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THE MESSENGER SPACECRAFT'S ORBIT-PHASE TRAJECTORY

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After MESSENGER's 18 March 2011 Mercury orbit insertion (MOI), the spacecraft began its yearlong primary science mission. Trajectory perturbations from solar gravity, Mercury's gravity field, and solar radiation pressure shift orbit periapsis higher in altitude and Mercury latitude during the primary mission. Five orbit-correction maneuvers (OCMs) will either lower periapsis altitude or increase orbit period. After the primary mission, MESSENGER will either drift until impacting Mercury or begin an extended mission. Extended mission options require OCMs to establish and maintain a new orbit. Final results for MOI and OCM-1 indicate a successful start to the primary mission.

INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft was designed and is operated by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in Laurel, Maryland, and the mission is led by the Carnegie Institution of Washington with key flight and science operation contributions from KinetX, Inc.; NASA's Jet Propulsion Laboratory and Goddard Space Flight Center; and numerous universities, research institutions, and subcontractors. Supported by NASA's Discovery Program, the spacecraft successfully launched from Cape Canaveral, Florida, aboard a Delta II 7925H-9.5 launch vehicle on 3 August 2004. During its 6.6-year interplanetary cruise phase, the spacecraft completed one Earth flyby, two Venus flybys, three Mercury flybys, and multiple orbit-correction maneuvers (OCMs) before becoming the first spacecraft to enter orbit about Mercury in March 2011.[1]

The orbital phase of the MESSENGER mission began with a single Mercury orbit insertion (MOI) maneuver on 18 March 2011 at 00:45:15 UTC. Lasting approximately 15 min and imparting an 861.714-m/s velocity change (ΔV), the MOI maneuver slowed the spacecraft's Mercury-relative velocity by using variable-direction thrust with the thrust vector nearly opposite to the instantaneous spacecraft velocity vector. The MOI safely delivered the spacecraft into an orbit with a 206.77-km periapsis altitude, 12.07-hour orbit period, 59.98°N sub-spacecraft periapsis latitude, 350.17° right ascension of ascending node, and 82.52° initial orbit inclination. For the first 89 days in Mercury orbit, the spacecraft coasted with propulsive angular momentum adjustments occurring approximately every one to two weeks. The first 12 of these early orbital-phase propulsive momentum adjustments imparted to the spacecraft a residual ΔV of 14.8 mm/s. The lengthy coast between MOI and the first OCM (OCM-1) provided time to refine Mercury's

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gravity-field model and update perturbing force models to minimize trajectory propagation errors. A number of trajectory perturbations, including those due to solar pressure, variations in Mercury's gravity, and solar gravity, create the need for periodic OCMs. These maneuvers occur approximately once every 44 days, or half of a Mercury year, beginning 89–90 days after MOI. Each of five OCMs either returns the spacecraft to the initial orbit's periapsis altitude or adjusts the orbit period to an average of 12 hours through the start of the next planned OCM. OCM-1, -3, and -5 each impart a ΔV opposite the spacecraft velocity direction at apoapsis, lowering the periapsis altitude back to 200 km. Because each periapsis altitude reduction also decreases orbit period, OCM-2 and -4 each increase the orbit period to 12 hours by imparting a smaller ΔV in the spacecraft velocity direction at periapsis.

Multiple options have been developed for extending the mission beyond the yearlong primary mission. Each extended mission option is a variation of one of two low-periapsis-altitude science orbits, an 8-hour orbit and a 12-hour orbit. Each extended mission orbit begins with a periapsis-altitude-reduction OCM in early March 2012, when the spacecraft maneuver attitude ensures spacecraft bus protection behind the sunshade at <0.31 AU (astronomical units) from the Sun. Although one or two OCMs to support the extended mission will occur approximately two weeks before the 18 March 2012 end of the primary science mission, the orbit changes from these OCMs will likely bring minimal improvement to the quality of science data acquired for the final two weeks of the primary mission. For the extended mission option with an 8-hour orbit, the OCM that reduces the orbit period to 8 hours will not occur until approximately one month after the 18 March 2012 end of the primary mission. Additional studies by engineering and flight operations teams will determine the safety, data collection, and data downlink strategies that are key factors in the evaluation of an 8-hour orbit. Transition to an 8-hour orbit provides new science potential not available with a continuation of an orbit with a period near 12 hours. Another extended mission option would target a 200-km periapsis altitude by 12.2-hour orbit period on 2–4 March 2012 and proceed to execute a periapsis-lowering OCM in multiples of 44 days for the next eight months. This maneuver plan would maintain an orbit period that never strays more than 0.2 hours from 12 hours and would leave the spacecraft in an 11.8-hour orbit two years after MOI. Near the end of a one-year extended MESSENGER mission, dominant trajectory perturbations from solar gravity cause the rate of increase in Mercury altitude to slow and then reverse, setting the stage for Mercury surface impact as early as autumn 2013. The transition from increasing to decreasing Mercury altitude and sub-spacecraft Mercury latitude will occur near the date when periapsis reaches a maximum northerly latitude, passing near Mercury's north pole as periapsis trends southward.

MERCURY ORBIT INSERTION

Although the date for MOI has remained 18 March 2011 since launch, many aspects of MOI changed in the 6.6 years from launch to MOI.[2] 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. Note that the lowest MOI ΔV was for the final design of two bi-propellant maneuvers in sequence, where ~96% of MOI ΔV was followed by 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 min after MOI. During 2009, the project determined that increasing the post-MOI orbit inclination from 80.0° to 82.5° would enhance science return without increasing risk to spacecraft health. Along with this change in target orbit inclination was a reduction in inclination tolerance from ±2° to ±1°, which would ensure compliance with the requirement to avoid exceeding an inclination of 85.0° 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 min before the bipropellant thruster attained steady-state operation. Early in 2010, a detailed Mercury orbital-phase science observation analysis first revealed that an orbit period of 12 hours ± 10 min would enable successful completion of science goals. This change in orbit-period tolerance eliminated the need for an adjustable MOI cleanup maneuver. With the change from a two-part MOI strategy 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 change was made to improve MOI performance by shifting the MOI start time 5 s earlier, a change that effectively reduced the orbit-period error by 35–40 s.

Table 1. Orbital Elements of Initial Mercury Orbit at Periapsis on 18 March 2011 (Mercury-Centered Inertial Frame).

	Semi-Major Axis (km)	Orbit Eccentricity	Orbit Inclination (°)	Right Ascension Ascending Node	Argument of Periapsis (°)	Time, UTC (hh:mm:ss)
Targeted	10135.120	0.740	82.50	350.17	119.13	12:47:56.0
Achieved	10175.39	0.740	82.52	350.17	119.16	12:52:19.9
Deviation	40.27	0.00038	0.0219	–0.0039	0.034	263.9 s

The final requirements for the MESSENGER spacecraft's initial orbit consisted of a 200-km (125–225 km) periapsis altitude, a 12-hour (±10 min) orbit period, a 60°N (56°–62°N) periapsis latitude, a 350° (169°–354°) right ascension of ascending node, and an initial orbit inclination of 82.5° (±1°). These requirements, expressed in Mercury-centered inertial coordinates of epoch January 1.5, 2000, were defined from science and engineering requirements along with characteristics of the Mercury arrival geometry. Whereas the optimal heliocentric trajectory provided 49°N initial periapsis latitude, the start time and variable-thrust direction of MOI were designed to achieve the remaining 11°N rotation of the line of apsides necessary to achieve 60°N latitude at the first periapsis after MOI. Table 1 lists the spacecraft's targeted and achieved classical orbital elements in the Mercury-centered inertial frame at the first periapsis (0° true anomaly) after MOI.

The MOI strategy used a single maneuver, minimizing the time and propellant required to deliver the spacecraft into the primary science orbit. This strategy used one "turn while burning" variable-thrust-direction maneuver with the large velocity adjust (LVA) bipropellant thruster operating during steady-state at 679.5-N thrust, 316.1-s specific impulse, and a fuel-oxidizer mixture ratio of 0.837. For most of the first 2 min of LVA thruster firing, before steady-state performance begins, the MOI maneuver design accounted for variable-thrust magnitude and variable-specific impulse. The difference during LVA thruster operation between using an average, constant thrust and specific impulse and using the more precise variable-thrust and variable-specific impulse during the first 2 min was determined to be approximately 0.1 m/s in ΔV and 3 s in thrust duration. The maneuver's start time, duration, and time-varying orientation were optimized 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. Views of the trajectory during MOI and the resulting initial orbit are shown in Figure 1. Implementation of this MOI strategy was designed to be versatile enough to accommodate an MOI cleanup maneuver even though none was required. A Sun–Earth–spacecraft angle of 17.3° for MOI ensured that solar interference did not corrupt communications with the spacecraft during orbit insertion. The time of day for MOI corresponded to nearly equal spacecraft elevation angles (see Figure 2) relative to two widely separated Deep Space Network (DSN) ground antennas. Goldstone, California, was the primary location for monitoring MOI, and Canberra, Australia, was the backup tracking site. Because of Earth–spacecraft–ΔV geometry, 72.8% of the MOI maneuver ΔV was visible via Doppler shift during real-time MOI monitoring.

