IAC-12-C1.5.6

MESSENGER AT MERCURY: FROM ORBIT INSERTION TO FIRST EXTENDED MISSION

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After more than 6.6 years in interplanetary cruise, NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft entered orbit about Mercury on 18 March 2011. Operating from a highly eccentric, near-polar orbit designed to keep the spacecraft safe and to facilitate the required observations, MESSENGER is using its payload of seven instruments and its radio-frequency telecommunications system to characterize the planet's interior, surface, atmosphere, magnetosphere, and heliospheric environment. Because one Earth year spans two Mercury solar days, MESSENGER's science data-collection campaign includes two opportunities each calendar year to observe any location on Mercury with a given viewing geometry. The focus of the first solar day was on global map products, and the second solar day provided opportunities for targeted observations, to recover measurements missed during the first six months, and to acquire images complementary to those from the first solar day to form a global stereo map. The spacecraft's orbit has completed six local-time rotations and nine rotations in longitude, allowing spatial characterization of Mercury's magnetic field, construction of an elevation model from northern-hemisphere altimetry, and global to regional measurements of surface abundances of major elements. Six orbit-correction maneuvers (OCMs) kept minimum altitude low and the orbit period near 12 hours during the first year after Mercury orbit insertion (MOI). Within one year of MOI, all MESSENGER full-mission success criteria were either met or exceeded. In mid-April 2012 two OCMs consumed most of the remaining propellant to lower orbit period from 11.6 to 8.0 hours. During the first two years after MOI, MESSENGER's minimum altitude drifted upward as the periapsis latitude drifted from 60°N to 84°N. About two years after MOI, periapsis will begin drifting southward and periapsis altitude will decrease until Mercury surface impact occurs. The 8-hour orbit will delay Mercury impact months longer than had the spacecraft remained in a 12-hour orbit for the second year at Mercury and used remaining propellant to raise periapsis altitude. Relative to the 12-hour orbit, the 8-hour orbit has 50% more low-altitude passes and a 32% lower apoapsis altitude for higher-resolution observations of Mercury's southern hemisphere. Certifying the 8-hour orbit in the extended mission required extensive engineering and operational analysis to ensure that the spacecraft remains safe and that all scientific objectives will be met.

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I. MISSION OVERVIEW

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft was designed, built, and is operated by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in Laurel, Maryland, and the mission is led by Principal Investigator Sean Solomon 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 solar-powered, dual-propulsion-mode spacecraft 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 became the first to utilize more than four gravity-assist flybys of planets: one Earth flyby, two Venus flybys, and three Mercury flybys[1,2,3,4]. Many trajectory-correction maneuvers (TCMs) targeted each planetary flyby and the first spacecraft entry into orbit about Mercury in mid-March 2011. In another first, the MESSENGER spacecraft cancelled many planned TCMs during interplanetary cruise by using solar sailing, i.e., effectively utilizing solar radiation pressure and carefully planned dwell times at spacecraft sunshade orientations and solar panel tilt angles[5]. After Mercury orbit insertion (MOI), lower accuracy requirements for orbit-correction maneuvers (OCMs) ended the need for solar sailing.

MESSENGER at Mercury

MOI marked the start of a yearlong primary mission in Mercury orbit. A 15-minute-duration propulsive maneuver early on 18 March 2011 slowed the spacecraft's velocity with respect to Mercury enough to place the spacecraft into an orbit with a 206.77-km periapsis altitude, 12.07-hour orbit period, 59.98°N sub-spacecraft periapsis latitude, and 82.52° initial orbit inclination[6]. After spacecraft functional checkout, the full suite of science observations began on 4 April 2011. The primary mission included six OCMs to correct upward drift of periapsis altitude and adjust orbit period. These OCMs had to be scheduled near dawn-dusk spacecraft orbits, which occur every 44 days (half of Mercury's heliocentric orbit period) to enable the sunshade to protect the spacecraft before, during, and after each OCM.

Extended mission operations began one year after MOI, soon after the successful fulfillment of primary mission scientific objectives. Less than five weeks into the extended mission, a pair of OCMs guided the spacecraft into an 8-hour orbit. Near the end of the first extended mission in March 2013, solar gravity perturbations will have shifted periapsis to the northernmost sub-spacecraft latitude of the entire Mercury orbital mission phase. This polar crossing will end the northward periapsis progression and increasing periapsis altitude, and will begin the equator-directed periapsis movement with periapsis altitude decreasing progressively, leading to eventual impact of the spacecraft with Mercury's surface.

