The Final Two Years: MESSENGER's Trajectory from the Third Year in Orbit through Mercury Impact

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Abstract: *The MESSENGER spacecraft began its Second Extended Mission (XM2) on 18 March 2013. This final phase of the mission will end when the spacecraft impacts Mercury in late March 2015. Design of the XM2 trajectory and associated maneuvers accounted for propellant location and utilization, altitude selection for periods during which periapsis altitude changes little over several orbits, spacecraft thermal management, timing of communication-disrupting solar conjunctions, expected levels of solar activity, visibility of Earth near the spacecraft orbit's periapsis, and surface lighting during periods of lower altitude. Several trajectory perturbations, including those due to solar radiation pressure, variations in Mercury's gravity field, solar gravity, and offloading of spacecraft angular momentum, cause perturbations to the spacecraft's orbit throughout XM2. MESSENGER was also able to observe comets 2P\Encke and 2012 S1 (ISON) successfully in November 2013. Four orbit correction maneuvers, OCMs 9–12, will enable a low-periapsis-altitude campaign during the final eight months of the mission with unprecedented opportunities to observe Mercury.*

Keywords: *MESSENGER, mission design, trajectory, extended mission, orbit correction maneuver*

1. Introduction

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft, designed and operated by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in Laurel, Maryland, began its Second Extended Mission (XM2) on 18 March 2013 after successful completion of its Primary Mission and First Extended Mission (XM1) [1]. This XM2 orbital phase will continue until the spacecraft impacts Mercury in late March 2015. During XM1, the MESSENGER team evaluated several XM2 options that efficiently utilized all remaining available propellant to extend mission duration and achieve the proposed scientific objectives. In November 2013, MESSENGER observed short-period comet 2P/Encke near its perihelion and hyperbolic-orbit comet 2012 S1 (ISON) shortly before its final perihelion from distances as close as 0.0249 AU and 0.2420 AU, respectively.

The spacecraft's orbit is continually evolving throughout XM2 due to perturbations caused by to solar gravity, spatial variations in Mercury's gravity field, solar radiation pressure (SRP), commanded offloads of angular momentum, and planned maneuvers. This evolution includes changes in the spacecraft orbit's inclination, periapsis latitude, and periapsis altitude. The variation in periapsis altitude will, in combination with planned OCMs, lead to Mercury impact on or about 28 March 2015. Although the impact of the spacecraft onto the surface of Mercury in late March 2015 will not be visible from Earth, impact should occur before communications are disrupted by a solar conjunction in early April 2015.

Four orbit correction maneuvers (OCMs 9–12) during XM2 will each create an opportunity for Mercury observation from low altitude, and together they will delay Mercury impact by about seven months. The first 15 months of XM2 is spent in an 8-hour orbit around Mercury with the periapsis altitude decreasing from around 450 km at the start of XM2 to 115 km just prior to OCM-9 on 17 June 2014. Each OCM will then raise periapsis altitude just enough to target periods of multiple days during which periapsis altitude will change little because the spacecraft orbit plane will be nearly orthogonal to the spacecraft-Sun line. OCMs 9, 10, and 11 will each target a 25-km minimum altitude above Mercury's terrain just prior to the next scheduled OCM. OCM-12 will target an extended period when periapsis altitude will vary little from 15 km over several successive orbits. The combined periapsis-raising effect of OCMs 9–12 will delay Mercury surface impact from late August 2014 until late March 2015. This low-periapsis-altitude campaign provides approximately 200 orbits with periapsis altitudes at or below 30 km.

2. Tools, Resources, and Assumptions Used in Trajectory Design

Assumptions involving Mercury physical parameters, spacecraft characteristics, spacecraft attitude, SRP, and engine performance provide the basis for designing the orbit-phase trajectory to meet XM2 scientific objectives. The Mercury gravity model used by the mission design team for trajectory propagation is HgM005, a spherical harmonic model expanded to degree and order 50 developed by the MESSENGER Science Team that utilizes data gathered through 18 June 2013. The Mercury spin axis and libration definitions match models that were adopted by the International Astronomical Union (IAU) in 2011 [2]. Finally, the Mercury prime meridian reference matches the existing IAU convention, which is based on the location of crater Hun Kal. These Mercury reference parameters were adopted by the MESSENGER project in November 2010 in accordance with recommendations of MESSENGER's configuration control board.

The Mercury orbit-phase design relied on Satellite Tool Kit (STK)/Astrogator software, with trajectory propagation that accounted for SRP, general relativity, and the gravitational attraction of Mercury, all seven other planets, the Earth's Moon, Pluto, and the Sun (DE423 ephemerides). Note that the current version of STK has been renamed to Systems Tool Kit. Small-force trajectory perturbations from planetary radiation pressure and thermal radiation are computed only by the navigation team [3]. The navigation team provides a short-term predicted ephemeris that extends about one month from the release date [4], and the mission design team merges this short-term ephemeris with the mission-design-generated long-term predicted ephemeris that extends to the current best estimate of Mercury surface impact. With the long-term predicted ephemeris being updated every six weeks, the mission design team monitors the orbit discontinuity at the merge time of the short-term and long-term ephemerides. Generation of a precise trajectory required iteration with JHU/APL's SciBox science and flight operations planning tool [5], which defines spacecraft bus attitude, and with the guidance and control (G&C) team, which adds solar panel orientation. This SciBox tool manages the transition between the near-term (≤ 4 weeks) active command sequence planning and the long-term science operations plan by implementing a smooth transition across the orbit discontinuity where the short-term and long-term ephemerides merge. Propellant consumption from future commanded momentum dumps (CMDs) was simulated by periodically updating the spacecraft fuel mass to account for one momentum offload per week with an assumed depletion of 6 g of fuel mass per offload. These fuel mass updates are placed just before each maneuver and after each solar eclipse season. Since CMD fuel consumption is related to the nature and frequency of science-based observations and thermal management, the fuel consumption rate is evaluated at least annually and, if necessary, fuel mass offload assumptions are updated to refine estimates of propellant margin.

3. Orbit Evolution

During XM2, knowledge of the predicted spacecraft attitude is vital for accurate orbit propagation and design of OCMs. Trajectory perturbations due to SRP, variations in Mercury's gravity, solar gravity, and general relativity, must be carefully coordinated with the spacecraft's complex attitude profile. All of these factors are included during trajectory propagation. Although Mercury's albedo and infrared radiation perturbations also affect the orbit, accounting for these trajectory perturbations is not required until the navigation team creates precise reconstructions of the spacecraft's orbit [6]. The currently modeled perturbing effects, of which solar gravity is the most dominant, as well as the four planned orbit correction maneuvers and frequent CMDs, contribute to variations in the spacecraft's orbit.

The Second Extended Mission began on 18 March 2013, two years after Mercury orbit insertion (MOI). Figure 1 depicts the periapsis evolution during the entire orbital phase and marks the start of XM2 as "MOI + 2 years". At that time, the orbit had an 8.0-h period, 451-km periapsis altitude, 84.0° orbit inclination, 83.9° N sub-spacecraft periapsis latitude, 342.7° right ascension of ascending node, and 89.4° argument of periapsis (angles expressed in the Mercury-centered inertial of epoch J2000 frame). This 8-h orbit period will have little variation for the first year and three months of XM2. Then, on 17 June 2014, OCM-9, the first course-correction maneuver of XM2, will be performed. The small variations in orbit period between the conclusion of OCM-8 on 20 April 2012 and the start of OCM-9 are shown in Figure 2 below. Although there is a slight upward trend in orbit period between OCMs 8 and 9, the period remains within 11 s of the 8-h post-OCM-8 target. The orbit prior to OCM-9 will have an $8^h\ 9^s$ orbit period, a 114-km periapsis altitude, an 83.7° orbit inclination, a 69.0° N sub-spacecraft periapsis latitude, a 338.6° right ascension of ascending node, and a 69.9° argument of periapsis. The cumulative effect of OCMs 9-12 will include an increase in orbit period to $8^h\ 17^m$ by the first orbit after OCM-12 on 21 January 2015. The sub-spacecraft periapsis latitude, the right ascension of ascending node, and the argument of periapsis all continue to decrease throughout the final nine months of XM2 until they reach 58.2° N, 335.7°, and 58.8° respectively, just prior to Mercury impact on or about 28 March 2015. The non-uniform variation of each of these orbital parameters throughout XM2 can be seen in Figures 3 and 4, and Figure 5 provides a profile of Mercury orbit period.

