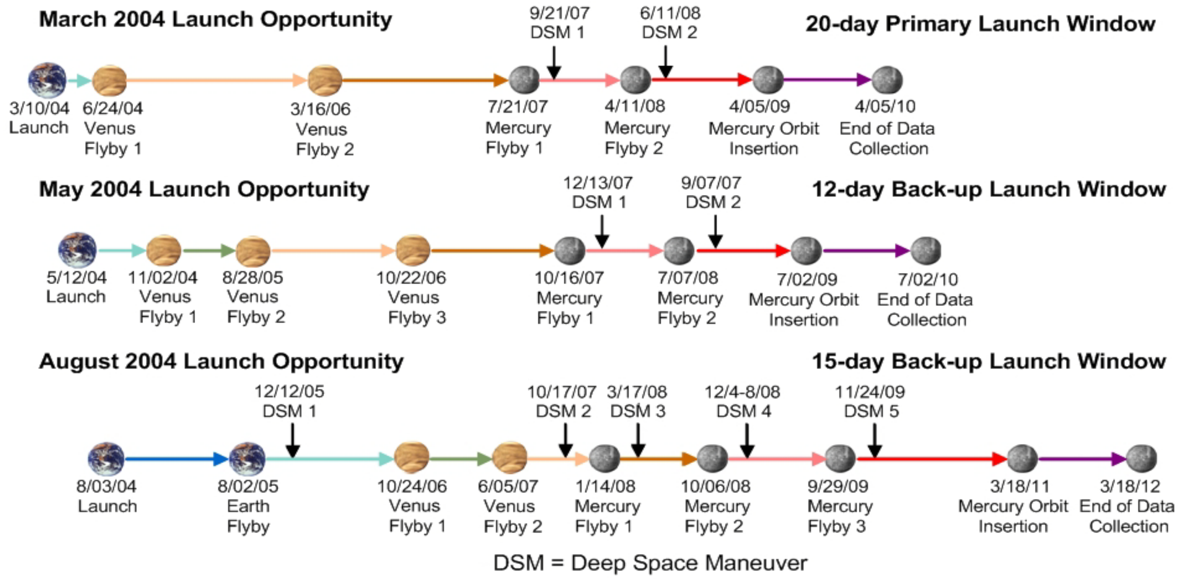

Figure 1. Three 2004 Launch Windows for MESSENGER

Additional factors affecting MOI ΔV are the spacecraft mass and propulsion system performance. These factors helped determine the extra ΔV for conducting a finite-duration (versus impulsive) MOI deep within Mercury's gravity field. The spacecraft completes large TCMs such as MOI with a four-segment sequence using different primary thruster sets and additional small-force thrusters pulsed on infrequently to maintain the desired thrust direction. When planning MOI, mission planners accounted for primary and attitude control thrust force and specific impulse from four propulsive segments. These segments included two lower-thrust segments that settled hydrazine over the fuel tank and refilled a smaller auxiliary fuel tank used for smaller TCMs, followed by the primary bi-propellant thrust segment that used a mix of hydrazine and oxidizer and a 680-N thruster to impart > 99.4% of the total MOI ΔV, and a short clean-up trim segment with four 26-N hydrazine thrusters. An additional complication for MOI is that the bi-propellant thrust segment minimized ΔV by using a "turn while burning" strategy with variable thrust direction, variable thrust magnitude, and variable specific impulse prior to reaching steady-state thrust operating at 679.6-N thrust, 316.1-s specific impulse, and a fuel-oxidizer mixture ratio of about 0.846.