Spacecraft Design and Operation

The spacecraft design and operational constraints influenced the selection and periodic adjustment of the primary science orbit at Mercury. The MESSENGER spacecraft combines carefully selected advanced technologies, minimal moving parts, and a design strategy that involved simple, proven techniques. Key design features include a ceramic-cloth sunshade, a dual-mode (bipropellant-monopropellant) propulsion system, two rotatable solar arrays, three-axis stabilization, and a versatile telecommunications system[7]. The large bipropellant thruster, for which the final use was to decrease the orbital period, is mounted on the spacecraft deck opposite the deck with many of the science instruments (see Fig. 1). Spacecraft sub-systems, Earth-based communication links, and numerous scientific and operational constraints were coordinated during the Mercury orbital phase by SciBox[8], a multi-faceted software tool that enables highly efficient data collection and return.

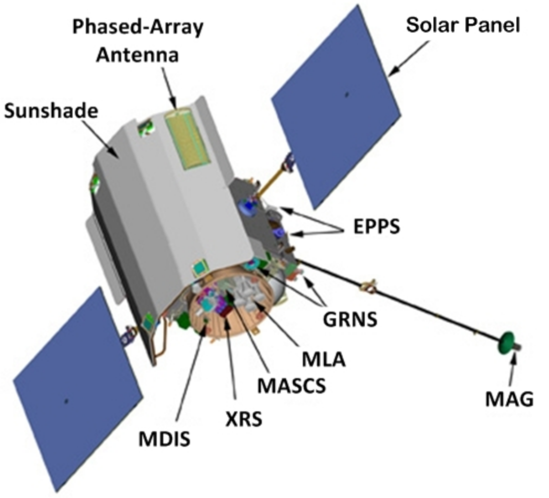

Fig. 1: MESSENGER spacecraft diagram showing primary components and science instruments.

Science Objectives and Payload

Orbit selection and scientific observation sequences are based on sets of science questions and related scientific objectives for both the primary and first extended missions. The MESSENGER mission was designed to address six important scientific questions[9]. The answers to these questions, which offer general insights into the formation and evolution of the inner planets as a group, are the basis for the following primary mission science objectives[9].

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.

These science objectives are the basis for the measurement objectives and the science instrument payload. The MESSENGER science payload has seven science instruments weighing 50 kg and using 84 W of power[9]. The seven science instruments are the Mercury Dual Imaging System[10] (MDIS), the Gamma-Ray and Neutron Spectrometer[11] (GRNS), the X-Ray Spectrometer[12] (XRS), the Magnetometer[13] (MAG), the Mercury Laser Altimeter[14] (MLA), the Mercury Atmospheric and Surface Composition Spectrometer[15] (MASCS), and the Energetic Particle and Plasma Spectrometer[16] (EPPS). The X-band transponder[17], the key spacecraft component for radio science, completes the science payload. Fig. 1 shows the location on the spacecraft of these science instruments and sensors, most inside or near the payload adapter ring.

Objectives for the First Extended Mission

Objectives for the first extended mission, which employs a second year of orbital operations, were motivated by discoveries made during the primary mission. The extended-mission themes include more comprehensive measurement of the magnetosphere and exosphere during a period of more active Sun, greater focus on observations at low altitudes, and a greater variety of targeted observations.

The first extended mission offers an opportunity to observe the Mercury system under higher rates of imposed solar activity than during either the flybys or the primary mission. Extended mission observations are improving our ability to distinguish among postulated exospheric source processes and are facilitating a fuller characterization of the range in behavior of Mercury's dynamic magnetosphere. Increased solar activity brings about far greater variability in solar extreme ultraviolet and X-ray emissions and solar energetic particle fluences[18]. The first extended mission provides conditions for the study of Mercury's magnetosphere and exosphere that were neither sampled by Mariner 10 nor observed by MESSENGER during the primary mission. Targeted observations by the particle spectrometers and the Ultraviolet and Visible Spectrometer[16] (UVVS) sensor on the MASCS instrument will enable MESSENGER to provide insight into the source, loss, and transport processes for plasma and energetic particles within Mercury's magnetosphere and for neutral species in the exosphere with measurements not possible during the primary mission.

Extended mission measurements are already providing improved accuracy in the higher-order structure of Mercury's internal magnetic field and are helping to refine lower- and higher-order terms in Mercury's gravity field. Complementary measurements are being provided by color imaging of the northern hemisphere using fewer filters but maintaining the full spatial resolution of the MDIS instrument. The MLA is making off-nadir observations of targets of high geological interest, such as apparent centers of past volcanic activity, fault structures, and impact craters. The MASCS instrument is using extended-duration and directed observations to address questions of surface mineralogical variations and exospheric dynamics beyond that which was possible during the primary mission. A potential opportunity for a unique scientific observation will arise with a rare, close encounter (0.025 AU) with comet 2P Encke on 18 November 2013, three days before Encke's perihelion when the spacecraft is less than 0.34 AU from the Sun. However, comet Encke observations are outside of the scope of the MESSENGER's first extended mission.