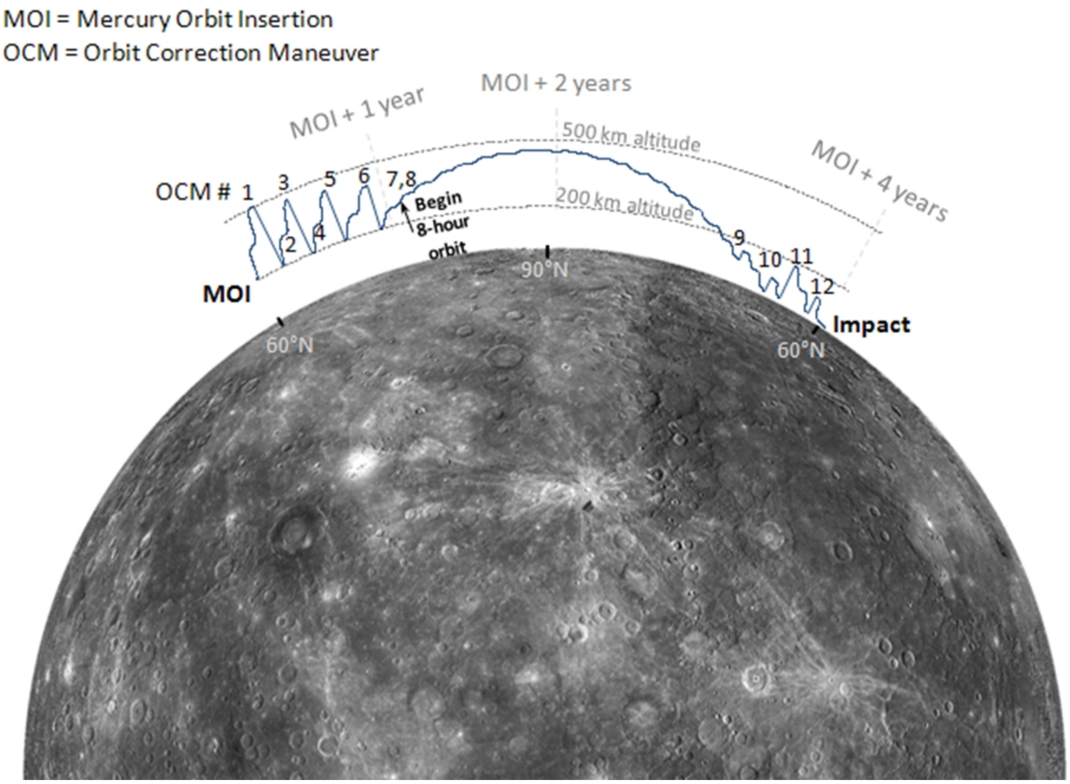


Figure 1. Periapsis evolution from Mercury orbit insertion through impact

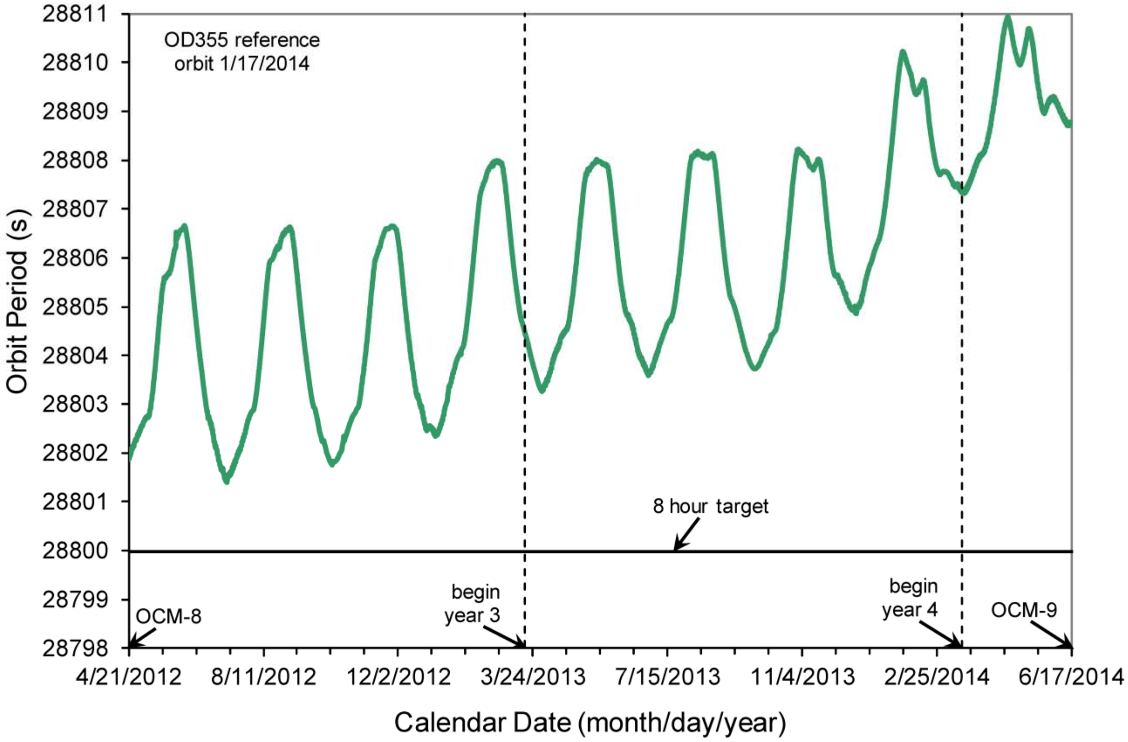


Figure 2. Spacecraft 8-hour orbit period from OCM-8 to OCM-9

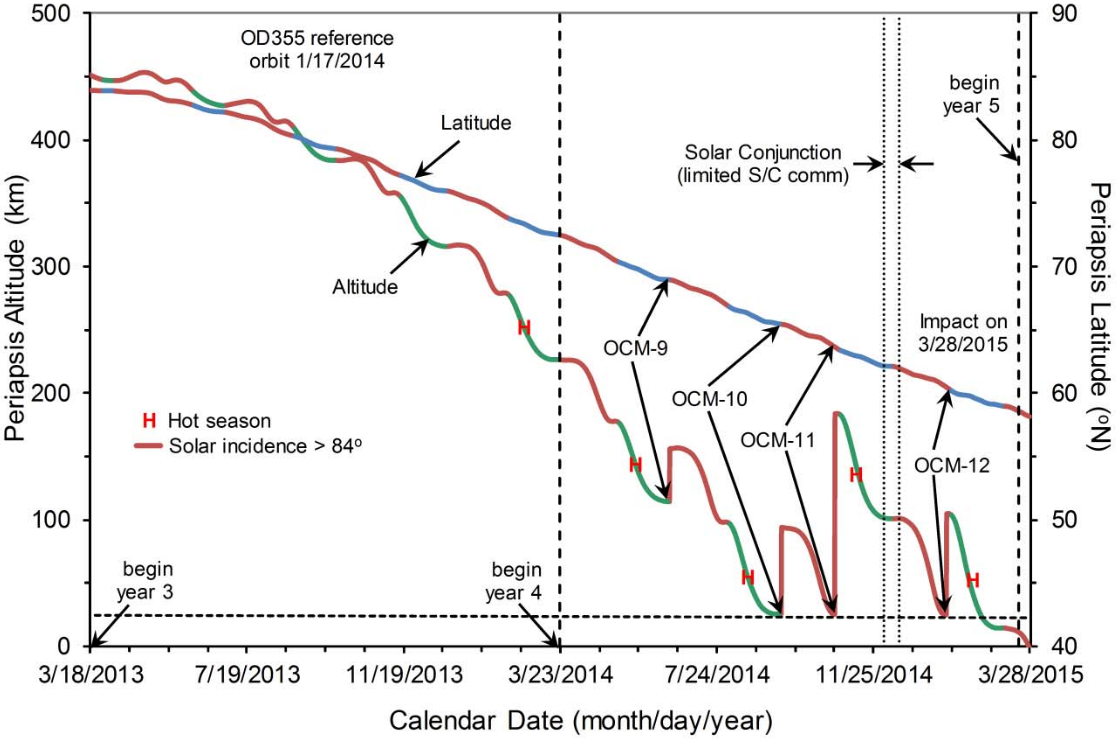


Figure 3. Evolution of the latitude and altitude of periapsis during XM2

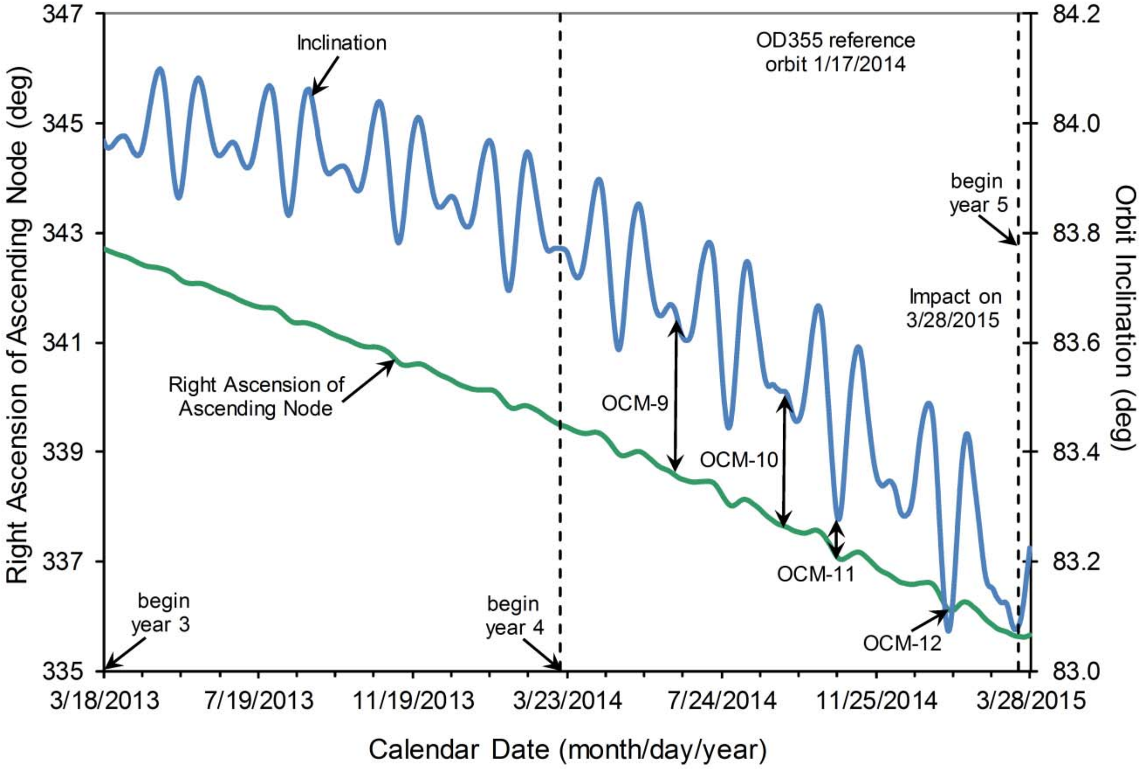


Figure 4. Examples of orbit-plane rotation during XM2

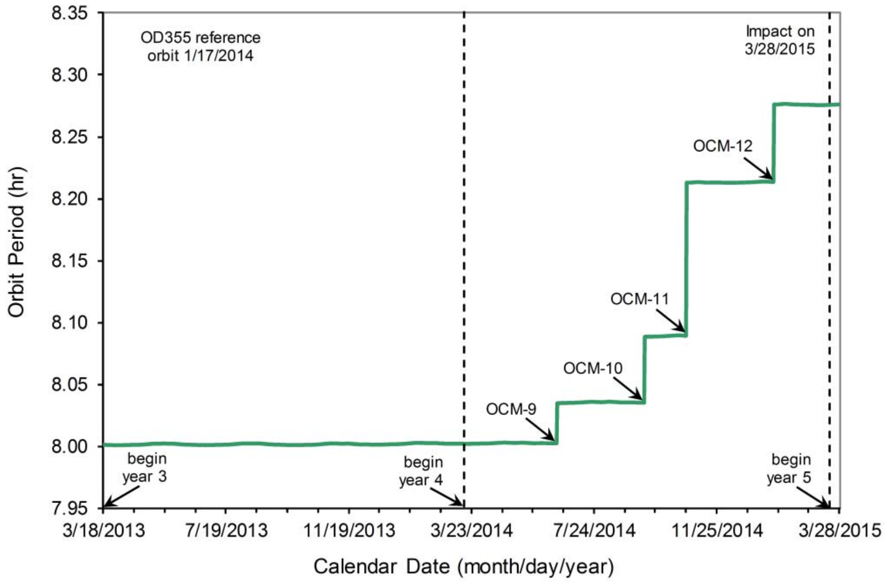


Figure 5. Spacecraft orbit period during XM2

Figures 6 and 7 contain Earth occultation and solar eclipse durations, respectively, as well as the locations of OCMs relative to these events. As seen in Figure 6, only OCM-12 will occur during an Earth occultation season. However, all four OCMs will be performed at apoapsis – at least 2.5 hours from the nearest Earth occultation. Figure 7 shows that no XM2 OCM will occur during an eclipse season; although, OCMs 11 and 12 will occur shortly after the end of an eclipse season. There are also two lunar occultations that will occur during XM2. The first will occur when the Moon passes between MESSENGER and the Deep Space Network (DSN) tracking station near Madrid, Spain on 26 June 2014 at about 11:23:53 UTC at the spacecraft and lasts for 5,078 s. The second lunar occultation will last only 3,784 s and will occur with the DSN station at Canberra, Australia on 22 October 2014 at about 20:04:04 UTC at the spacecraft. Scheduled DSN coverage will avoid using the affected DSN antenna facilities during these lunar