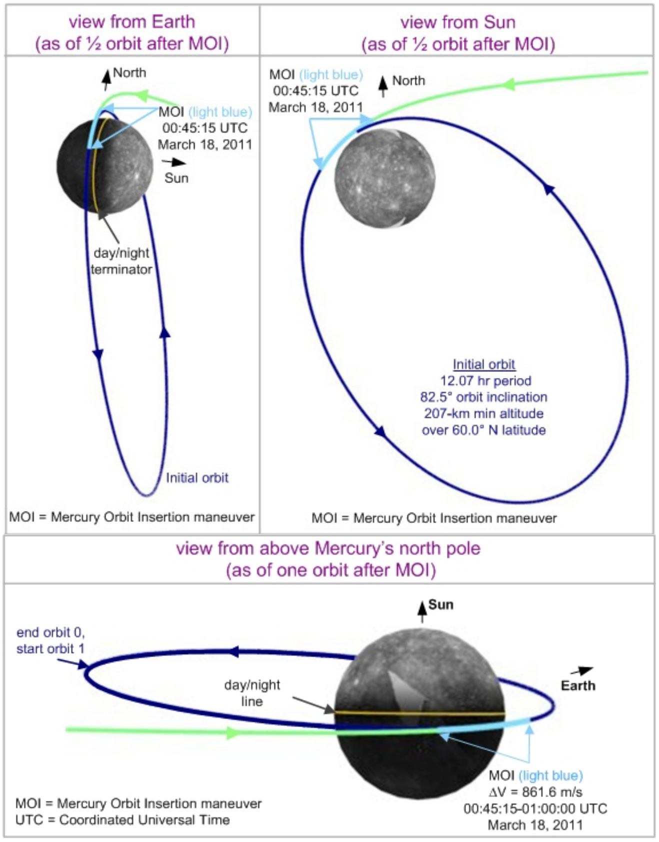

Figure 1. Three Views of MESSENGER's Orbit Insertion and Initial Orbit Around Mercury.

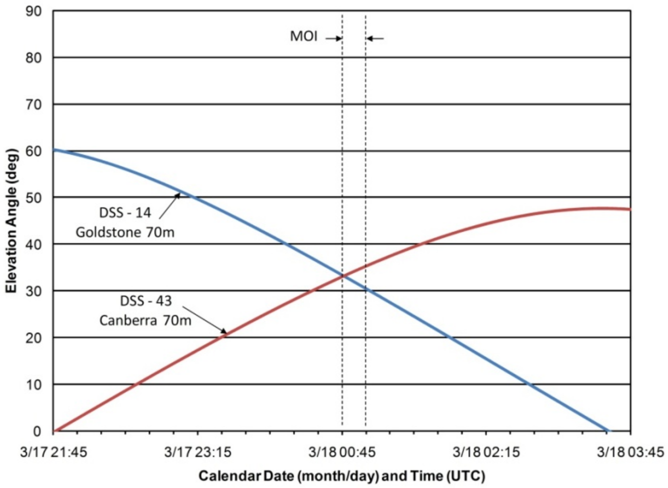

Figure 2. Ground Station Visibility of MESSENGER during Orbit Insertion.

The engine-performance parameters used to design the MOI maneuver were based on input from the MESSENGER propulsion team. The fuel and oxidizer used by the MESSENGER spacecraft are hydrazine and nitrogen tetroxide, respectively. Smaller monopropellant maneuvers use only the fuel, whereas larger bipropellant maneuvers use both fuel and oxidizer. Information on the location and performance of the MESSENGER spacecraft's thrusters, as well as a summary of propulsive maneuver implementation options,[3] provides most of the course-correction options available for MESSENGER. The MOI maneuver had three segments: a fuel settle/auxiliary tank refill segment, a main LVA segment, and a trim segment. The first 26-s settle/refill segment used four small A and B thrusters that were modeled as providing 16.24 N of total thrust at a specific impulse (I_{sp}) of 227.5 s and 25.9% efficiency due to thruster cant angles. The main portion of burn was modeled as seven segments to account for the variable-thrust blow-down period of the LVA thruster as well as steady-state thrust. The first six of these main LVA segments were each modeled by using a variable-thrust profile based on a fifth-order polynomial curve fit to predicted thrust data that was provided by the propulsion team. The I_{sp}, constant for each segment, was set to equal the average I_{sp} of the predicted variable-I_{sp} data (provided by propulsion) over the duration of the segment. The duration of each of these six segments was determined by the timing of the predicted fuel tank switching. The final design duration of the first segment was 12 s, and the durations of the remaining segments were each 20 s. The seventh main segment modeled the LVA thruster once it reached steady state by using a constant thrust of 683.5 N and an I_{sp} of 316.1 s. The 830-s LVA segment duration was the only MOI thrust segment allowed to have a variable duration; the preceding and following segments were designed with fixed durations. The final maneuver segment was designed as a 22-s-duration trim segment and was modeled by using all four C thrusters, each operating at 25.94 N and 234.8-s I_{sp}. This lower-thrust trim provided a more precise ΔV cutoff than an abrupt end to the high-thrust bipropellant segment, a standard feature for all bipropellant MESSENGER maneuvers.

Table 2. Comparison of Final MOI Design with Final Reconstructions by Navigation, Guidance and Control, and Propulsion.

	Resultant ΔV (m/s)	Integrated ΔV (m/s)	Pointing Error (°)	Duration (s)	Mass (kg)
Final Design	851.124	862.166	N/A	878.1	185.328
Navigation	N/A	861.714	0.472	878.589	185.526
Guidance and Control	851.056	N/A	0.003	885.040	185.729
Propulsion	N/A	861.7	N/A	887	185.555

N/A, not applicable.

The performance of the MOI maneuver and the Mercury orbit resulting from that maneuver differed slightly from those in the final design.[3] This difference was mainly due to an arrival B-plane location that was offset from the targeted arrival point, as well as to fuel pressures that were lower than those used to model 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. This offset corresponds to a 6.0-km increase in the minimum altitude 5.4 min 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 bipropellant segment. Because the transition from heliocentric to Mercury-centered orbit required lowering spacecraft velocity, the MOI ΔV was oriented nearly opposite to the spacecraft velocity direction. 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 the 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. A summary comparison of the final MOI design versus the final reconstructions from navigation, guidance and control, and propulsion is provided in Table 2. The resulting orbit about Mercury had a periapsis altitude of 206.77 km (6.77 km above the 200-km target), an orbit period of 43,456.86 s (261.38 s longer than the 43195.6-s target), an inclination of 82.52° (0.02° above the 82.5° target), and a sub-spacecraft periapsis latitude of 59.976° (–0.024° below the 60.0°N target). These orbital parameters were all well within the requirements for the initial orbit about Mercury, so no cleanup or contingency maneuver was required.

MERCURY ORBITAL PHASE

After the completion of MOI, the spacecraft entered its initial orbit (orbit 1), which began at apoapsis, approximately one-half orbit after the MOI cutoff, on 18 March 2011 at 06:50:12 UTC. After completing the orbit-insertion maneuver, the spacecraft began an 89-day-long coast phase with no OCMs but with propulsive momentum-adjustment maneuvers as needed. The first 12 post-MOI thruster firings that adjusted spacecraft angular momentum perturbed the trajectory by a total of only 14.8 mm/s of residual ΔV. The first 35 days of ground tracks after MOI included equator crossings spanning approximately 215° of Mercury longitude. The navigation team used orbital data over this time to provide an initial refinement of Mercury's gravity model.

Table 3. Mapping Science Objectives into Mercury Orbit Design.[1]

Mission Objectives	Mission Design Requirements	Mission Design Features
Globally image surface at 250-m resolution	Provide two Mercury solar days at two geometries for stereo image of entire surface; near-polar orbit for full coverage (MDIS)	Orbital phase of one Earth year (13 days longer than two Mercury solar days) with periapsis altitude controlled to 200–505 km; 82.5°-inclination initial orbit
Determine the structure of Mercury's magnetic field	Minimize periapsis altitude; maximize altitude-range coverage (MAG)	Mercury orbit periapsis altitude from 200 to 505 km; apoapsis altitude near 15,200 km; orbit period from 11.76 to 12.07 hours
Simplify orbital mission operations to minimize cost and complexity	Choose orbit with period of 8, 12, or 24 hours	
Map the elemental and mineralogical composition of Mercury's surface	Maximize time at low altitudes (GRNS, XRS)	
Measure the libration amplitude and gravitational field structure	Minimize orbital-phase thrusting events (RS, MLA)	Initial orbital inclination of 82.5°; periapsis latitude drifts from 60°N to 74°N; primarily passive momentum management; first one orbit-correction ΔV after 89 days and then one orbit-correction ΔV every 44 days
	Orbit inclination of 82.5°; latitude of periapsis near 60°N (MLA, RS)	
Determine the composition of radar-reflective materials at Mercury's poles	Orbit inclination of 82.5°; latitude of periapsis maintained near 60°N (GRNS, MLA, MASCS, EPPS)	
Characterize exosphere neutrals and accelerated magnetosphere ions	Wide altitude range coverage; visibility of atmosphere at all lighting conditions	Extensive coverage of magnetosphere; orbit cuts bow shock, magnetopause, and upstream solar wind

During MESSENGER's Mercury orbital phase, the spacecraft's seven science instruments and 13 instrument sensors are acquiring data to address six important questions on Mercury's composition and field structure.[4,5] Answers to these questions, which offer insights well beyond increased knowledge of the planet Mercury, are the basis for the science objectives:

1. Map the elemental and mineralogical composition of Mercury's surface.
2. Image globally the surface at a resolution of hundreds of meters or better.
3. Determine the structure of the planet's magnetic field.
4. Measure the libration amplitude and gravitational field structure.
5. Determine the composition of radar-reflective materials at Mercury's poles.
6. Characterize exosphere neutrals and accelerated magnetosphere ions.