II. MERCURY ORBIT INSERTION

The orbital phase of the MESSENGER mission began with a single Mercury orbit insertion maneuver starting at 00:45:15 UTC on 18 March

2011. 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 and a thrust vector nearly opposite to the instantaneous spacecraft velocity vector. The MOI maneuver 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.

Orbit Insertion Changes Since Launch

The design of the MOI maneuver for the March 2011 arrival at Mercury, first identified[19] in 1998, underwent a number of important improvements and changes[20] in the 6.6 years from launch to MOI. For more than five years after launch, it was thought that MOI required two bi-propellant maneuvers in sequence, whereby ~96% of MOI ΔV preceded a more precise, adjustable cleanup of the final ~4% of MOI ΔV by six orbits or 3.6 days[21]. This two-part MOI was needed to meet an orbit-period requirement of 12 hours ±1 min after MOI. During 2009, the project chose to increase post-MOI orbit inclination from 80.0° to 82.5°, because this change would enhance science return without increasing risk to spacecraft health. This change in target orbit inclination was accompanied by 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 improved engine model fidelity for the bi-propellant thruster and the optimality of variable-direction thrust pointing. 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, precise MOI cleanup maneuver.

Orbit Insertion Requirements

To meet science requirements and engineering safety constraints, the final requirements for the MESSENGER spacecraft's 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 prevented end-of-mission inclination from exceeding 85.0º relative to Mercury's equator. The final Mercury orbit-insertion strategy used 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. Fig. 2 includes three viewpoints of MESSENGER's initial orbit size and orientation, including the MOI maneuver location and evidence of 100% observability from Earth.

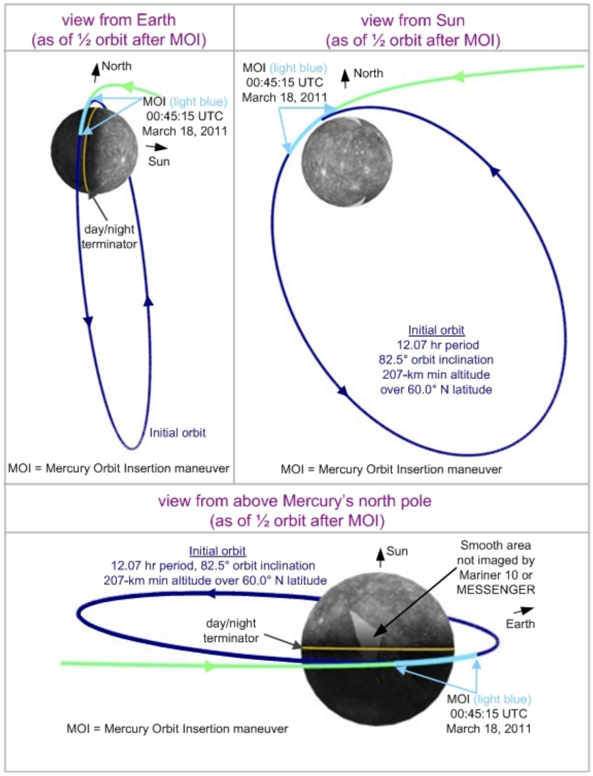

Fig. 2: Three views of MESSENGER's initial orbit around Mercury.

Orbit Insertion Performance

The performance of the MOI maneuver[20] and the characteristics of the Mercury orbit resulting from MOI differed slightly from the final design targets. This difference was mainly due to an offset from the targeted arrival point in the Mercury arrival B-plane, as well as fuel pressures that were lower than used for the final maneuver design, resulting in lower thrust during MOI. 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. This Mercury arrival offset corresponds to a 6.0 km increase in the minimum altitude, which occurred 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 only 7 s longer than predicted. Nearly all of the 0.038°/s thrust-direction turn rate occurred during the 834-s-duration bi-propellant segment. During MOI the spacecraft’s sunshade tilt reached 2.5º from the maximum allowable tilt that ensures protection of the spacecraft from direct sunlight (or 1.6° closer to the constraint than for the final MOI 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. A summary comparison of the final MOI design versus the final reconstructions from the navigation, guidance and control, and propulsion teams is provided in Table 1. Final reconstruction of the MOI maneuver indicated successful placement of the spacecraft into the science orbit well within allowable tolerances. 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°N sub-spacecraft periapsis latitude (0.024° south of the 60.0° N target). These orbit parameters were all well within the MESSENGER project’s requirements for the initial orbit about Mercury, thereby eliminating the need for either a cleanup or contingency maneuver between Mercury orbit insertion and the first OCM. The on-time, accurate orbit insertion enabled primary science phase full science to start on 4 April 2012.