3. Mercury Orbit Insertion Design Chronology since MESSENGER Launch

The MOI date remained at 18 March 2011 since launch, but many aspects of MOI changed in the 6.6 years from launch to MOI. For instance, improvements in trajectory optimization and maneuver design lowered MOI ΔV from 868 m/s at launch to 862 m/s for the MOI final design. An even lower 860 m/s MOI ΔV was for a two bi-propellant maneuver sequence, where ~96% of MOI ΔV preceded a more precise, adjustable cleanup of the final ~4% of MOI ΔV six orbits or 3.6 days after MOI. This two-part MOI met an orbit period requirement of 12 hours ± 1 minute after MOI. During 2009 the project increased the post-MOI orbit inclination from 80.0° to 82.5° to enhance science return without increasing risk to spacecraft health. Another change that affected MOI was a reduction in inclination tolerance from ± 2° to ± 1°, which would ensure compliance with a requirement to not exceed an 85.0° inclination within one year after MOI. Also in 2009, the mission design team incorporated a detailed variable-thrust, variable-specific-impulse engine model for the first 1.5-2.0 minutes before the bipropellant thruster attained steady-state operation. Early in 2010, a detailed Mercury orbit-phase science observation analysis first revealed that an orbit period of 12 hours ± 10 minutes would enable successful completion of science goals. This change in orbit period tolerance eliminated the need for an adjustable MOI clean-up maneuver. With the change from a two-part to a one-part MOI strategy in early 2010, the higher efficiency bipropellant maneuver segment contained a larger percentage of MOI ΔV, thus reducing total propellant consumed during MOI by 0.1 kg. On 11 March 2011, a final MOI performance improvement came with an MOI start time shift 5 seconds earlier. This change reduced the orbit period error by 35-40 seconds. See Figure 2 for three viewpoints of MESSENGER's initial orbit size and orientation, including MOI location and evidence of 100% observability from Earth.

4. Mercury Orbit Insertion Final Design and Results

The performance of the Mercury orbit insertion maneuver and the Mercury orbit resulting from that maneuver differed slightly from the final design. This difference was mainly due to an offset from the targeted arrival point in the arrival B-plane, as well as fuel pressures that were lower than used for the final maneuver design, resulting in lower thrust during the maneuver. The arrival B-plane location, whose 2.8-standard-deviation error had the largest effect on the resulting orbit, was determined by the navigation team to be 8.0 km from the target in the approach B-plane, which corresponds to a 6.0 km increase in the minimum altitude 5.4 minutes after the start of the MOI maneuver. Excluding a 30-s "tweak" segment that ensured spacecraft attitude stability after the spacecraft met its target ΔV, the total thrust duration was 885 s, or 7 s longer than predicted. Nearly all the 0.038°/s thrust-direction turn occurred during the 834-s duration bi-propellant segment. Since the transition from heliocentric to Mercury-centered orbit requires lowering spacecraft velocity, the MOI ΔV was oriented nearly opposite to the spacecraft velocity direction. During MOI the spacecraft's sunshade tilt reached 2.47º from the maximum (vs. 4.06º for the final design). The MOI resultant ΔV was 851.056 m/s, as given by the guidance and control team, or 0.008 % less than the 851.124 m/s goal, and the pointing error was 0.003°. The navigation team estimated an MOI integrated (along flight path) ΔV of 861.714 m/s, or 0.052 % less than the 862.166 m/s target, with 0.472° of pointing error. The resulting orbit about Mercury had a 206.77-km periapsis altitude (6.77 km above the 200 km target), a 43,456.86-s orbit period (261.38 s longer than the 43195.6 s target), an 82.52° inclination (0.02° above the 82.5° target), and a 59.976° sub-spacecraft periapsis latitude (-0.024° below the 60.0° N target). These orbit parameters were all well within the requirements for the initial orbit about Mercury, so no cleanup or contingency maneuver was required.