The science instruments include the wide-angle and narrow-angle field-of-view imagers of the Mercury Dual Imaging System (MDIS), the Gamma-Ray and Neutron Spectrometer (GRNS), the X-Ray Spectrometer (XRS), the Magnetometer (MAG), the Mercury Laser Altimeter (MLA), the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), the Energetic Particle and Plasma Spectrometer (EPPS), and an X-band transponder for the Radio Science (RS) experiment. Table 3 shows how these instruments link the six science objectives presented above to the spacecraft orbit at Mercury. Other publications offer a more comprehensive examination of the structure and function of all seven science instruments.[6,7]

During the Mercury orbital phase, knowledge of the predicted spacecraft attitude is vital for accurate orbit propagation and design of upcoming OCMs. Trajectory perturbations due to solar pressure, variations in Mercury's gravity, solar gravity, general relativity, Mercury surface albedo, and planetary infrared (IR) radiation must be carefully coordinated with the spacecraft's complex attitude profile. All of these factors, except for Mercury albedo and IR radiation, are accounted for during the Mercury orbital-phase trajectory propagation by the mission design team. The process of updating the predicted orbit incorporates a weekly, short-term spacecraft ephemeris file released by the navigation team with a less frequently updated long-term spacecraft ephemeris file released by the mission design team. The short-term ephemeris extends approximately five weeks into the future, and the long-term ephemeris continues from the end of the short-term ephemeris until the current end of mission. A merged version of the best available reconstructed and predicted spacecraft ephemeris files is created and distributed weekly by the mission design team.

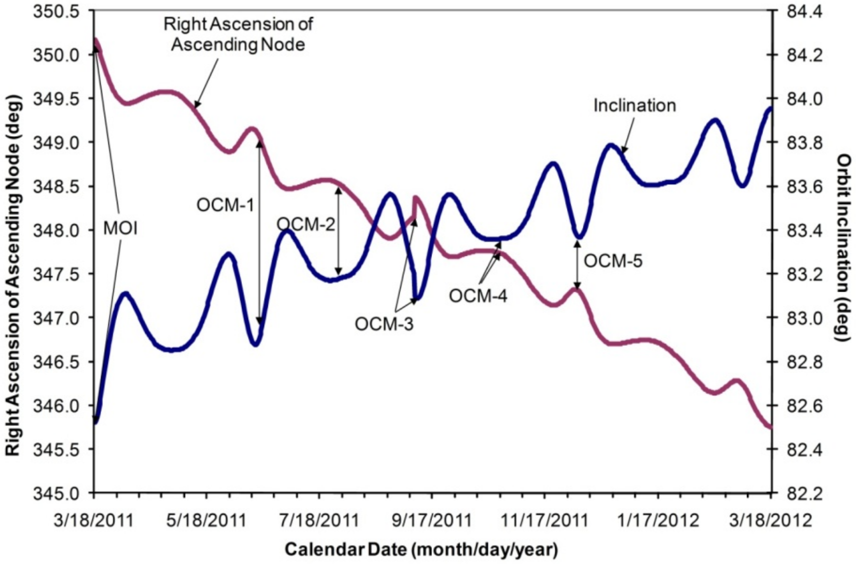

Figure 3. Examples of Orbit-Plane Rotation during Mercury Orbit.

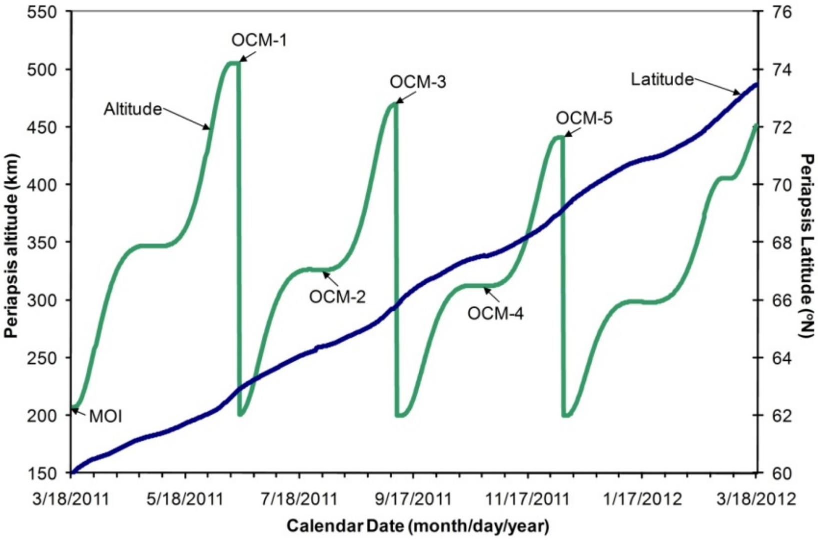

Figure 4. Periapsis Evolution during Mercury Orbit.

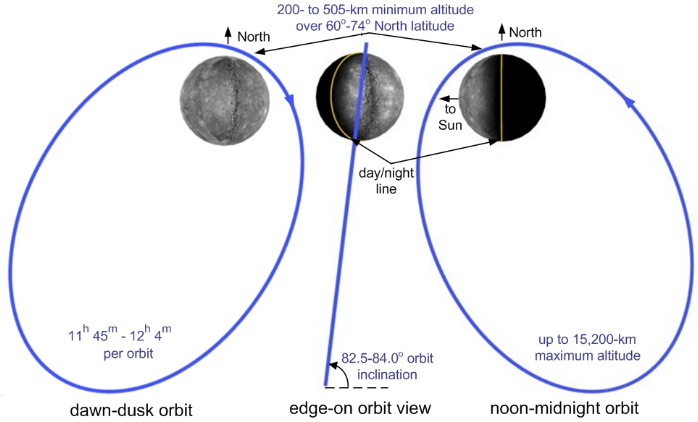

Figure 5. Three Views of MESSENGER's Orbit around Mercury.

The magnitude of the albedo-IR accelerations generated by the MESSENGER mission design team show close agreement with values estimated by the navigation team from tracking data. However, these accelerations have little effect on the orbit over the maximum 89-day time between OCMs, perturbing the semi-major axis by <1 m. The precision of science requirements indicates that inclusion of an albedo-IR model for mission planning is not necessary over the duration of the mission. However, inclusion of an albedo-IR model for navigation is necessary to accurately determine higher-order terms in Mercury's gravity field. Further details on the albedo-IR analysis for the MESSENGER mission may be found in a companion paper.[8]

The currently modeled trajectory-perturbing effects, of which solar gravity and Mercury's small gravitational oblateness, J_2, are dominant factors, cause periapsis altitude to increase to between 441 km and 505 km, periapsis latitude to drift northward approximately 13.5° (decreasing the argument of periapsis), orbit inclination to increase by approximately 1.4°, and right ascension of ascending node to decrease by 4.4° between the initial orbit and the nominal mission end one year after MOI. The non-uniform variation of each of these orbital parameters can be seen in Figures 3 and 4. Furthermore, Figure 5 offers three views of MESSENGER's Mercury orbit and contains information about orbital variation during the first year after MOI.

Each OCM (see Figures 3 and 4 for OCM timing) either lowers periapsis altitude or increases orbit period. The larger bipropellant maneuvers at apoapsis lower periapsis to a 200-km altitude. A secondary consequence of lowering periapsis altitude is an ~15-min reduction in the 12-hour orbit period. One-and-a-half months after each of the first two bipropellant OCMs, a smaller monopropellant maneuver at periapsis returns the average orbit period over the next one-and-a-half months to 12 hours. All OCMs are designed to begin at the nearest minute to the epoch required to center the ΔV about apoapsis (OCM-1, -3, and -5) or periapsis (OCM-2 and -4). The trajectories before and after each type of OCM, and the relative OCM orbital locations, are shown in Figures 6 and 7. Figure 6 illustrates what occurred when OCM-1 corrected the spacecraft's periapsis altitude, and Figure 7 illustrates how OCM-2 corrected the spacecraft's orbit period. OCM-1 imparted, and OCM-3 and -5 will each impart, a ΔV opposite the spacecraft velocity direction at apoapsis, lowering the periapsis altitude back to 200 km. OCM-2 increased and OCM-4 will increase the average orbit period to 12 hours by imparting a smaller ΔV in or near the spacecraft velocity direction at periapsis.

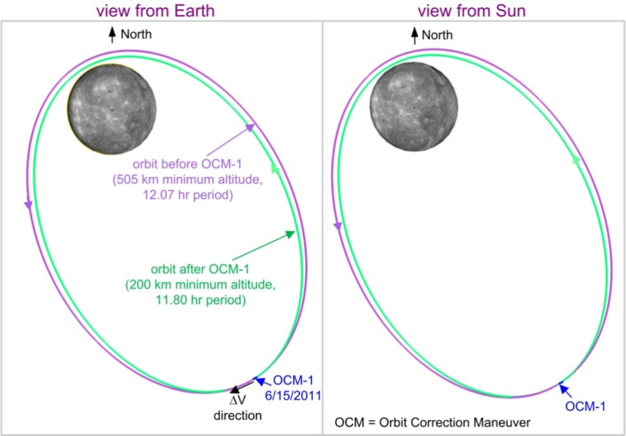

Figure 6. Mercury Orbit Periapsis Altitude Correction Strategy.