occultations. During XM2, the high Mercury true anomaly (high-MTA) eclipse seasons are defined as periods of eclipses occurring when Mercury's heliocentric orbit true anomaly is greater than 180° and the spacecraft orbit's lowest altitude equator crossing is on the night side of Mercury. In contrast, the low Mercury true anomaly (low-MTA) eclipse seasons are defined as periods of eclipses occurring when Mercury's heliocentric orbit true anomaly is less than 180° and the spacecraft orbit's lowest altitude equator crossing is on the Sun-facing side of Mercury. The difference in lowest-altitude equator crossing location between high-MTA and low-MTA seasons causes high-MTA seasons to have shorter since the portion of the orbit in eclipse is closer to periapsis than during low-MTA eclipse seasons, thereby yielding a higher Mercury-relative velocity than for the low-MTA eclipses. About 12 days before the start of XM2, the orbit's line of apsides rotated over the pole (see Figure 8) as the sub-spacecraft periapsis latitude reached its northernmost point. After this orbit "rollover" event, the lowest altitude equator crossing occurs at the orbit's ascending node throughout XM2. As the line of apsides continues rotating southward, the difference in eclipse durations between the low- and high-MTA seasons will increase. The resulting southward periapsis progression and trend of declining periapsis altitude requires careful planning of strict spacecraft and instrument operational procedures to prevent overheating and loss of functionality.