	Resultant ΔV (m/s)	**Integrated ΔV (m/s)**	**Pointing Error (°)**	**Duration (s)**	**Mass (kg)**
Final Design	851.124	862.166	not applicable	878.1	185.328
Navigation	not applicable	861.714	0.472	878.589	185.526
Guidance and Control	851.056	not applicable	0.003	885.040	185.729
Propulsion	not applicable	861.7	not applicable	887	185.555

Table 1. Comparison of final MOI design with final reconstructions by the navigation, guidance and control, and propulsion teams.

III. ORBIT CORRECTION MANEUVERS

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. This initial orbit about Mercury marked the start of an 89-day-long coast phase with no OCMs, but with propulsive momentum-adjustment maneuvers as needed. The first five OCMs were each separated by approximately 44 days, or half a Mercury year. The final OCM of the primary mission phase, OCM-6, occurred 89 days after OCM-5. This inter-OCM timing allowed each OCM to occur when the spacecraft orbit’s line of nodes was nearly perpendicular to the spacecraft–Sun direction, thereby meeting sunshade orientation constraints. This timing also enabled the OCMs to keep periapsis altitude below 506 km and orbit period longer than 11.6 hours. Furthermore, all OCMs occurred when there was coverage from at least one Deep Space Network ground station.

Primary Mission Orbit Evolution

During the Mercury orbital phase, knowledge of the predicted spacecraft attitude was 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 radiation had to be carefully coordinated with the spacecraft’s complex attitude profile. All of these factors were included during the Mercury orbital-phase trajectory propagation by the navigation team. Solar gravity and the small Mercury oblateness (J_2), the most dominant trajectory perturbation factors, contribute to the following changes in the spacecraft orbit during the first year after MOI. Periapsis altitude increased from about 200 km to 441–506 km prior to OCMs that lowered periapsis altitude. Periapsis latitude drifted northward by 13.5°, corresponding to a decrease in the argument of periapsis. Orbit inclination increased by nearly 1.4°, and right ascension of the ascending node decreased by 4.4°.

Each of these observed orbital parameter variations was within 1% of the value predicted before Mercury orbit insertion with the best available Mercury gravity field model[22]. This Mercury gravity field model, produced late in 2009 by the MESSENGER navigation team, was based on three Mercury flybys each by Mariner 10 in 1974 and 1975 and MESSENGER in 2008 and 2009. The non-uniform variation of each of these orbital parameters is shown in Figs. 3 and 4. In addition, Fig. 5 offers three views of MESSENGER's primary mission orbit around Mercury, including highlights of extremes in selected orbital parameters.

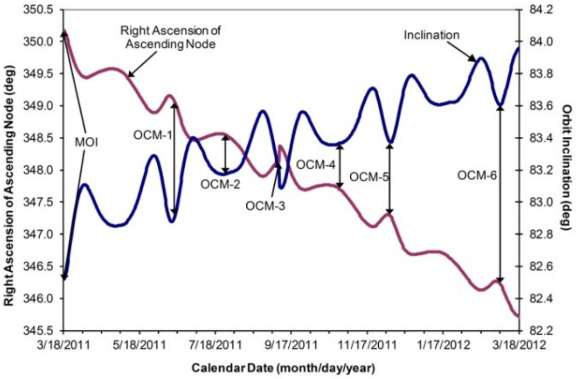

Fig. 3: Orbit plane progression during the primary mission.

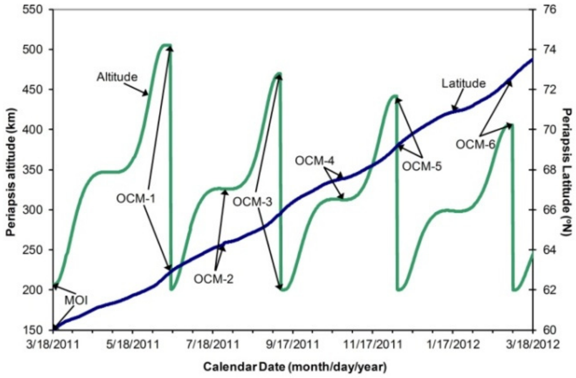

Fig. 4: Periapsis evolution during the primary mission.