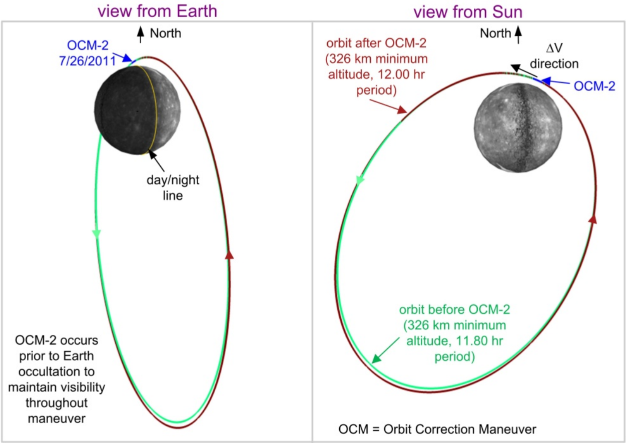

Figure 7. Mercury Orbit Period Correction Strategy.

Table 4. Post-MOI Burn Sequence Requirements.

<table>
<tr><th colspan="4">Nominal Post-MOI Bipropellant (Mode 3) Burn Sequence</th></tr>
<tr><th>Burn Segment</th><th>Thruster(s)</th><th>Minimum Duration (s)</th><th>Propellant Source</th></tr>
<tr><td>Settle</td><td>A1, A2, B1, & B2</td><td>60</td><td>Auxiliary Tank</td></tr>
<tr><td>Settle/Refill</td><td>C1 & C4 or C2 & C3</td><td>23</td><td>Main Fuel Tanks</td></tr>
<tr><td>Main</td><td>LVA</td><td>12</td><td>Main Fuel and Oxidizer Tanks</td></tr>
<tr><td>Trim</td><td>C1 & C4 or C2 & C3</td><td>61</td><td>Main Fuel Tanks</td></tr>
<tr><td colspan="4">Note: No LVA (mode 3) maneuvers may be performed after the minimum per tank fuel load limit of 8 kg has been reached.</td></tr>
<tr><th colspan="4">Post-MOI Final Bipropellant (Mode 3) Maneuver Burn Sequence</th></tr>
<tr><th>Burn Segment</th><th>Thruster(s)</th><th>Minimum Duration (s)</th><th>Propellant Source</th></tr>
<tr><td>Settle</td><td>A1, A2, B1, & B2</td><td>60</td><td>Auxiliary Tank</td></tr>
<tr><td>Settle/Refill</td><td>C1 & C4 or C2 & C3</td><td>23</td><td>Main Fuel Tanks</td></tr>
<tr><td>Main</td><td>LVA</td><td>12</td><td>Main Fuel and Oxidizer Tanks</td></tr>
<tr><td>Trim</td><td>C1 & C4 or C2 & C3</td><td>36</td><td>Main Fuel Tanks</td></tr>
<tr><th colspan="4">Nominal Post-MOI Monopropellant (Mode 2) Burn Sequence with Main Fuel Tank Fill Fraction Greater Than the Minimum per Tank Fuel Load Limit</th></tr>
<tr><th>Burn Segment</th><th>Thruster(s)</th><th>Minimum Duration (s)</th><th>Propellant Source</th></tr>
<tr><td>Settle</td><td>A1, A2, B1, & B2</td><td>60</td><td>Auxiliary Tank</td></tr>
<tr><td>Main</td><td>C1 & C4 or C2 & C3</td><td>35</td><td>Main Fuel Tanks</td></tr>
<tr><td>Trim</td><td>A1, A2, B1, & B2</td><td>50</td><td>Main Fuel Tanks</td></tr>
<tr><th colspan="4">Post-MOI No-Trim Monopropellant (Mode 2) Burn Sequence with Main Fuel Tank Fill Fraction Greater Than the Minimum per Tank Fuel Load Limit</th></tr>
<tr><th>Burn Segment</th><th>Thruster(s)</th><th>Minimum Duration (s)</th><th>Propellant Source</th></tr>
<tr><td>Settle</td><td>A1, A2, B1, & B2</td><td>60</td><td>Auxiliary Tank</td></tr>
<tr><td>Main</td><td>C1 & C4 or C2 & C3</td><td>67</td><td>Main Fuel Tanks</td></tr>
<tr><th colspan="4">Nominal Post-MOI Monopropellant (Mode 2) Burn Sequence with Main Fuel Tank Fill Fraction Greater Than the Minimum per Tank Fuel Load Limit</th></tr>
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<tr><td>Settle</td><td>A1, A2, B1, & B2</td><td>60</td><td>Auxiliary Tank</td></tr>
<tr><td>Main</td><td>C1 & C4 or C2 & C3</td><td>35</td><td>First 40 s: Auxiliary Tank
After 40 s: Main Fuel Tanks</td></tr>
<tr><td>Trim</td><td>A1, A2, B1, & B2</td><td>50</td><td>If main burn < 40 s: Auxiliary Tank
If main burn > 40 s: Main Fuel Tanks</td></tr>
<tr><th colspan="4">Post-MOI No-Trim Monopropellant (Mode 2) Burn Sequence with Main Fuel Tank Fill Fraction Greater Than the Minimum per Tank Fuel Load Limit</th></tr>
<tr><th>Burn Segment</th><th>Thruster(s)</th><th>Minimum Duration (s)</th><th>Propellant Source</th></tr>
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After 40 s: Main Fuel Tanks</td></tr>
</table>

After the MOI maneuver was completed, the fuel and oxidizer levels were substantially less than they had been at any time since launch. Therefore, the risk that fuel slosh results in fuel permanently caught in the tank baffles increased. To prevent this eventuality, the propulsion team released specific requirements for the number of segments, and the duration of and thrusters used for each of those segments, for all maneuvers after MOI. Once the mass of fuel in either main fuel tank falls below 8 kg, a further set of restrictions is imposed. However, the fuel mass does not fall below this minimum per tank fuel load limit until after the nominal mission ends one year after MOI. A summary of these maneuver implementation requirements appears in Table 4.

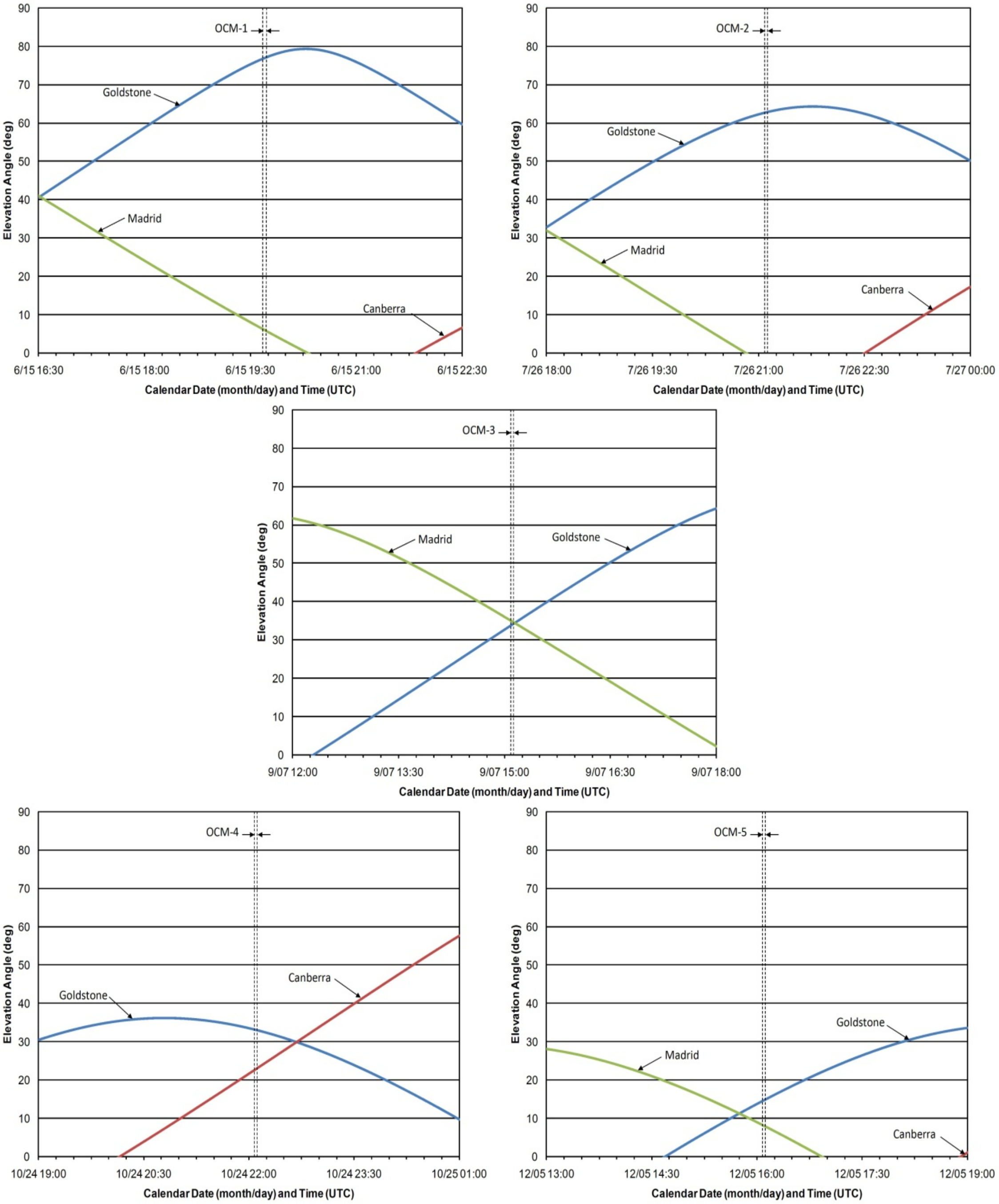


Figure 8. Ground Station Visibility of MESSENGER during Orbit-Correction Maneuvers (OCMs).