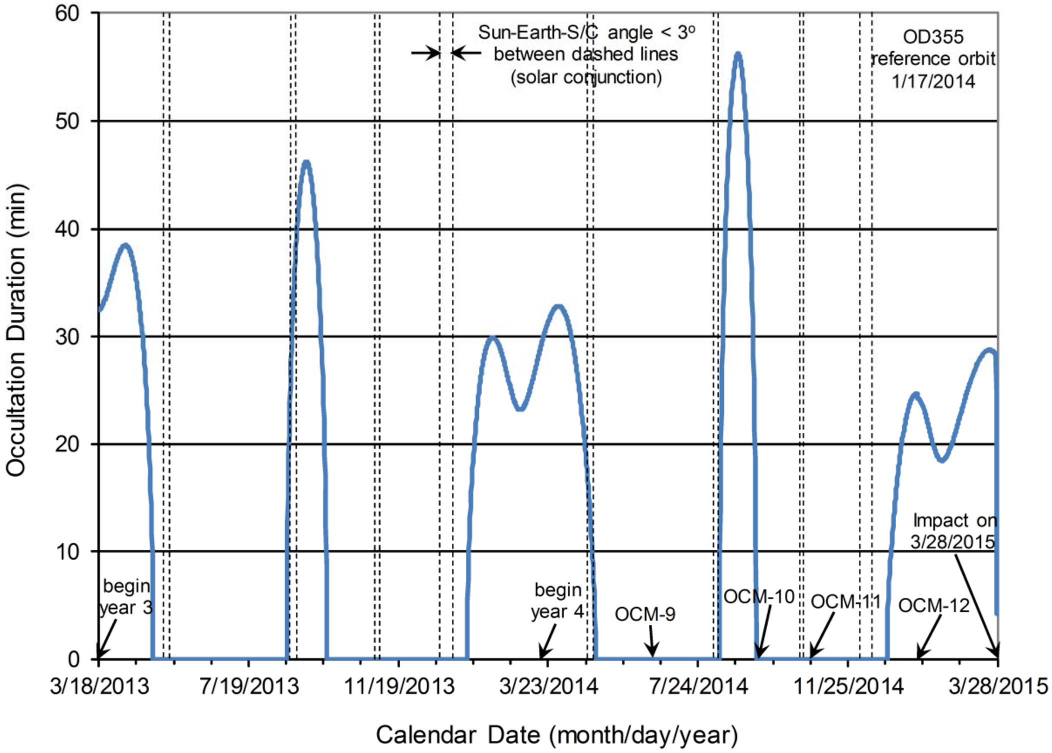


Figure 6. Earth occultations and solar conjunctions during XM2

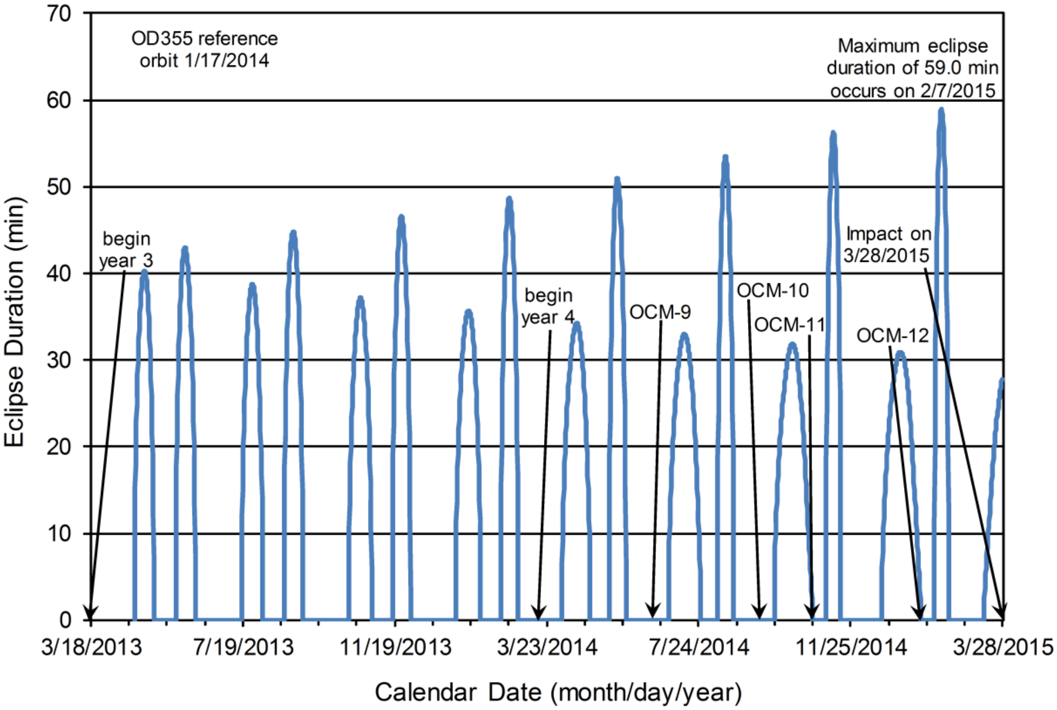


Figure 7. Solar eclipses during XM2

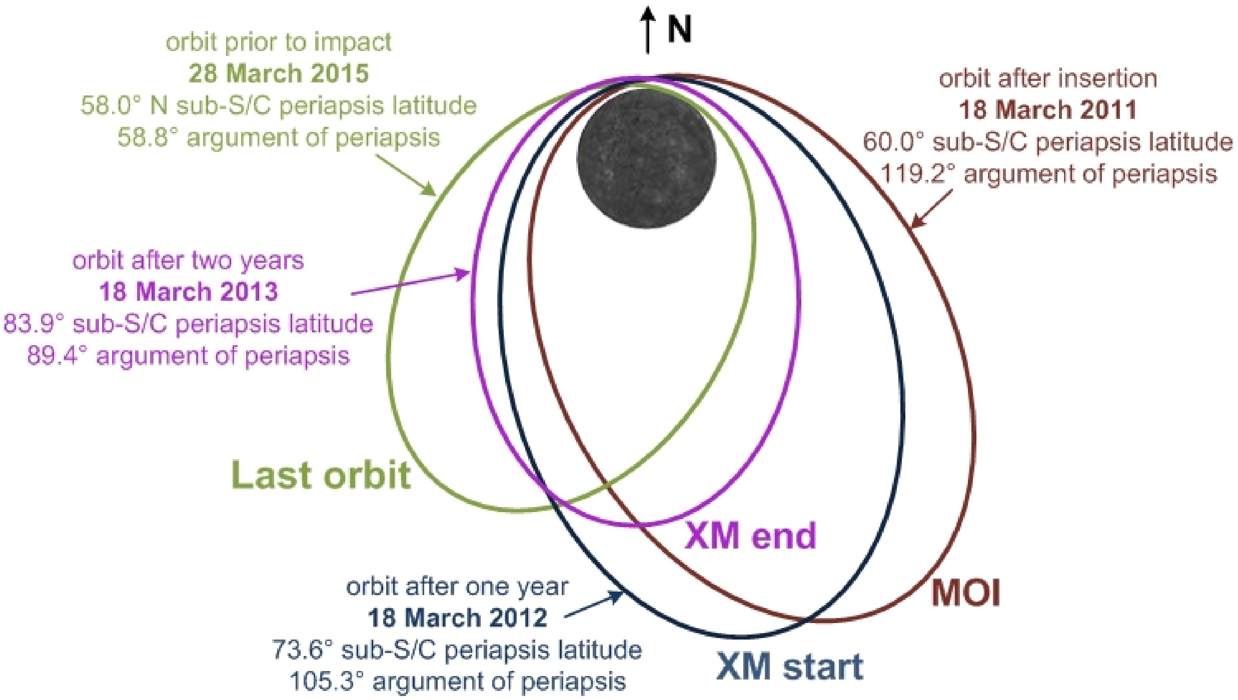


Figure 8. Rotation of line of apsides from orbit insertion through impact

4. Comet Observations

A most unusual convergence of events in November of 2013 gave MESSENGER scientists the opportunity to observe short-period comet 2P/Encke and hyperbolic orbit comet 2012 S1 (ISON) [7]. Mission planners and scientists discovered that the two comets would be closest to the MESSENGER spacecraft in orbit around Mercury on 18 and 19 November 2013, respectively. The closest approach by Encke of 0.0249 AU, which is only 9.7 times the average Earth-Moon distance, occurred a few days before Encke's orbit perihelion, and less than 1.5 days before the 0.2420 AU closest approach by ISON. Figure 9 depicts the cometary orbits and marks the comet positions at the time of Encke-MESSENGER closest approach. Note that the Figure 9 depiction of comet ISON's post-perihelion orbit illustrates where the comet would have gone had it remained intact after its perihelion at a solar distance of 0.0125 AU on 28 November 2013. Figure 10 offers a high-level planning guide for Encke observations within about 12 days of MESSENGER-Encke closest approach. Careful planning culminated in observations of both comets over a period from 26 October to 4 December 2013, with 711 Mercury Dual Imaging System (MDIS) images of ISON (280) and Encke (431) acquired, along with data from MESSENGER's Mercury Atmospheric and Surface Composition Spectrometer (MASCS) and X-Ray Spectrometer (XRS).

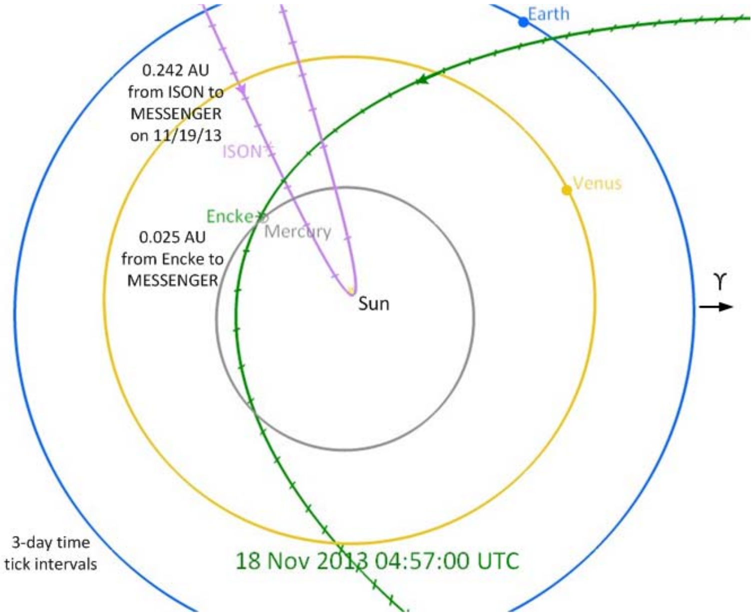


Figure 9. North-ecliptic-pole view of the orbits of comets observed by MESSENGER

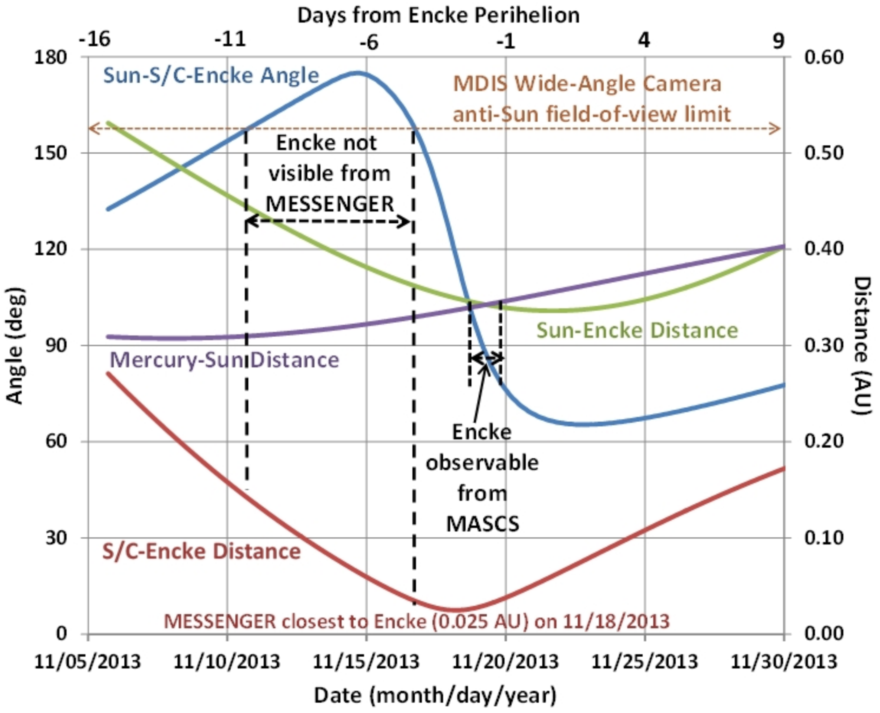


Figure 10. Macro-level planning of comet Encke observability by MESSENGER

5. Maneuver Design and Implementation