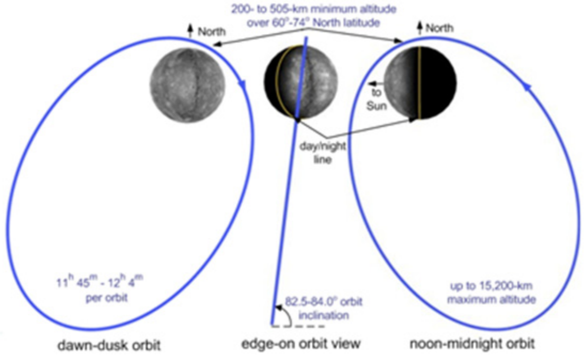

Fig. 5: Three views of MESSENGER's orbit around Mercury during the primary mission.

Orbit Correction Maneuver Strategy and Results

Each OCM either lowered periapsis altitude or increased orbit period. The larger bi-propellant maneuvers at apoapsis lowered periapsis to a 200-km altitude. A secondary consequence of lowering periapsis altitude was a ~15-min reduction in the 12-hour orbit period. One-and-a-half months after each of the first two bi-propellant OCMs (OCM-1 and OCM-3), a smaller monopropellant maneuver at periapsis returned the average orbit period over the next 1.5 months to 12 hours. All OCMs were designed to begin at the nearest minute to the epoch required to center the ΔV about apoapsis (OCM-1, -3, -5, and -6) or periapsis (OCM-2 and -4) until the final pre-OCM orbit determination update revealed an integer-second shift needed to place initial thrust at the same orbital location as for the final OCM design. The trajectories before and after each type of OCM, and the relative OCM orbital locations, are shown in Figs. 6 and 7. OCMs 1, 3, 5, and 6 each

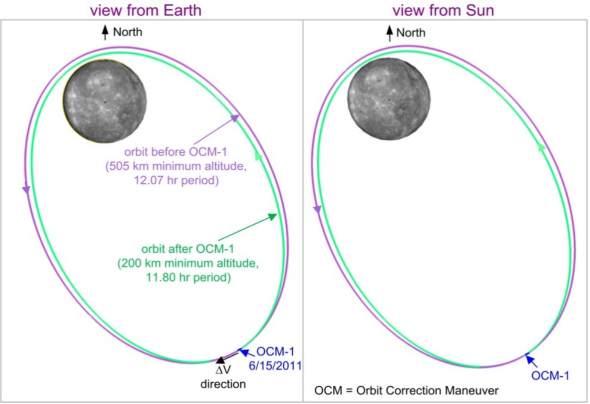

Fig. 6: Periapsis altitude correction strategy.

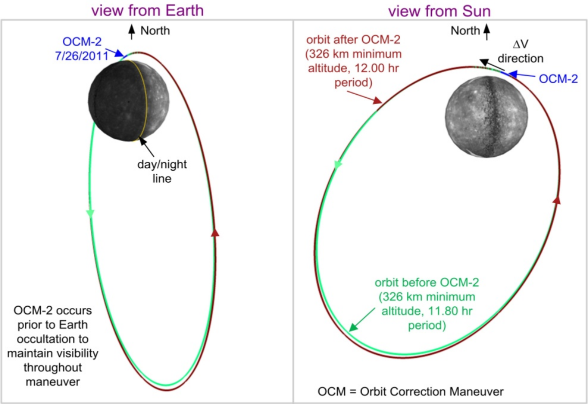

Fig. 7: Orbit period correction strategy.

imparted a ΔV opposite to the spacecraft velocity direction at apoapsis, lowering the periapsis altitude to 200 km. OCMs 2 and 4 increased the average orbit period to 12 hours by imparting a smaller ΔV close to the spacecraft velocity direction at periapsis.

Maneuver		**Orbit Period (s)**	**Periapsis Altitude (km)**	**Periapsis Time (UTC)**
OCM-1	Actual	42483.50	200.14	01:35:18.8
	Target	42481.12	200.00	01:35:17.6
	Offset	2.38	0.41	1.2 s
OCM-2	Actual	43201.83	325.99	09:06:13.2
	Target	43200.09	325.73	09:06:11.6
	Offset	1.74	0.27	1.6 s
OCM-3	Actual	42341.14	200.34	21:03:13.8
	Target	42338.97	200.00	21:03:12.0
	Offset	2.17	0.34	1.8 s
OCM-4	Actual	43197.17	312.55	10:13:12.0
	Target	43199.96	312.63	10:13:14.7
	Offset	-2.79	-0.08	-2.7 s
OCM-5	Actual	42429.61	200.25	22:05:03.2
	Target	42427.82	200.00	22:05:3.7
	Offset	1.79	0.25	-0.5 s
OCM-6	Actual	41779.42	199.62	07:34:39.1
	Target	41777.07	199.55	07:34:38.9
	Offset	2.35	0.06	0.2 s

Table 2. Orbit target performance for the primary mission orbit-correction maneuvers.