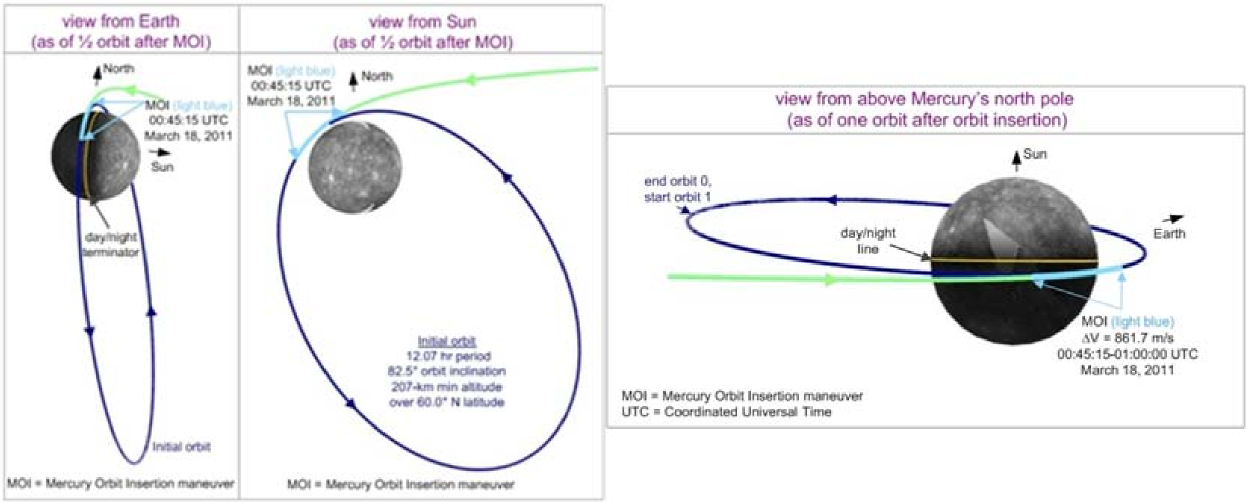

Figure 2. Three Views of MESSENGER's Initial Orbit around Mercury

5. Recovery from Heliocentric Orbit (< 70% MOI ΔV completed)

If less than 70% of the MOI ΔV had been achieved, MESSENGER would have escaped Mercury's gravitational sphere of influence by entering an altered heliocentric orbit with a period close to the 88-day Mercury period. Methods used to calculate minimum-ΔV trajectories to return to Mercury were described previously[5]. Because conditions governing the first arrival at Mercury following a failed MOI attempt are never suitable for satisfying the full orbital mission goals, a Mercury flyby must first place MESSENGER into a one-Mercury-year return trajectory. A continuum of such return trajectories exists for which the heliocentric inclination to the ecliptic and flight path angle lead to a new MOI that will achieve the 82.5° target inclination relative to Mercury's equator, the desired node (a Mercury-centered orbit nearly perpendicular to the Sun direction), and the remaining goals of the planned science orbit. The new MOI must satisfy the constraints listed previously. If the new MOI maneuver is not fully visible from Earth, a flyby will send the spacecraft onto another one-Mercury-year return loop – a strategy that repeats until finding an MOI that satisfies every engineering constraint and Mercury orbital goal. Also, the Mercury flyby altitude must be at least 200 km if communication with the spacecraft is to be possible during the flyby, or at least 1.50 Mercury radii (altitude over 1220 km) if the flyby occurs during a superior solar conjunction, i.e., when solar elongation < 3.0° and Earth-to-Mercury distance exceeds 1.3 AU. If there is an eclipse of the Sun during the flyby, it must last < 68 minutes to satisfy the maximum allowed battery depth of discharge.

After achieving a suitable Mercury arrival, the periapsis altitude and parameters of the new MOI maneuver were varied to achieve the following post-MOI periapsis goals: 12.0-hr period, 500-km periapse altitude, and 65° N Mercury latitude. These differ from the nominal MOI insertion targets since Mercury orbit evolution following heliocentric recovery MOIs cause both the periapse altitude and periapse latitude to decrease. This orbit evolution is opposite to that following the nominal 18 March 2011 MOI because the initial argument of periapsis shifts from ~119° to ~61°. All heliocentric recovery arrivals have northern periapse latitudes, just as for the nominal MOI.

The MOI recovery ΔV penalty is the amount of ΔV over the nominal MOI needed to accomplish both the Mercury targeting and new MOI maneuvers. A ΔV penalty above 228 m/s is undesirable because 100% of the estimated usable fuel would be consumed (and the orbit period may be far longer than 12 hours), leaving no ΔV for the OCMs needed to adjust the science orbit. Having no fuel for OCMs after MOI applies to the 60% completed MOI ΔV case shown in Table 1. A ΔV penalty less than 146 m/s would deplete the available fuel margin but leave enough for the OCMs to complete the full one-Earth-year science mission. Penalties between 146 and 228 m/s, though not desirable, would allow for a partial science mission with orbit adjustments via one or more OCMs.