During the later part of XM2, the combined periapsis-raising effect of OCMs 9–12 will delay Mercury surface impact from August 2014 until March 2015, as well as enable a low-periapsis-altitude campaign resulting in approximately 190 days of spacecraft operation while in an orbit with periapsis altitude at or below 100 km. OCMs 9-11 each impart a ΔV in the spacecraft velocity direction at apoapsis in order to raise periapsis such that the minimum altitude, during a period when periapsis altitude will experience little variation over several orbits just before the next OCM, will be only 25 km above the surface. Moreover, OCM-12 will also impart a ΔV in the spacecraft velocity direction at apoapsis in order to raise periapsis such that the minimum altitude during an extended period when periapsis altitude has little variation over several orbits will be 15 km above the terrain a few weeks prior to Mercury impact. The mission design team identifies terrain-based altitudes for OCM targeting and impact time calculation by applying a digital elevation model for Mercury's northern hemisphere provided by the MESSENGER Mercury Laser Altimeter (MLA) team. Figure 11 depicts the difference between the altitude above terrain and the altitude above a 2440-km-radius sphere around the time of the OCM-10 target periapsis. As seen in the figure, the altitude above the terrain varies both above and below the altitude above the reference sphere. Furthermore, the minimum altitude above the terrain will occur 25.9 s prior to the orbit's periapsis. Figure 12 illustrates the location of OCM-11, the largest of the four planned OCMs, and subsequent changes in the spacecraft orbit. Each OCM will occur when the spacecraft orbit's line of nodes is nearly perpendicular to the spacecraft-Sun direction, allowing sunshade orientation constraints to be met. The timing, duration, and purpose of each of the four maneuvers are summarized in Table 1. Each OCM design is updated every six weeks as part of a trajectory optimization update process with the delivery of new maneuver times and accompanying spacecraft ephemeris to the SciBox software team.