Correction Maneuver, Date, and Objective		**Start Time (UTC)**	**ΔV (m/s)**	**Pointing Error (°)**	**Duration (s)**	**Mass (kg)**
OCM-1 on 15 Jun 2011	Final Design	19:39:00	27.868	not applicable	172.0	6.099
periapsis 505 to 200 km	Reconstruction	19:39:50	27.840	0.093	173.62	6.229
OCM-2 on 26 Jul 2011	Final Design	21:04:00	4.076	not applicable	157.0	1.714
period 11.80 to 12.00 hr	Reconstruction	21:04:03	4.036	0.927	187.54	1.918
OCM-3 on 7 Sep 2011	Final Design	15:08:00	24.962	not applicable	171.8	5.622
periapsis 470 to 200 km	Reconstruction	15:08:24	24.936	0.106	165.5	5.645
OCM-4 on 24 Oct 2011	Final Design	22:12:00	4.155	not applicable	166.7	1.793
period 11.76 to 12.00 hr	Reconstruction	22:11:46	4.140	0.736	159.44	1.797
OCM-5 on 5 Dec 2011	Final Design	16:08:00	22.214	not applicable	286.8	5.945
periapsis 441 to 200 km	Reconstruction	16:08:27	22.138	0.112	291.22	6.057
OCM-6 on 3 Mar 2012	Final Design	01:43:00	19.234	not applicable	169.7	5.052
periapsis 405 to 200 km	Reconstruction	01:43:55	19.212	0.052	171.38	5.162

Table 3. Final design and reconstructed results for the primary mission orbit correction maneuvers.

Table 2 provides a summary of how well each maneuver performed relative to the targeted orbit parameters. Table 3 lists timing, ΔV, and other details for both the final design and reconstruction of each OCM. Maneuver start time was adjusted between the final design and the final execution based on pre-OCM updates to the spacecraft's predicted orbital position. The final OCM start time, listed as "Reconstruction – Start Time (UTC)" in Table 3, reflects a time shift designed to place the OCM at the same point in the spacecraft's orbit.

IV. EXTENDED MISSION ORBIT DESIGN

Less than five weeks after the start of MESSENGER's first extended mission on 18 March 2012, two OCMs reduced the spacecraft's orbit period from 11.6 to 8 hours. Although it is possible to implement this 3.6-hour orbit period reduction with a single maneuver, two OCMs minimized risk and enabled use of remaining accessible propellant. The first maneuver, OCM-7, effectively utilized all remaining usable oxidizer in a final firing of the large bi-propellant thruster. A second maneuver, OCM-8, was the last OCM to draw fuel from one of the spacecraft's two main fuel tanks. Both OCMs slowed the spacecraft's velocity relative to Mercury while it was closest to Mercury (see Fig. 8). Since the amount of usable oxidizer remaining onboard was not well known, OCM-7 accounted for an uncertain thruster on-time required to achieve the 53.3 m/s target velocity change and 9-hour, 5-min orbit period. The uncertainty in usable oxidizer on MESSENGER meant that the spacecraft's large bi-propellant thruster and all four of its largest monopropellant thrusters could operate between 0 and 29 s at almost eight times greater thrust level than is possible without the bi-propellant thruster. The result of OCM-7 was a highly accurate velocity change for the full 29-s maximum operation with the bi-propellant thruster. Four days after OCM-7, the clean-up maneuver, OCM-8, used fuel remaining in one of the two main fuel tanks as well as fuel in the auxiliary fuel tank to complete the spacecraft's transition to the 8-hour orbit. Table 4 provides maneuver performance for OCM-7 and OCM-8 relative to the targeted orbit parameters.

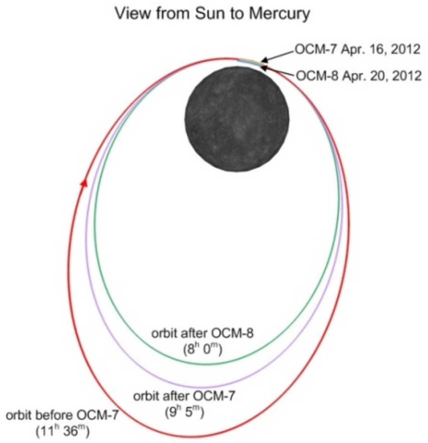

Fig. 8: Two orbit-correction maneuvers provided the transition to the 8-hour extended-mission orbit.