All Mercury periapse-altitude-altering maneuvers after MOI (i.e., OCMs with ΔV greater than 22 m/s) can be performed either as bipropellant OCMs using four segments or as monopropellant OCMs using two segments as described in Table 4. The segments for a bipropellant maneuver include a fuel-settle segment, an auxiliary fuel tank refill segment, a main bipropellant segment, and a cleanup (trim) segment. The fuel-settle segments use four of the A and B thrusters that provide 16.24 N of total thrust at an I_{sp} of 227.5 s. This settle segment duration is required to be

60 s. The subsequent refill segment lasts 23 s and uses two C thrusters, each operating at 26.92-N thrust and 234.9-s I_{sp}. After MOI, the bipropellant LVA thruster used for the main segment will use between 701.7 and 702.6 N average thrust and an average I_{sp} between 316.2 and 316.3 s depending on the LVA thrust duration. The duration of this main segment varies with each maneuver because it depends on the amount of ΔV required; however, the segment duration must be an integer number of seconds with a 12-s minimum. The final trim segment uses the same A and B thrusters as the settle segment and must last at least 61 s. Actual trim duration depends on the maneuver ΔV. An exception to the 61-s minimum trim duration requirement is allowed only for the final bipropellant maneuver of the mission, which has a 36-s minimum trim duration requirement. To minimize any potential of running out of oxidizer during a bipropellant OCM, either one or two OCMs, OCM-3 and/or OCM-5, could be performed as a less efficient monopropellant maneuver.

Table 5. Mercury Orbital-Phase Maneuver Summary.

Orbit-Correction Segment	Calendar Date (day month year)	Start UTC (hh:mm:ss)	Sun–S/C–ΔV (°)	Sun–Earth–S/C (°)	Duration (s)	ΔV (m/s)
OCM-1 A/B settle	15 June 2011	19:39:49	96.2	3.7	60.0	0.423
OCM-1 C refill	15 June 2011	19:40:49	96.2	3.7	23.0	2.097
OCM-1 LVA main: periapsis 505–200 km	15 June 2011	18:41:12	96.2	3.7	15.0	18.409
OCM-1 C trim	15 June 2011	18:41:27	96.2	3.7	74.0	6.911
OCM-1 total	**Post-OCM-1 spacecraft mass = 569.146 kg**					**27.840**
OCM-2 A/B settle	26 July 2011	21:04:00	97.6	25.6	60.0	0.430
OCM-2 C main: period 11.80–12.00 hours	26 July 2011	21:05:00	97.6	25.6	34.0	3.193
OCM-2 A/B trim	26 July 2011	21:05:34	97.6	25.6	63.0	0.452
OCM-2 total	**Post-OCM-2 spacecraft mass = 567.455 kg**					**4.076**
OCM-3 A/B settle	8 September 2011	15:06:00	79.9	17.1	60.0	0.429
OCM-3 C refill	8 September 2011	15:07:00	79.9	17.1	23.0	2.163
OCM-3 LVA main: periapsis 467–200 km	8 September 2011	15:07:23	79.9	17.1	12.0	14.987
OCM-3 C trim	8 September 2011	15:07:35	79.9	17.1	77.9	7.377
OCM-3 total	**Post-OCM-3 spacecraft mass = 561.905 kg**					**24.956**
OCM-4 A/B settle	24 October 2011	22:04:00	98.8	16.5	60.0	0.434
OCM-4 C main: period 11.76–12.00 hours	24 October 2011	22:05:00	98.8	16.5	35.0	3.335
OCM-4 A/B trim	24 October 2011	22:05:35	98.8	16.5	50.0	0.362
OCM-4 total	**Post-OCM-4 spacecraft mass = 560.215 kg**					**4.131**
OCM-5 A/B settle	5 December 2011	16:04:00	81.1	3.5	60.0	0.435
OCM-5 C refill	5 December 2011	16:05:00	81.1	3.5	23.0	2.158
OCM-5 LVA main: periapsis 441–200 km	5 December 2011	16:05:23	81.1	3.5	12.0	15.182
OCM-5 C trim	5 December 2011	16:05:35	81.1	3.5	36.0	4.415
OCM-5 total	**Post-OCM-5 spacecraft mass = 555.386 kg**					**22.190**
periapsis: 451.2-km altitude over 73.5°N latitude; period 11.79 hours (MOI + one year)	18 March 2012	01:33:43	**Total orbital-phase ΔV: 83.199 m/s*** **Approx. ΔV remaining: 144.001 m/s*** ***Current estimate—subject to change**			

S/C, spacecraft.

The smaller monopropellant OCMs that occur before the minimum per tank fuel load limit is reached, OCMs with ΔV less than 22 m/s, are to be performed in three segments: a fuel settle, a main burn, and a trim segment. The 60-s fuel-settle segment uses the same four 4.06-N A and B thrusters as the fuel-settle segment in a larger bipropellant maneuver. The main segment, which uses two C-thrusters just as a bipropellant trim segment does, has a 35-s minimum-duration requirement. The trim segment uses the same A and B thrusters as the fuel-settle segment and lasts for at least 50 s. There is also a two-segment option for modeling monopropellant maneuvers that have ΔV large enough to support the corresponding 67-s minimum-duration requirement for the main burn segment. An exception to these monopropellant maneuver guidelines was made for the OCM-2 main segment. To guarantee that the final trim segment would not be cut off before the 50-s minimum, the main burn segment was shortened from 35 s to 34 s, resulting in a trim segment that is 63 s long.

Each OCM is separated by approximately 44 days, or half a Mercury year. This timing is important as it allows each OCM to occur when the spacecraft orbit's line of nodes is nearly perpendicular to the spacecraft–Sun direction, thereby meeting sunshade orientation constraints. This timing also maintains the periapsis altitude below 506 km and keeps the orbit period longer than 11.75 hours. Furthermore, as seen in Figure 8, all OCMs occur when there is coverage from at least one DSN ground station. Although the lower spacecraft elevation above the horizon for OCM-5 is offset by a low 0.682-AU Earth–spacecraft range, there remains flexibility to move the OCM-5 time by 12 hours. Table 5 lists timing, ΔV, and spacecraft orientation parameters for each OCM. For OCM-1, this information reflects what actually occurred, but for OCM-2 and all future OCMs, the design values appear.

The actual OCM-1 maneuver execution differed only slightly from the final design. Just before the OCM-1 maneuver, a 49-s time-tag bias delayed the maneuver start time in order to account for changes in the orbit determination between the time of the final design and time of maneuver execution. The reconstruction of OCM-1 by the guidance and control team was only 0.0018 m/s lower in ΔV magnitude than the final design with a 0.026° direction error. According to the final reconstruction provided by the navigation team, the ΔV magnitude was 0.0276 m/s less than the final design with a 0.061° pointing error. Furthermore, the resulting periapsis altitude was only 0.414 km above the targeted altitude of 200.0 km.

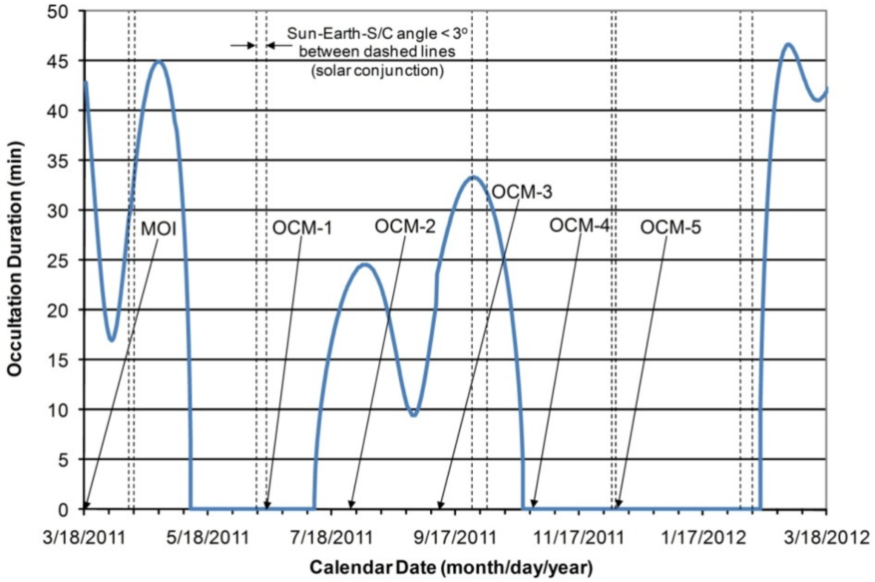


Figure 9. Earth Occultations and Solar Conjunctions during Mercury Orbit.