There are two possibilities for returning to Mercury from a heliocentric orbit. A quick return, performing the heliocentric (MOI-C1) ΔV soon after MOI for a direct transfer to Mercury, would deliver MESSENGER to Mercury about one Mercury year (87.969 days) after MOI-C1. A long return, involving a small C1ΔV soon after MOI in order to target Mercury after several heliocentric orbits, would achieve an orbit as close as possible to the beat, or resonant, period. The new orbit period, slightly different from a Mercury year, would allow the spacecraft to complete one orbit of the Sun more or one orbit less than Mercury completes, after several spacecraft orbits. The quick returns often incur delays of a few Mercury years, to decrease both the size of the C1ΔV and the ΔV penalty. The long returns that closely match the beat period often take too long to return to Mercury; so instead the C1 ΔV is increased to return to Mercury several Mercury years earlier, or as early as possible for a penalty of less than 146 m/s. If the C1 ΔV is < 2 m/s, the ΔV-Sun angle must be 90° or 270° ± 12°, so the large thrusters can be used while the sunshade protects temperature-sensitive spacecraft components. The maneuver must also be done when the Sun-Earth-spacecraft angle is greater than 3° (as little as 2° is possible, with a higher risk of degraded communication during the maneuver). The new MOI maneuvers for all heliocentric recovery options occur near Mercury orbit aphelion, saving about 200 m/s of ΔV. Consequently, some recovery trajectories have negative penalties, inasmuch as they consume less total ΔV than the nominal mission.

After the one-year science orbit with a successful 18 March 2011 MOI, an extended mission is possible since the periapse altitude will continue to increase and the periapse latitude will continue to move toward the north pole. After a few years, after periapse passes near Mercury's north pole, the periapse altitudes and latitudes will decrease until the spacecraft impacts the surface. For the heliocentric recoveries, in contrast, an extended mission would either not be possible, or would be short, because either the spacecraft would impact the planet soon after propellant depletion, or the spacecraft would see long, battery-draining eclipses closer to apoapse when apoapse and periapse latitudes move too close to Mercury's equator.

The best heliocentric recovery trajectories, listed in Table 1, are at intervals of 10% of the nominal MOI ΔV. The two 15% MOI trajectories mark a transition from long- to quick-return trajectories, and show that, at 15% MOI completion, both solutions are viable. In practice, the quick return in 2013 is preferable. Although early analysis indicated potential for a gap between 10% and 20% of MOI where neither the quick nor the long-return strategies would work, later calculations showed that there was no such gap. The 33.8%-achieved MOI case was included because the heliocentric orbit had a period of almost precisely one Mercury year, allowing a quick return with a small C1 ΔV and the greatest possible ΔV savings. The 51.4% MOI case was added to show a limit for a penalty that still allowed a full one-year science mission. For all MOI underburns with less than 51.4% completed ΔV, viable recovery trajectories were found. For achieved MOI ΔV from 51.4% to 60%, the trajectories become worse, with ΔV penalty increasing, allowing only a partial science mission and flight times longer than the six additional years, considered marginally acceptable. In the range from 60% to <70% completed MOI ΔV, no solutions were found that satisfied the full orbital goals. At best, the spacecraft would capture into an orbit much larger than desired, leading to either surface impact or a long, battery-draining eclipse a few months after MOI.

Table 1. Recovery options for large MOI underburns.

		First Recovery (C1) ΔV			New MOI Maneuver			Penalty	
Achieved MOI (%)	# of new ☿ fly-bys	Date (dd/mm/yyyy)	ΔV (m/s)	S/C-⊕-⊙ angle (deg)	Date (dd/mm/yyyy)	ΔV (m/s)	S/C-⊕-⊙ angle (deg)	Time (years)	ΔV (m/s)
0.0	3	18/06/2011	180.3	2.0	23/05/2016	624.3	18.5	5.18	-70.8
10.0	3	17/06/2011	359.4	2.7	23/05/2016	573.0	18.4	5.18	144.5
15.0	2	12/06/2011	298.3	3.0	23/05/2016	508.4	18.7	5.18	106.2
15.0	6	17/06/2011	347.7	3.0	02/07/2013	483.1	11.6	2.29	118.6
20.0	4	16/06/2011	249.2	3.0	02/07/2013	481.6	11.6	2.29	30.4
30.0	3	15/06/2011	109.2	2.7	18/04/2012	467.2	27.5	1.09	-18.6
33.8	3	28/03/2011	0.9	16.5	21/01/2012	425.1	10.9	0.85	-153.5
40.0	1	08/04/2011	193.2	3.0	24/10/2011	437.9	16.4	0.60	105.9
50.0	1	07/06/2011	201.1	5.3	18/08/2016	351.3	27.4	5.42	114.7
51.4	1	07/06/2011	213.9	5.1	18/08/2016	351.5	27.4	5.42	140.0
60.0	1	05/06/2011	260.5	7.1	29/10/2017	334.5	13.1	6.62	**244.8**