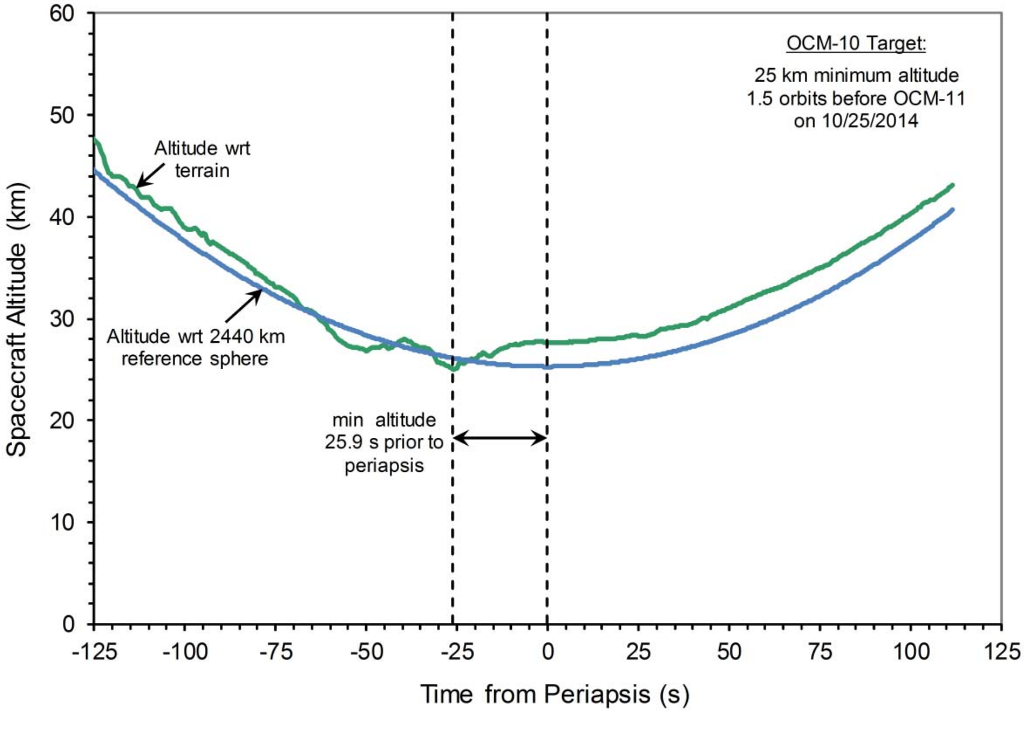


Figure 11. Comparison of altitude with respect to Mercury topography and that with respect to the reference sphere around the time of the OCM-10 target periapsis

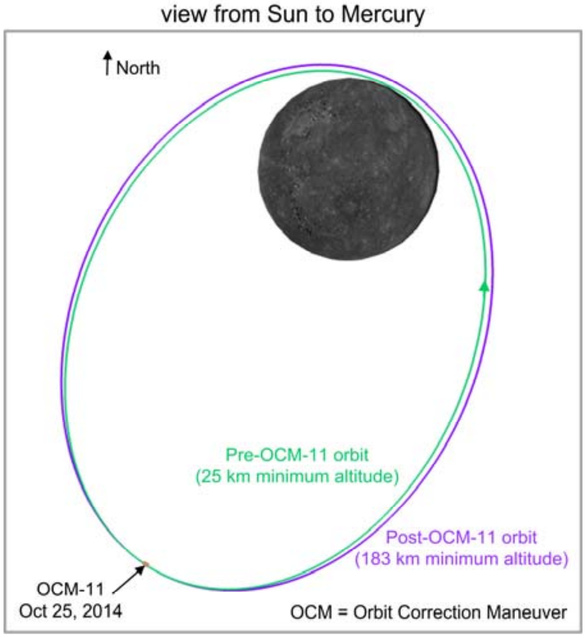


Figure 12. OCM-11 raises spacecraft periapsis altitude

Table 1. Mercury Orbit-Phase XM2 Maneuver Summary

Maneuver and Purpose	Orbit Correction Segment	Calendar Date (day month year)	Start UTC (hh:mm:ss)	Sun-S/C-ΔV (deg)	Duration (s)	ΔV (m/s)
OCM-9 raises periapsis such that periapsis altitude reaches a minimum of 25 km prior to OCM-10	A/B settle – aux tank	17 Jun 2014	14:54:00	95.60	60.0	0.438
	2C main – aux tank	17 Jun 2014	14:55:00	----	51.0	4.307
	A/B trim – aux tank	17 Jun 2014	14:55:51	----	56.8	0.349
	Post-OCM-9 usable fuel mass = 9.954 kg					**OCM-9 total ΔV = 5.094 m/s**
OCM-10 raises periapsis such that periapsis altitude reaches a minimum of 25 km prior to OCM-11	A/B settle – aux tank	13 Sep 2014	16:15:00	96.99	60.0	0.355
	2C main – aux tank	13 Sep 2014	16:16:00	-----	36.0	2.580
	4C main – main tank	13 Sep 2014	16:16:36	-----	15.0	2.869
	4C main – aux tank	13 Sep 2014	16:16:51	-----	15.9	2.663
	Post-OCM-10 usable fuel mass = 7.622 kg					**OCM-10 total ΔV = 8.467 m/s**
OCM-11 raises periapsis such that periapsis altitude reaches a minimum of 25 km prior to OCM-12	4C main – aux tank	25 Oct 2014	19:23:00	87.13	150.2	19.270
	Post-OCM-11 usable fuel mass = 3.073 kg					**OCM-11 total ΔV = 19.270 m/s**
OCM-12 raises periapsis such that periapsis altitude reaches a local minimum of 15 km during final near-constant periapsis region	4C main – aux tank	21 Jan 2015	18:11:00	85.97	98.7	9.744
	Post-OCM-12 usable fuel mass = 0.718 kg					**OCM-12 total ΔV = 9.744 m/s**

Note: aux = auxiliary, S/C = spacecraft

Although OCM-9 will be performed using only the auxiliary fuel tank, defined procedures must be followed to prevent usable fuel from migrating and becoming trapped above the main fuel tank baffles where it would be unusable [8]. The propellant management procedures for OCM-9 include using a fuel-settle segment with four 4.4-N A/B thrusters, a main segment with two (of four onboard) 22-N C thrusters, and a trim segment that uses the four A/B thrusters. (MESSENGER's thruster system has been described elsewhere [9].) This maneuver, designed to raise the periapsis altitude such that the spacecraft altitude reaches a minimum of 25 km above Mercury's terrain about 1.5 orbits prior to OCM-10 on 13 September 2014, will be performed on 17 June 2014 at the orbit's apoapsis.

The purpose of OCM-10, raising the periapsis altitude such that the spacecraft altitude reaches a minimum of 25 km above Mercury's terrain about 1.5 orbits prior to OCM-11 on 25 October 2014, will be achieved by executing the maneuver at apoapsis. OCM-10 is also designed to consume nearly all remaining usable fuel contained in main fuel tank 2, the only fuel tank with accessible hydrazine remaining. This strategy requires a four-segment design that includes a four-A/B-thruster fuel settle and a two-C-thruster fuel settle, both using fuel from the auxiliary tank. The settle segments are followed by a main segment with all four C thrusters firing and with fuel coming from main fuel tank 2. A conservative estimate of usable fuel in main fuel tank 2 will be consumed after 15 s. Then, a main segment using all four C thrusters drawing fuel from the auxiliary fuel tank will be performed to complete the maneuver. If the estimates of usable propellant are incorrect and the accessible propellant in fuel tank 2 is insufficient to support the full 15 s of four-C-thruster firing, the autonomy system will close fuel tank 2 and allow the maneuver to complete using propellant supplied from the auxiliary tank.

OCM-11 will be performed at apoapsis and, once again, will raise the periapsis altitude such that the altitude reaches a minimum of 25 km above Mercury's terrain about 1.5 orbits prior to OCM-12 on 21 January 2015. With no need to continue conserving usable fuel in the main fuel tanks, OCM-11 will not require any settling or trim maneuvers. The maneuver will be performed using a single four-C-thruster segment that draws fuel from the auxiliary tank.