Maneuver		Orbit Period (s)	Periapsis Altitude (km)	Periapsis Time (UTC)
OCM-7	Actual	32684.85	277.70	04:20:56.3
	Target	32688.28	277.45	04:20:59.4
	Offset	-3.43	0.25	-3.1 s
OCM-8	Actual	28801.89	277.67	07:08:28.3
	Target	28800.00	277.47	07:08:28.2
	Offset	1.89	0.20	0.1 s

Table 4. Orbit target performance for the first extended mission orbit-correction maneuvers.

Extended Mission Orbit Evolution

The initial 8-hour orbit remains highly eccentric, with MESSENGER travelling between 278 km and 10,314 km above Mercury's surface. The 8-hour orbit period not only increased the number of orbits per day by 50% relative to the primary orbital mission but also provided observation opportunities at maximum altitudes nearly one third lower than during the primary orbital mission. Late in the one-year first extended mission, the orbit inclination will reach a maximum of 84° and the sub-spacecraft latitude at minimum altitude will reach its most northerly extent at 84°N, thereby enabling closer study of permanently shadowed craters near Mercury's north pole. Without planned OCMs between OCM-8 and the end of the first extended mission, the spacecraft will be at about 450 km altitude as the orbit's closest point passes nearest Mercury's north pole (see Fig. 9). It is not necessary to repeat the extended-mission version of Fig. 3, which shows two characteristics of the spacecraft's orbit orientation, because the right ascension of the ascending node continues the same trend and orbit inclination follows the same trend until early March 2013, when orbit inclination begins a general downward trend until surface impact.

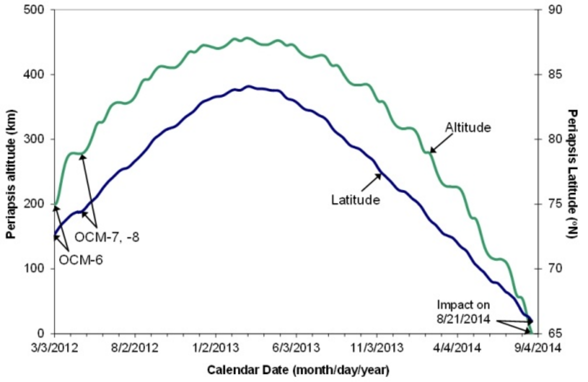

Fig. 9: Periapsis evolution during the extended mission if no further OCMs are conducted.

Encounter with Comet Encke

In November 2013 there will be an unusually close encounter between comet Encke and Mercury. The mission design team identified a 0.025 AU (3.7 million km) close approach between Mercury and short-term periodic comet 2P Encke years before MESSENGER's arrival at the planet. The perspective of the proximity of this comet-planet encounter can be compared with records of comet encounters with Earth; this encounter distance would be equivalent to the third closest comet to Earth in the last 2,000 years.

The timing and geometrical orientation of the Encke encounter can offer a favorable opportunity for observation sequences using multiple science instruments on MESSENGER. As illustrated in Fig. 10, science instrument fields of view and MDIS imager pivot limits enable views of comet Encke far from and near the minimum separation distance. This MESSENGER-to-Encke encounter will occur only three days before Encke's perihelion, near the period of highest cometary activity. At a minimum spacecraft-comet range of 0.025 AU, the science instruments will not be able to resolve Encke's nucleus. The nearest superior solar conjunction will occur 1.3 months after the closest Encke-to-spacecraft range, thereby ensuring that the Sun would not hinder the return of science data from MESSENGER soon after the Encke closest encounter. Such operations, however, are beyond the scope of the current MESSENGER first extended mission.

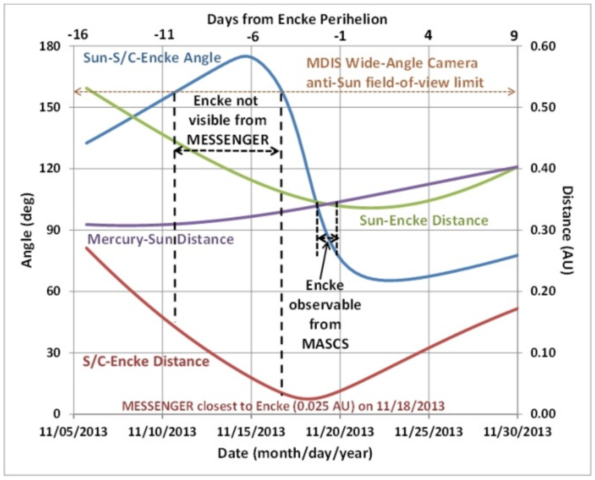

Fig. 10: Distance and viewing geometry for the November 2013 MESSENGER-Encke encounter.