The number in **bold** indicates insertion into Mercury orbit but no ability to adjust the orbit. S/C denotes spacecraft

6. Recovery from Heliocentric Orbit (≥ 70% MOI ΔV completed)

The MOI recovery scenarios for recovery from an undesirable Mercury orbit have four classifications: (1) recovery from accelerometer loss, (2) two-maneuver recovery from an underburn, (3) a large, single-maneuver recovery from an underburn, and (4) a small, single-maneuver recovery from an underburn or overburn. In order to recover from an accelerometer data loss, two maneuvers are required if the loss occurs within the first 646 s of the main large velocity adjust (LVA) thruster segment of MOI. After this 646 s threshold, only one recovery maneuver is required. A two-maneuver recovery is also necessary when the percentage of the MOI maneuver ΔV completed is from 70.0% to 79.4%. In this realm, the spacecraft would capture into an orbit around Mercury with a large period with solar gravity perturbations adversely affecting both orbit inclination and periapsis altitude. The recovery strategy utilizes two contingency maneuvers to achieve the desired initial Mercury orbit. An underburn from 79.4% to 97.4% of MOI ΔV completed will yield an orbit with a period sufficiently short to lessen the influence of solar perturbations, thereby eliminating the need for an inclination change. With no inclination change, recovery from underburns of 79.4% and 97.4% of MOI ΔV completed requires only a single, large maneuver. The orbit resulting from 97.4% to 99.7% MOI ΔV completed will have a period of at least 12 hours and 10 minutes, which requires only one small maneuver to place the spacecraft into the initial science orbit. A single, small maneuver is also needed for small overburns with over 100.2% ΔV completed, because the resulting orbit will have a period of 11 hours and 50 minutes or less.

If accelerometer function was lost during MOI, the required thrust direction turn cannot be completed and, without onboard autonomy in place, the maneuver finishes with the inertially fixed direction from the moment of accelerometer loss until the burn timeout. To prevent wasting a large amount of propellant while ensuring Mercury orbit capture, autonomy was in place that would activate 780 s after the start of the LVA burn. If the accelerometers were lost prior to this time, the autonomy would terminate the maneuver 780 s after initial LVA activity. However, if accelerometer function ended after this time, onboard autonomy would terminate the burn when accelerometer data was lost. This would lead to an MOI accelerometer-loss ΔV between 799.1 m/s and 858.3 m/s, depending on the time of accelerometer failure, compared with a nominal MOI ΔV of 862.2 m/s. The recovery plan also depends on the time of accelerometer failure. For accelerometer failure before LVA start + 228.6 s, two maneuvers are required to correct the period, periapsis altitude, and sub-spacecraft periapsis latitude. For accelerometer failure from 228.6 to 645.8 s after LVA initial thrust, the sub-spacecraft periapsis latitude needs no correction, and two maneuvers would correct period and periapsis altitude. After LVA start + 645.8 s, only one maneuver would be required to correct the period if the accelerometer function ceased.

To achieve the desired initial orbit after an MOI underburn that results in a very large orbit about Mercury, a two-maneuver recovery strategy is needed. The first maneuver occurs soon after apoapsis and corrects inclination and periapsis altitude errors. The second, larger maneuver occurs soon after periapsis and corrects apoapsis altitude and period. Design of this recovery sequence varied the ΔV magnitude, direction, and true anomaly of initial thrust for both contingency maneuvers to ensure that the Sun elevation angle (defined as Sun-spacecraft-ΔV angle – 89.31°) never exceeded |9.5|° during any maneuver so as not to violate the spacecraft Sun-keep-in (SKI) constraint. This SKI constraint, with ±12° Sun elevation angle, maintains sunshade orientation to protect all heat-sensitive areas of the spacecraft. Recovery maneuver sequence design also ensured that the desired orbit characteristics were achieved at the periapsis after the second maneuver. Scenarios 2 through 4 in Table 2 required that the second contingency maneuver be outside an eclipse. It was determined that, because of the SKI constraint, implementing a turn during either of the two contingency maneuvers would not save sufficient ΔV to justify this additional design complexity. Both contingency maneuvers were designed with inertially fixed thrust direction.