The purpose of OCM-12 is to raise the periapsis altitude such that the altitude reaches a local minimum of 15 km above Mercury's terrain during the final period when periapsis altitude is nearly constant over several orbits prior to the spacecraft's impact with Mercury. This state is accomplished by performing OCM-12 at apoapsis and using a single four-C-thruster segment drawing from the auxiliary tank. After OCM-12 is completed, there will be 0.718 kg of usable fuel remaining in the auxiliary tank, leaving ample margin for remaining commanded momentum dumps.

All four maneuvers (OCMs 9–12) need to impart a ΔV in the spacecraft velocity direction while at apoapsis in order to accomplish the periapsis altitude raises. However, none of these maneuvers is long enough for meaningful fuel savings to justify use of a complex "turn while burning" approach that keeps the thrust direction close to 0° from the Mercury-relative velocity direction. Therefore, each maneuver will maintain an inertially fixed thrust direction within a tight control dead band for the entire maneuver. For each OCM, the instantaneous velocity direction will be converted to an equivalent fixed-thrust-direction spacecraft orientation for the entire maneuver by using an average of the instantaneous directions for each thrust segment weighted by the ΔV applied during the segment.

During all deterministic maneuvers, the spacecraft sunshade offers ample protection from direct sunlight illumination of any vulnerable spacecraft component. The condition for this protection is a Sun-spacecraft-ΔV angle between 78.0º and 102.0º. The operational term Sun keep-in (SKI) rule applies to the restricted range for Sun elevation angle from -12º to 12º. For OCMs 9–12, the Sun elevation angle is the Sun-spacecraft-ΔV angle - 90°. The largest Sun elevation angle is 7° (see Table 1), which occurs during OCM-10.

With three of four XM2 OCMs to be performed while periapsis altitudes are near 25 km, a postponed OCM or significant under burn could lead to Mercury impact before the next maneuver opportunity that meets all constraints at least six weeks later. The first level of contingency will require little planning since a one-day-delayed implementation of the same OCM (change in periapsis altitude is nearly zero within three 8-h orbits) would meet the OCM objective if the nominal OCM imparted zero ΔV. The second level of contingency readiness would be planning the maximum-duration delay (up to a 10 day delay) that completes the full objective of the missed or anomalous OCM with an out-of-orbit-plane single-component OCM while consuming less than 20% of available propellant margin. A third level of contingency for longer delays until safe spacecraft operation is certified would be completing just enough of the periapsis raise with an out-of-orbit-plane single-component OCM to establish 15–20 km altitude about six weeks after the problematic OCM, a time sufficient to ensure compliance with Sun-spacecraft-ΔV angle limits. Then, a newly scheduled single-component OCM could impart the remainder of the desired periapsis altitude change to target the 25 km or 15 km altitude near periapsis. For OCM-9 or OCM-10 contingencies, additional fuel consumption from main fuel tank 2 may be pursued, as unusable propellant estimates for this tank have been shown to be conservative.

6. Low-Periapsis-Altitude Campaign

The combined periapsis-raising effect of OCMs 9–12 will delay Mercury surface impact by about seven months, and the timing of the OCMs provides for several periods during which orbits have low periapsis altitudes. Thruster firings that adjust spacecraft angular momentum (CMDs) and occur every one to two weeks will perturb the trajectory by, at most, a few mm/s of unintentional ΔV per occurrence. This low-periapsis-altitude campaign, during the last eight months of the mission, will provide approximately 200 orbits with periapsis altitudes at or below 30 km. Figure 13 provides the number of orbits in each time period when periapsis altitude is nearly constant over several orbits. These numbers are determined by first calculating the change in periapsis altitude between each orbit. An orbit is then counted as being within the region of minimal periapsis altitude change when the periapsis altitude changes $\leq |0.1|$ km/orbit. There are a total of 35 orbits in the three 25-km-periapsis-altitude regions (regions 3, 5, and 7 in Figure 13), and 46 orbits in the 15-km-periapsis-altitude region (region 9 in Figure 13). Real-time communication with Earth-based tracking stations during these intervals with minimally varying low-altitude orbits will help further refine Mercury's gravity field.

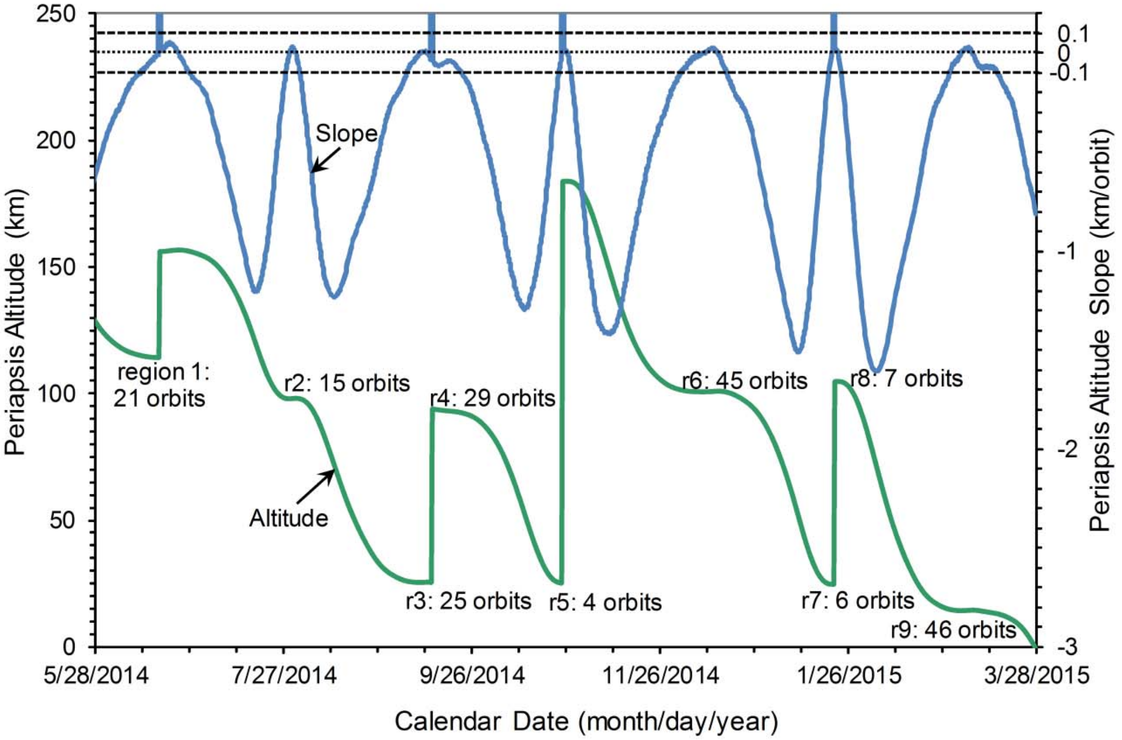
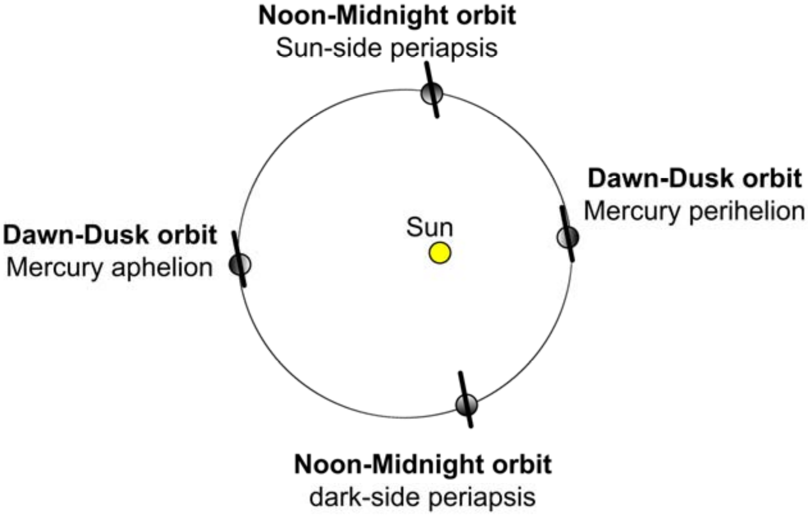