Option for Final Year of MESSENGER Operations

If NASA funding for MESSENGER flight operations were to be provided through four years after MOI, and if sufficient operational function remains on the spacecraft, the spacecraft has enough fuel on board to postpone Mercury surface impact until March or April 2015. A preliminary trajectory with four OCMs offers one potential scenario that would require the next OCM, OCM-9, no later than mid-March of 2014. This option delays Mercury impact until as late as 18 March 2015, but requires more detailed thermal, science, and other analyses to determine the practicality of implementation. This option accounts for a conservative fuel allocation for commanded spacecraft momentum adjustments.

The trajectory scenario achieves a late time for low-altitude northern hemisphere passages over the sunlit surface of Mercury. This option utilizes nearly all of the remaining usable fuel to conduct OCMs 9, 10, and 11 to postpone Mercury impact by increasing periapsis altitude when the spacecraft is near apoapsis. Each of these OCMs would execute once the periapsis altitude was close to 200 km, the lowest altitude planned during the primary mission. In addition, each of these OCMs would occur near Mercury aphelion close to a dawn-dusk (day-night terminator) orbit geometry to ensure effective sunshade orientation before, during, and after each OCM. OCM-9, which would occur on or close to 18 March 2014, would deplete all known usable fuel from the second main fuel tank[21]. OCM-10 and OCM-11 would draw fuel from the auxiliary fuel tank on 12 June 2014 and 10 September 2014, respectively. A final planned OCM-12 would occur on or near 24 October 2014, when Mercury is near perihelion. OCM-12 would reduce the orbit period from about 8.25 to 8.05 hours to ease scheduling of operations staff shifts and antenna resources for the final five months of orbital operations. A clean-up OCM at a later date is likely needed to decrease the uncertainty in the surface impact date. The direction of Earth relative to the final, lowest orbital periapsis altitudes would, however, prevent direct observation. The periapsis progression and relative timing of each OCM for a potential fourth year of Mercury orbital operations appears in Fig. 11. Timing Mercury impact just after the dawn-dusk orbit orientation at Mercury's aphelion leads to a periapsis-altitude "plateau" of up to 11 day duration and 2 to 3 km altitude, sufficiently high to safely miss surface topography known to be up to 1 km above the mean Mercury radius near projected periapsis passage. Such plateaus in orbit evolution naturally occur during dawn-dusk seasons due to the nearly uniform effect of solar gravity over each orbit of MESSENGER around the planet. This periapsis altitude plateau corresponds to an altitude of ~150 km over a wide range of sub-spacecraft Mercury longitudes at the northernmost orbit latitudes.

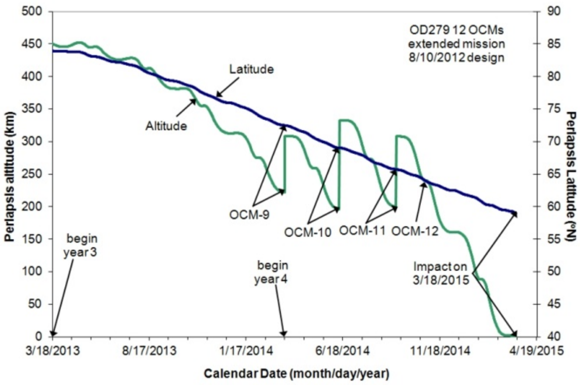

Fig. 11: Periapsis evolution for an extended mission option with 12 OCMs and one low-altitude season.

V. CONCLUSION

Having successfully completed the primary science phase of its investigation of Mercury, MESSENGER has ventured into its first extended mission. Mid-term through its first year of extended mission operations, the spacecraft and most instruments are performing nominally. The science observation plan has successfully been used to coordinate the measurements required to attain full mission success, and the team is continuing to work toward meeting the new success criteria established for the first extended mission. After successful implementation of Mercury orbit insertion and all subsequent eight orbit-correction maneuvers, an option for further orbital operations has been identified for additional study. This option offers a potential to postpone eventual impact with Mercury until as late as March 2015.

VI. ACKNOWLEDGEMENTS

The MESSENGER Team includes hundreds of scientists, engineers, designers, technicians, support personnel, subcontractors, and managers who helped MESSENGER reach all milestones to date. We acknowledge them as well the assistance of NASA personnel and others who gave of their time to oversee and review the program to assure mission success. Details on the mission, flybys, Mercury orbit insertion, and orbital operations for the primary and extended mission phases are maintained and updated at the MESSENGER website: http://messenger.jhuapl.edu/. The MESSENGER mission is supported by the NASA Discovery Program under contracts NAS5-97271 to The Johns Hopkins University Applied Physics Laboratory and contract NASW-00002 to the Carnegie Institution of Washington.

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