There are several limiting scenarios for these recoveries from underburns requiring two maneuvers. For this study, a limiting scenario occurs when a lower ΔV for the MOI maneuver would lead to a negative propellant margin at the end of the nominal one-year orbital phase and require a departure from either the initial orbit requirements or the nominal orbit-phase trajectory correction plan. Three limiting scenarios define recovery strategy transition points. The first scenario is the maximum MOI maneuver underburn possible while achieving full recovery of the initial primary science orbit. The second scenario is the maximum underburn possible while achieving full recovery without performing a contingency maneuver during an eclipse. The third scenario is the maximum underburn possible with the first contingency maneuver occurring soon after the second apoapsis crossing. Since any MOI underburn with ΔV less than this third case must have the first contingency maneuver performed soon after the first apoapsis crossing in order to achieve the desired initial orbit, the shortest possible duration between the MOI maneuver and the first contingency maneuver for a large underburn is related to the percentage of MOI ΔV completed. The resulting contingency maneuver details, percentage of MOI ΔV completed, eclipse timing, and orbit for each of these large underburn scenarios are summarized in Table 2. In the table, propulsive mode 2 corresponds to medium-thrust hydrazine ΔV and mode 3 to large-thrust bipropellant ΔV.

The single-maneuver contingencies were designed by varying the ΔV magnitude, direction, turn rate, and initial thrust true anomaly while maintaining the SKI constraint and avoiding any eclipses, until the desired orbit characteristics were met at the periapsis following the maneuver and the ΔV was minimized. Two scenarios were identified for recovery from an MOI maneuver resulting in an orbit with near-nominal inclination. The first scenario is the maximum mode-3 maneuver needed to achieve the desired initial orbit. Since any inclination change is much more efficiently performed using a two-maneuver cleanup strategy, the maximum ΔV single-maneuver cleanup occurs when the pre-recovery orbit has an inclination of 83.5°, i.e., the upper limit of the initial orbit inclination constraint. This scenario, which occurs with completion of 79.4% of the MOI ΔV, defines the limit of efficient recovery to the initial science orbit with a single contingency maneuver. Anything less than the 79.4% MOI ΔV completion would result in a pre-recovery orbit requiring an additional inclination correction maneuver. Another scenario is the maximum underburn possible with the ability to recover and complete all OCMs in the nominal one-year mission without firing the LVA bipropellant thruster. The need to perform all maneuvers on monopropellant thrusters would arise if, after the MOI maneuver cuts off prematurely, the LVA thruster cannot be recertified for further use. With no LVA use allowed after an anomalous MOI, 91.1% MOI ΔV completion is the maximum underburn from which recovery can occur using a single mode-2 MOI-C1 maneuver.

The remaining scenarios examined include underburns or overburns requiring only small, single-maneuver recoveries. The first such scenario is the underburn corresponding to the minimum possible mode-3 recovery maneuver. After MOI, propellant fluid dynamics in mostly empty onboard tanks lower the minimum thrust time for the LVA thruster to 12 s. A required propellant settling segment lasts 60 s and a second, mode-2 settling segment lasts 23 s before the LVA segment; the maneuver is completed with a 61-s duration medium-thrust trim segment. This scenario leads to a 156-s minimum mode-3 burn duration after MOI. In Table 3, this minimum bipropellant recovery maneuver would occur after 97.4% of the MOI ΔV was completed. The final scenario studied in the small underburn category corresponds to the minimum possible ΔV that the spacecraft is able to complete as a contingency maneuver. This occurs when the orbit period after the MOI maneuver is either 10 minutes longer or shorter than the targeted 12-hr initial period. The thrust-on duration for the minimum ΔV, mode-2 maneuver is 145 s; this includes a 60-s settle segment, a 35-s main segment, and a 50-s trim segment. For both minimum recovery cases, the ΔV needed to recover is less than this minimum mode-2 ΔV. Therefore, the maneuvers would be performed inefficiently to achieve the minimum thruster firing times.

Table 2. Contingency maneuvers and resulting orbits for scenarios requiring two maneuvers to recover.