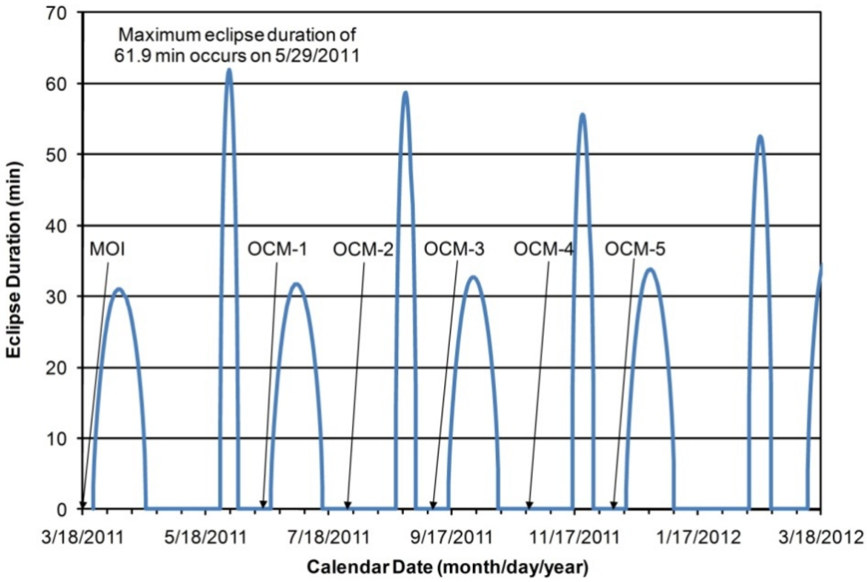
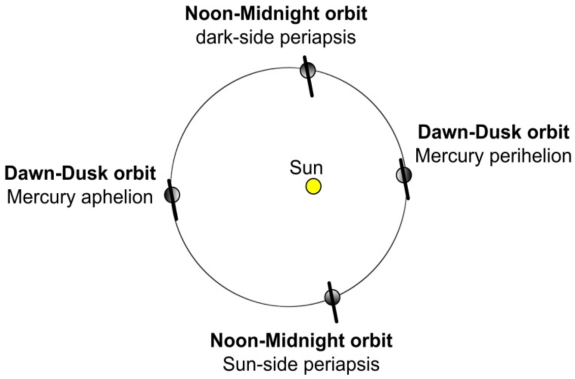


Figure 10. Solar Eclipses (Short Eclipses Include Periapsis) during Orbital Phase.

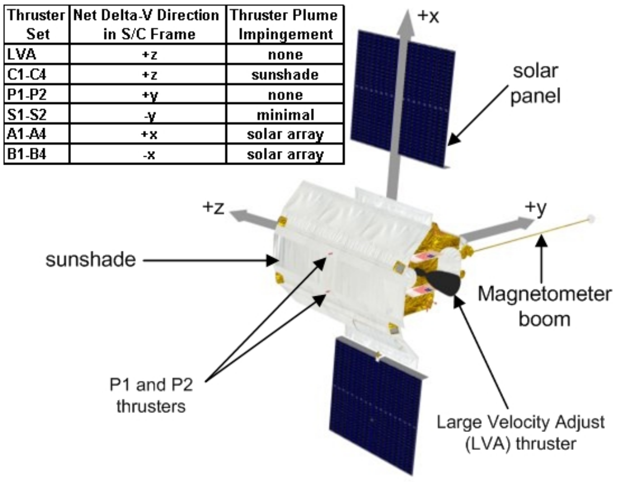
Accurate prediction of the timing and duration of Earth occultations, i.e., when Mercury blocks spacecraft–Earth communication, and solar eclipses is critical when determining the timing of OCMs. Figures 9 and 10 contain the timing and duration of the occultations and eclipses, as well as the locations of OCMs relative to these events. The labels in Figure 9 illustrate how OCM-1 and -5 occur shortly after solar conjunction, when the Sun–Earth–spacecraft angle is <3°. The Sun–Earth–spacecraft angle for OCM-1 and -5 are 3.7° and 3.5°, respectively. Each of these OCMs could be implemented one orbit earlier while complying with the sunshade orientation constraint and remaining outside solar conjunction. However, doing so would not keep all OCM maneuver times during daytime working hours, and it could interfere with an operations requirement to have two OCM command-load uplink opportunities before the start of a pre-OCM command sequence. As seen in Figures 9 and 10, OCM-1 and -5 occur between a solar conjunction and an eclipse season that includes the periapsis of each orbit. In Figure 10, eclipse duration includes both partial and total eclipse. Note the 61.9-min maximum solar eclipse duration on 29 May 2011 when Mercury is at 281° true anomaly in its orbit around the Sun. The short-duration eclipse season began four to five days after MOI. Short eclipse seasons, defined as having eclipses lasting fewer than 35 min, occur when the spacecraft orbit's lowest-altitude equator crossing (known as the descending node) occurs on Mercury's nightside. The portion of the orbit in eclipse is closer to periapsis during short eclipses than it is during long eclipses, thereby yielding a higher Mercury-relative velocity than during the long eclipses.

Knowledge of timing for particular Sun-relative orbit orientations aids in planning scientific observations of Mercury. One Sun-relative orbit orientation is the dawn–dusk orbit configuration (see Figure 11), which is defined as the spacecraft crossing Mercury's equatorial plane closest to the day/night terminator. This orientation occurs near both Mercury's perihelion and aphelion. During dawn–dusk orbits, the spacecraft can point its science instrument deck at Mercury for an entire orbit by rotating about the Sun–spacecraft direction with the front side of the sunshade facing the Sun. Another Sun-relative orbit orientation, the noon–midnight orbit configuration, occurs when the spacecraft crosses Mercury's equatorial plane closest to local solar times of noon and midnight. The noon–midnight configuration has two variations, the dayside periapsis, also called "hot pole," and the nightside periapsis. During major portions of noon–midnight orbits, the sunshade-orientation constraint prevents scientific observations that require pointing the instrument deck toward Mercury's surface. Most science instruments have fields of view that include the spacecraft +*z*-axis direction, shown in Figure 12.



Type of Orbit	Calendar Date (month/day/year)
Noon-Midnight, Sun-side periapsis	05/29/2011, 08/25/2011, 11/20/2011, 02/17/2012
Noon-Midnight, dark-side periapsis	04/04/2011, 07/01/2011, 09/26/2011, 12/23/2011
Dusk-Dawn, Mercury perihelion	06/14/2011, 09/09/2011, 12/06/2011, 03/03/2012
Dusk-Dawn, Mercury aphelion	05/03/2011, 07/30/2011, 10/25/2011, 01/21/2012

Figure 11. Sun-Relative Orbit Orientations during Orbital Phase.



Thruster Set	Net Delta-V Direction in S/C Frame	Thruster Plume Impingement
LVA	+z	none
C1-C4	+z	sunshade
P1-P2	+y	none
S1-S2	-y	minimal
A1-A4	+x	solar array
B1-B4	-x	solar array

Figure 12. Sunward Side of the MESSENGER Spacecraft.

During dayside, low-altitude portions of hot-pole orbits, solar radiation reflected off Mercury's surface increases the environmental thermal input on the spacecraft's anti-Sun surfaces, thereby elevating spacecraft operating temperatures. The current limits for these hot-pole orbits are when Mercury is between 220° and 360° true anomaly in its orbit around the Sun.

During these hot pole seasons, the temperatures on the spacecraft are higher because of the close proximity of the planet and the radiation that is reflected back to the spacecraft from the surface. To mitigate the risk of overheating the battery or other temperature-sensitive items located behind the sunshade, the spacecraft is oriented as shown in Figure 13. When the spacecraft is over the Sun-facing northerly latitudes, as in position A in Figure 13, the instrument deck or +*z*-axis (see Figure 12) is pointed 90° from the surface of Mercury and the solar panels are edge-on to the Sun. When the spacecraft is over nightside northerly latitudes, as in from just after position B until over Mercury's north pole in Figure 13, the instrument deck may be pointed toward the planet and the solar panels are pointed off the Sun direction by ~70°.

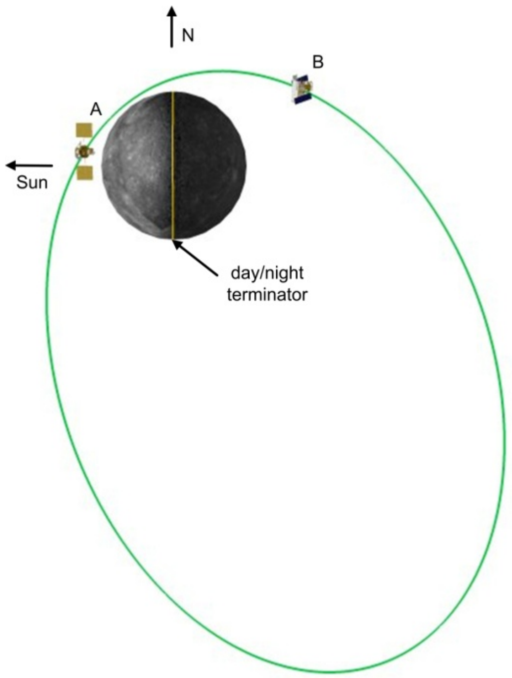


Figure 13. Spacecraft Attitude during Hot-Pole-Season Orbits.