Scenario	% MOI ΔV completed	Maneuver	Mode	Start Time (UTC)	ΔV (m/s)	TA (deg)	Sun Elevation Angle (deg)	Eclipse Timing
1	70.0	MOI-C1	2	25 Mar 2011 01:45:36	141.2	192.0	9.0	n/a
		MOI-C2	3	27 Mar 2011 21:02:58	262.1	14.0	-9.0	5.6 min into 23.6 min eclipse
	Resulting orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 82.5°, Periapse Latitude = 56.7°, RAAN = 341.8°						
2	70.8	MOI-C1	2	23 Mar 2011 16:13:17	96.5	192.0	9.5	n/a
		MOI-C2	3	25 Mar 2011 18:11:09	292.0	63.0	-8.5	1 min after end
	Resulting orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 82.5°, Periapse Latitude = 63.2°, RAAN = 345.3°						
3	72.4	MOI-C1 *	2	27 Mar 2011 06:44:52	78.3	192.0	9.0	n/a
		MOI-C2	3	28 Mar 2011 15:20:58	301.9	73.9	-9.0	1 min after end
	Resulting orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 82.5°, * MOI-C1 just after second apoapsis Periapse Latitude = 64.8°, RAAN = 345.6°						
4	72.4	MOI-C1 **	2	22 Mar 2011 04:57:15	53.6	192.0	9.0	n/a
		MOI-C2	3	23 Mar 2011 07:30:17	241.0	37.2	-9.0	1 min after end
	Resulting orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 82.5°, ** MOI-C1 just after first apoapsis Periapse Latitude = 59.7°, RAAN = 347.5°						

All contingency maneuvers in these scenarios are inertially fixed.

The accelerometer loss and underburn scenarios indicate that a recovery to the desired initial orbit and an ability to perform the nominal one-year orbital-phase mission are possible for an accelerometer loss at any point during the LVA burn as well as any MOI ΔV completion above 70.0%. Furthermore, there is only a small range of underburns, between 70.0% and 70.8% of MOI ΔV completion, for which a contingency maneuver would be required during an eclipse. If the LVA thruster is unusable after the end of MOI, the full mission science goals can be achieved using monopropellant thrusters after completion of 91.1% or more of the MOI ΔV. Finally, the smallest underburn or overburn cleanup that would be performed corresponds to a pre-recovery orbit period of 12 hours and 10 minutes or 11 hours and 50 minutes, respectively, and requires only a 3.9 m/s ΔV.

7. Summary

After many years of planning variations in Mercury orbit insertion, the MESSENGER spacecraft safely entered into the desired orbit around Mercury on 18 March 2011. The variations in MOI considered arose from a variety of launch options and Mercury arrival velocities, as well as from changes in strategy (one maneuver or two maneuvers) and orbit target tolerances. The final integrated ΔV of 861.714 m/s was within 0.5 m/s of the ΔV design and 0.5° of the ΔV direction during an 885-s duration MOI maneuver that was flawlessly executed with the bipropellant thruster orientation updated to keep close to the spacecraft's velocity direction. This "turn while burning" strategy minimized propellant usage while slowing the spacecraft sufficiently to enable Mercury orbit capture. Figure 3 offers a high-level summary of conditions from which MOI recovery was available within six years of an anomalous MOI, had such a recovery been needed.

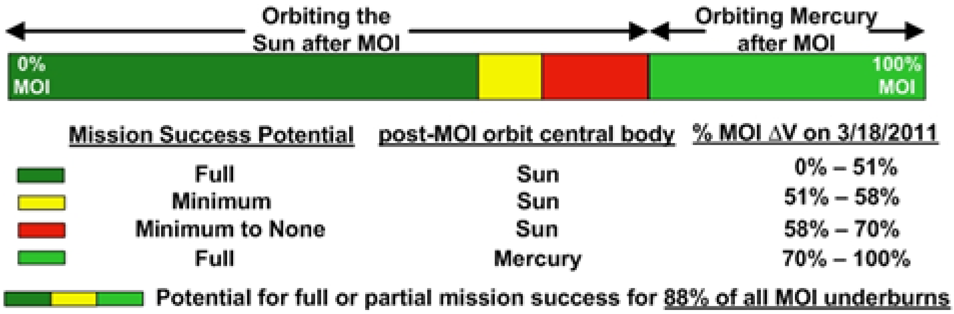

Figure 3. Recovery outlook for all MOI underburn options.

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