One year after orbit insertion, estimates of orbital parameters include an 84.0° orbit inclination, 451-km periapsis altitude, 345.8° right ascension of ascending node, and 73.5°N sub-spacecraft periapsis latitude. Without an extended mission, propagation of the nominal end-of-mission state leads to an estimated Mercury impact on 7 August 2014 near 63.9°N latitude. Any estimate of end-of-mission orbit and Mercury surface impact will vary in accordance with updates in the accuracy of Mercury's gravity field and the accuracy of future maneuver performance.

MERCURY ORBIT EXTENDED MISSION OPTIONS

Two options for a one-year extension of the baseline one-year orbital phase have been designed. The option that is most similar to the baseline mission involves maintaining the spacecraft's orbit period close to 12 hours while using as few OCMs as possible. This option offers the opportunity for a variety of scientific questions to be answered as the periapsis latitude passes through its orbital-phase maximum near Mercury's north pole, which harbors permanently shadowed craters that could contain water ice deposits. Another option establishes an 8-hour orbit period with periapsis altitude in the 200- to 500-km range experienced by the spacecraft during the baseline mission. In addition to providing improvements in low-altitude observation of Mercury's permanently shadowed craters at the north pole, a one-third reduction in apoapsis altitude relative to the 12-hour orbit facilitates higher-resolution imaging of the southern hemisphere. Both extended mission options begin with an OCM on 2 March 2012.

Table 6. Mercury Extended Mission Maneuver Summary for a 12-Hour-Period Option.

Orbit-Correction Segment	Calendar Date (day month year)	Start UTC (hh:mm:ss)	Sun–S/C–ΔV (°)	Sun–Earth–S/C (°)	Duration (s)	ΔV (m/s)
OCM-6 A/B settle	2 March 2012	20:03:00	83.7	17.8	60.0	0.439
OCM-6 C auxiliary tank	2 March 2012	20:04:00	83.7	17.8	40.0	3.585
OCM-6 C main: period adjustment	2 March 2012	20:04:40	83.7	17.8	56.2	5.429
OCM-6 total	**Post-OCM-6 spacecraft mass = 552.631 kg**					**9.453**
OCM-7 C settle	4 March 2012	15:19:00	94.6	18.2	60.0	0.441
OCM-7 C auxiliary tank	4 March 2012	15:20:00	94.6	18.2	40.0	3.602
OCM-7 C main: periapsis altitude 200 km, period 12.18 hours	4 March 2012	15:20:40	94.6	18.2	150.0	14.588
OCM-7 total	**Post-OCM-7 spacecraft mass = 547.820 kg**					**18.631**
OCM-8 A/B settle	18 April 2012	19:45:00	89.7	27.5	60.0	0.445
OCM-8 C auxiliary tank	18 April 2012	19:46:00	89.7	27.5	40.0	3.634
OCM-8 C main: periapsis altitude 200 km, period 12.10 hours	18 April 2012	19:46:40	89.7	27.5	38.6	3.779
OCM-8 total	**Post-OCM-8 spacecraft mass = 545.553 kg**					**7.858**
OCM-9 A/B settle	29 May 2012	16:13:00	84.3	3.0	60.0	0.447
OCM-9 C auxiliary tank	29 May 2012	16:14:00	84.3	3.0	40.0	3.649
OCM-9 C main: periapsis altitude 200 km, period 12.02 hours	29 May 2012	16:14:40	84.3	3.0	42.9	4.213
OCM-9 total	**Post-OCM-9 spacecraft mass = 543.177 kg**					**8.309**
OCM-10 A/B settle	25 August 2012	20:56:00	87.1	14.7	60.0	0.449
OCM-10 C auxiliary tank	25 August 2012	20:57:00	87.1	14.7	40.0	3.666
OCM-10 C main: periapsis altitude 200 km, period 11.91 hours	25 August 2012	20:57:40	87.1	14.7	77.6	7.666
OCM-10 total	**Post-OCM-10 spacecraft mass = 539.847 kg**					**11.781**
OCM-11 A/B settle	21 November 2012	17:43:00	88.0	9.2	60.0	0.451
OCM-11 C auxiliary tank	21 November 2012	17:44:00	88.0	9.2	40.0	3.689
OCM-11 C main: periapsis altitude 200 km, period 11.84 hours	21 November 2012	17:44:40	88.0	9.2	30.4	3.021
OCM-11 total	**Post-OCM-11 spacecraft mass = 537.660 kg**					**7.161**
periapsis: 219.3-km altitude over 83.9°N latitude; period 11.84 hours (MOI + two years)	18 March 2013	11:22:59	**Total extended orbital-phase ΔV: 63.193 m/s*** **Approx. ΔV remaining: 80.451 m/s*** ***Current estimate—option not finalized**			

The minimum-risk extended mission option has orbit period remaining within 0.18 hour of 12 hours. This 12-hour-orbit-period option provides operational planning and a spacecraft environment with a proven success record from early Mercury orbital operations. The first extended mission OCM, OCM-6, would occur with a ΔV directed near the spacecraft velocity direction near periapsis to increase orbit period to just over 12 hours. The start time for OCM-6 would occur approximately 13 min after the spacecraft exits an Earth occultation zone without communication with Earth-based tracking antennas. For this option, none of the remaining OCMs, all of which occur at apoapsis, will be near an Earth occultation or detract from high-value science observations near periapsis. Establishment of the new orbit would be completed with an OCM-7 ΔV directed nearly opposite to the spacecraft velocity direction at apoapsis, thereby lowering periapsis altitude to 200 km. This OCM is followed by more periapsis-lowering OCMs as needed when Mercury is near its orbit's aphelion or perihelion because these times correspond to OCM ΔV direction consistent with sunshade orientation constraints. The leftmost column of Table 6 provides OCM objectives, which reveal that this extended mission option maintains an orbit period that never strays from 12 hours by more than 0.2 hours. The time between OCMs is longer during the extended mission because solar gravity perturbations have less of an effect on periapsis altitude near polar periapsis latitudes. A second extended mission is feasible because ΔV margin remains at the end of this one-year extension. The effect on periapsis latitude and periapsis altitude of solar gravity perturbations and other lesser trajectory perturbations is depicted in Figure 14 for the 12-hour and 8-hour extended-mission options.

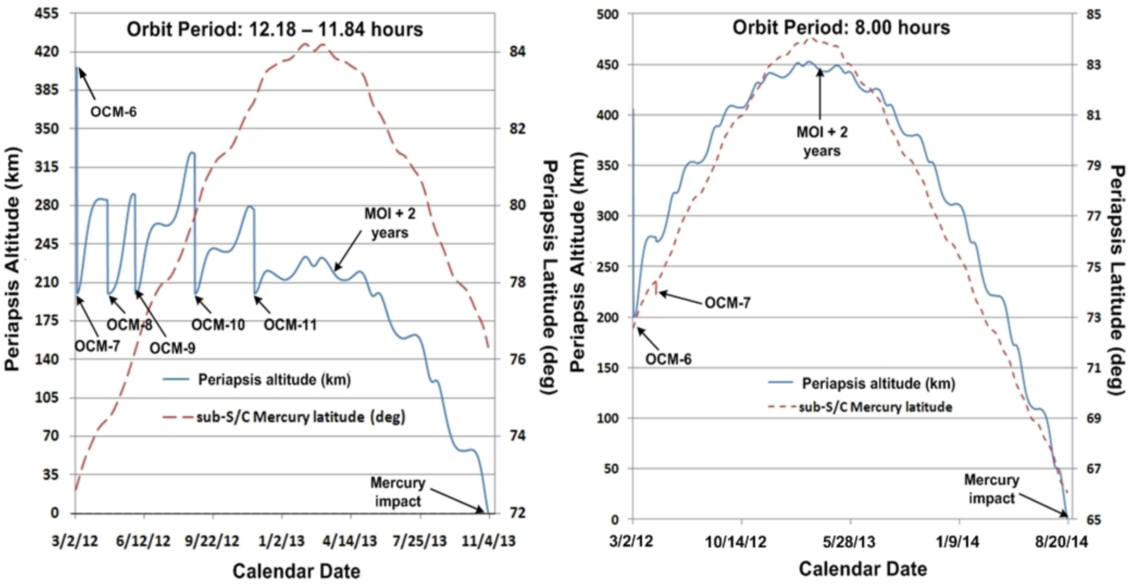


Figure 14. Periapsis Trends for 12-Hour and 8-Hour-Period Extended Mission Options.

An extended mission option with an orbit period of 8 hours is being examined to determine whether the new environmental risks from a lower average altitude can be managed. This 8-hour orbit period would begin after a 2 March 2012 OCM-6 that lowers periapsis altitude to 200 km and an 18 April 2012 OCM-7 that decreases orbit period to 8 hours. Because the 8-hour orbit has a higher velocity when the spacecraft passes through Mercury's shadow during the long-eclipse season, and because periapsis latitude will approach Mercury's north pole, the 47.6-min longest-duration solar eclipse is more than 14 min shorter (see Figure 10) than during the first year after MOI. After only two OCMs, the spacecraft will drift in a stable 8-hour orbit until passing over maximum latitude just before the end of the one-year extended mission. With the spacecraft spending less time farther from Mercury, solar gravity perturbations slow down the journey to Mercury surface impact, delaying impact by 0.8 years relative to the 12-hour-orbit extended-mission option. The first extended-mission OCM, OCM-6, would occur on 2 March 2012 with a ΔV directed nearly opposite to the spacecraft velocity direction at apoapsis, thereby lowering periapsis altitude to 200 km. The next and final maneuver on 18 April 2012, OCM-7, would establish an 8-hour period orbit by using a ΔV directed near the spacecraft velocity direction near periapsis. The start time for OCM-7 would occur approximately 4.2 min after the spacecraft exits an Earth occultation zone without communication with Earth-based tracking antennas. OCM timing and performance for this 8-hour-orbit extended mission option are summarized in Table 7. As with the 12-hour-orbit extended mission option, a second extended mission is feasible because significant ΔV margin remains two years after MOI.

Table 7. Mercury Extended Mission Maneuver Summary for an 8-Hour-Period Option.

Orbit-Correction Segment	**Calendar Date (day month year)**	**Start UTC (hh:mm:ss)**	**Sun–S/C–ΔV (°)**	**Sun–Earth–S/C (°)**	**Duration (s)**	**ΔV (m/s)**
OCM-6 A/B settle	2 March 2012	14:09:00	82.1	17.8	60.0	0.439
OCM-6 C auxiliary tank	2 March 2012	14:10:00	82.1	17.8	40.0	3.585
OCM-6 C main: periapsis altitude 200 km	2 March 2012	14:10:40	82.1	17.8	156.5	15.150
OCM-6 total	**Post-OCM-6 spacecraft mass = 550.304 kg**					**19.174**
OCM-7 C settle	18 April 2012	17:54:00	92.2	27.5	60.0	0.443
OCM-7 C auxiliary tank	18 April 2012	17:55:00	92.2	27.5	40.0	3.618
OCM-7 C main: period to 8.00 hours	18 April 2012	17:55:40	92.2	27.5	824.4	81.707
OCM-7 total	**Post-OCM-7 spacecraft mass = 529.805 kg**					**85.768**
periapsis: 447.0-km altitude over 83.9°N latitude; period 8.00 hours (MOI+ two years)	18 March 2013	10:09:39	**Total extended orbital-phase ΔV: 104.942 m/s*** **Approx. ΔV remaining: 47.330 m/s*** ***Current estimate—option not finalized**			

SUMMARY

MESSENGER became the first spacecraft to orbit Mercury when it successfully completed its orbit insertion maneuver on 18 March 2011 at 01:00:00 UTC. According to reconstructions of the MOI maneuver provided by the navigation and guidance and control teams, the maneuver ΔV magnitude and direction nearly matched the designed values. The resulting orbit had a 206.77-km periapsis altitude, 12.07-hour orbit period, 59.98°N sub-spacecraft periapsis latitude, 350.17° right ascension of ascending node, and 82.52° orbit inclination. Furthermore, these initial orbital characteristics were well within all requirements. After an initial 2.5-week engineering checkout period, the spacecraft entered the prime science portion of the yearlong orbital phase of the mission. During this time in Mercury orbit, information is being gathered to address the mission's science objectives.

To maintain the orbit required to address the mission's science objectives, periodic correction maneuvers are needed to counter various perturbing forces, including those of solar gravity and Mercury's slight oblateness. The first of these OCMs, which occurred on 15 June 2011, 89–90 days after orbit insertion, succeeded in lowering the periapsis from 505 km to 200 km. After OCM-1, the next four OCMs are approximately 44 days apart. OCM-3 and -5 are, like OCM-1, designed to lower the upward drifting periapsis altitude to 200 km. However, the reduction in periapsis altitude also reduces the orbit period by ~15 min from the desired 12 hours. OCM-2 and -4 increase the orbit period back to 12 hours. If no OCMs occur after OCM-5, the current best estimates for the date and latitude that the spacecraft will impact Mercury's surface are 7 August 2014 and near 63.9°N latitude.

Two options for a one-year extension of the baseline yearlong orbital phase have been designed. The first would maintain the spacecraft's orbit period within 0.2 hours of 12 hours while performing as few OCMs as possible. The first two OCMs, OCM-6 and -7, would target

200-km periapsis altitude by 12.2-hour orbit period on 2–4 March 2012 followed by a periapsis-lowering OCM every 44 days over the next eight months. Near the end of this extended mission option, dominant trajectory perturbations from solar gravity cause the rate of Mercury altitude increase to slow and then reverse, resulting in the spacecraft impacting the surface in November 2013. A second option for extending the mission would place the spacecraft into an 8-hour orbit with a periapsis altitude ranging between 200 km and 460 km. After only two OCMs, the first on 2 March 2012 and the second on 18 April 2012, the spacecraft maintains a stable 8-hour orbit until passing over maximum latitude just before the end of the one-year extended mission. Because the spacecraft spends more time closer to Mercury, the effect of solar perturbations on MESSENGER's orbit yield a later Mercury surface impact in August 2014. Both options would provide low-altitude observation of Mercury's permanently shadowed craters at the north pole; however, the 8-hour option has the additional benefit of a lower apoapsis altitude that would result in higher-resolution imaging of Mercury's southern hemisphere.

ACKNOWLEDGMENTS

The authors acknowledge the contributions of Tony Taylor and Ken Williams of KinetX, Inc., for independent verification of MOI and OCM design, and for providing hundreds of orbit ephemeris files as well as Mercury gravity field updates during the course of the MESSENGER mission. Chris Scott and Jack Ercol of JHU/APL also provided input on the trajectory perturbation effects of Mercury albedo and IR radiation pressure.

REFERENCES

[1] J. V. McAdams, D. W. Dunham, R. W. Farquhar, A. H. Taylor, and B. G. Williams, "Trajectory Design and Maneuver Strategy for the MESSENGER Mission to Mercury." *Space Flight Mechanics 2005: Part II, Advances in the Astronautical Sciences* 120, pp. 1185–1204, 2005.

[2] J. V. McAdams, D. P. Moessner, and D. W. Dunham, "MESSENGER's Orbit Insertion Maneuver: Design Chronology, Contingency Preparedness, and Final Results." *9th IAA Low-Cost Planetary Missions Conference*, 8 pp., Laurel, MD, June 21–23, 2011.

[3] J. V. McAdams, D. J. O'Shaughnessy, A. H. Taylor, K. E. Williams, and B. R. Page, "Maneuver Design Strategy Enables Precise Targeting of the First MESSENGER Mercury Flyby." *AIAA/AAS Astrodynamics Specialist Conference*, paper AIAA 2008-7367, 15 pp., Honolulu, HI, August 18–21, 2008.

[4] S. C. Solomon, R. L. McNutt, Jr., R. E. Gold, and D. L. Domingue, "MESSENGER Mission Overview." *Space Sci. Rev.* 131, pp. 3–39, 2007.

[5] S. C. Solomon, R. L. McNutt, Jr., R. E. Gold, M. H. Acuña, D. N. Baker, W. V. Boynton, C. R. Chapman, A. F. Cheng, G. Gloeckler, J. W. Head III, S. M. Krimigis, W. E. McClintock, S. L. Murchie, S. J. Peale, R. J. Phillips, M. S. Robinson, J. A. Slavin, D. E. Smith, R. G. Strom, J. I. Trombka, and M. T. Zuber, "The MESSENGER Mission to Mercury: Scientific Objectives and Implementation." *Planet. Space Sci.* 49, pp. 1445–1465, 2001.

[6] R. E. Gold, S. C. Solomon, R. L. McNutt, Jr., A. G. Santo, J. B. Abshire, M. H. Acuña, R. S. Afzal, B. J. Anderson, B. G. Andrews, P. D. Bedini, J. Cain, A. F. Cheng, L. G. Evans, W. C. Feldman, R. B., Follas, G. Gloeckler, J. O. Goldsten, S. E. Hawkins III, N. R. Izenberg, S. E. Jaskulek, E. A. Ketchum, M. R. Lankton, D. A. Lohr, B. H. Mauk, W. E. McClintock, S. L. Murchie, C. E. Schlemm II, D. E. Smith, R. D. Starr, and T. H. Zurbuchen, "The MESSENGER Mission to Mercury: Scientific Payload." *Planet. Space Sci.* 49, pp. 1467–1479, 2001.

[7] R. E. Gold, R. L. McNutt, Jr., S. C. Solomon, and the MESSENGER Team, "The MESSENGER Science Payload." *Proceedings of the 5th AIAA International Conference on Low-Cost Planetary Missions,* Special Publication SP-542, European Space Agency, Noordwijk, The Netherlands, pp. 399–405, 2003.

[8] C. J. Scott, J. V. McAdams, D. P. Moessner, and C. J. Ercol, "Modeling the Effects of Albedo and Infrared Radiation Pressures on the MESSENGER Spacecraft." *AAS/AIAA Astrodynamics Specialist Conference*, paper AAS 11-552, 18 pp., Girdwood, AK, July 31–August 4, 2011.