Figure 13. Number of orbits in each region where periapsis altitude changes ≤ |0.1| km/orbit during the last 10 months of XM2

Knowing the timing of certain Sun-relative orbit orientations is important for planning scientific observations of Mercury and minimizing orbit prediction uncertainty. The dawn-dusk orbit configuration (see Figure 14) occurs when the spacecraft crosses Mercury's equatorial plane at the day/night terminator. This orientation occurs shortly before Mercury reaches either perihelion or aphelion. Another Sun-relative orientation is the noon-midnight orbit configuration, which 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 Sun-side periapsis, also called "hot pole," and the dark-side periapsis. During "hot pole" orbits, solar radiation reflected off of Mercury's surface increases the environmental thermal input onto the spacecraft's anti-Sun surfaces while the spacecraft is at low altitudes, thus elevating spacecraft operating temperatures. During XM2 the "hot pole" configuration occurs when Mercury is near a true anomaly of 90˚ relative to the Sun as seen at the top of Figure 14.

Several factors, including spacecraft heating and Mercury surface lighting, were carefully considered when designing the low-periapsis-altitude campaign. Marked on Figure 3 are "hot seasons," periods containing "hot pole" orbits. Although periods of low-altitude operation during a hot season increase spacecraft temperature near to allowable limits, Mercury surface visibility was also considered. The surface below the spacecraft is too dark to be visible at periapsis when the solar incidence angle at periapsis is greater than 84°. Although the surface may not be visible during the lowest altitude of the orbit (i.e., periapsis) at such times, the surface is visible from higher altitudes when the spacecraft is in other portions of the orbit. As seen in Figure 3, periods of surface visibility at periapsis occur around a hot season. In the current trajectory design, the first time at or near 25-km periapsis altitude and the only time at or near 15-km periapsis altitude will occur soon after a hot season containing periapsis altitudes near 50 km. The second and third times at or near 25-km periapsis altitude, in contrast, will not occur shortly after a hot season.



Type of Orbit	Calendar Date (month/day/year)
Dusk-Dawn, Mercury aphelion	04/03/2013, 06/30/2013, 09/26/2013, 12/23/2013, 03/20/2014, 06/16/2014, 09/11/2014, 12/08/2014, 03/06/2015
Noon-Midnight, dark-side periapsis	04/30/2013, 07/27/2013, 10/23/2013, 01/19/2014, 04/17/2014, 07/13/2014, 10/09/2014, 01/05/2015
Dusk-Dawn, Mercury perihelion	05/16/2013, 08/12/2013, 11/08/2013, 02/04/2014, 05/03/2014, 07/29/2014, 10/25/2014, 01/21/2015
Noon-Midnight, Sun-side periapsis	06/02/2013, 08/29/2013, 11/25/2013, 02/20/2014, 05/19/2014, 08/15/2014, 11/11/2014, 02/06/2015

Figure 14. Sun-relative orbit orientations during XM2 – "hot pole" orbits occur near Mercury true anomaly 90°

7. Impact with Mercury

Trajectory perturbations, in combination with planned OCMs and CMDs, cause changes in the spacecraft's orbit, including variations in periapsis altitude that lead to Mercury impact on or about 28 March 2015. Estimated orbit parameters from the final orbit of XM2 include an 83.2° orbit inclination, -1.5-km periapsis altitude (referenced to a 2440-km planetary radius), 335.7° right ascension of ascending node, and 58.1° N sub-spacecraft periapsis latitude. Propagation of the post-OCM-12 spacecraft state leads to impact with Mercury's surface on 28 March 2015, 10:45:50 UTC, near 55.9° N latitude and 55.8° E longitude. Mercury gravity model or terrain model updates, changes in planned spacecraft attitude, orbit changes from CMDs, or modifications of any future OCMs will introduce additional variation in this predicted date and location of Mercury surface impact. Although the impact of the spacecraft onto the surface of Mercury in late March 2015 will not be visible from Earth as depicted in Figures 15 and 16, impact should occur before communications are disrupted by a solar conjunction in early April 2015. As seen in Figure 17, impact will occur when Earth is 1.316 AU from Mercury.

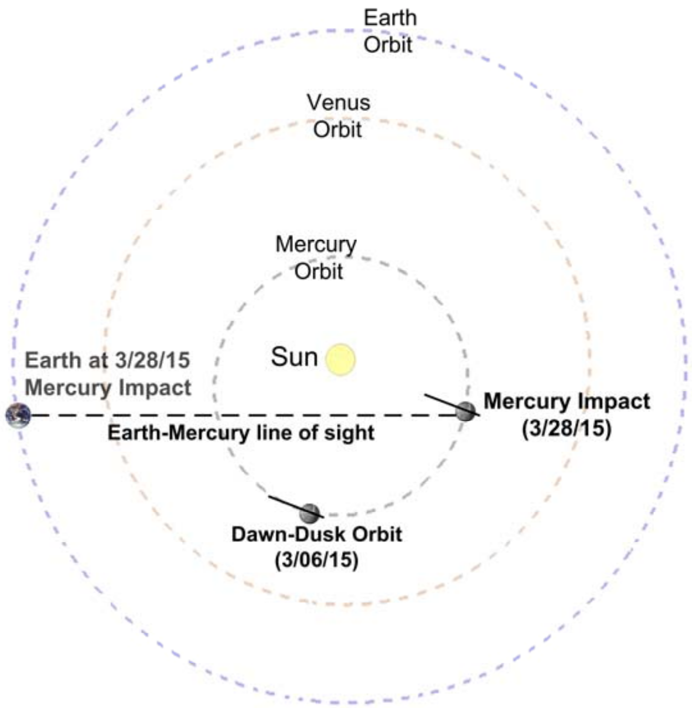


Figure 15. Heliocentric view of Mercury and Earth at the time of MESSENGER's impact onto the surface

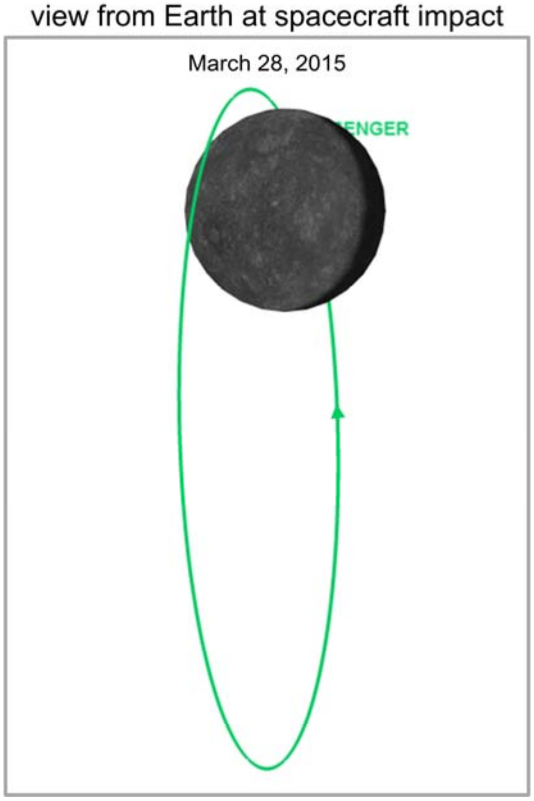


Figure 16. View of Mercury from Earth at the time of MESSENGER's impact onto the surface

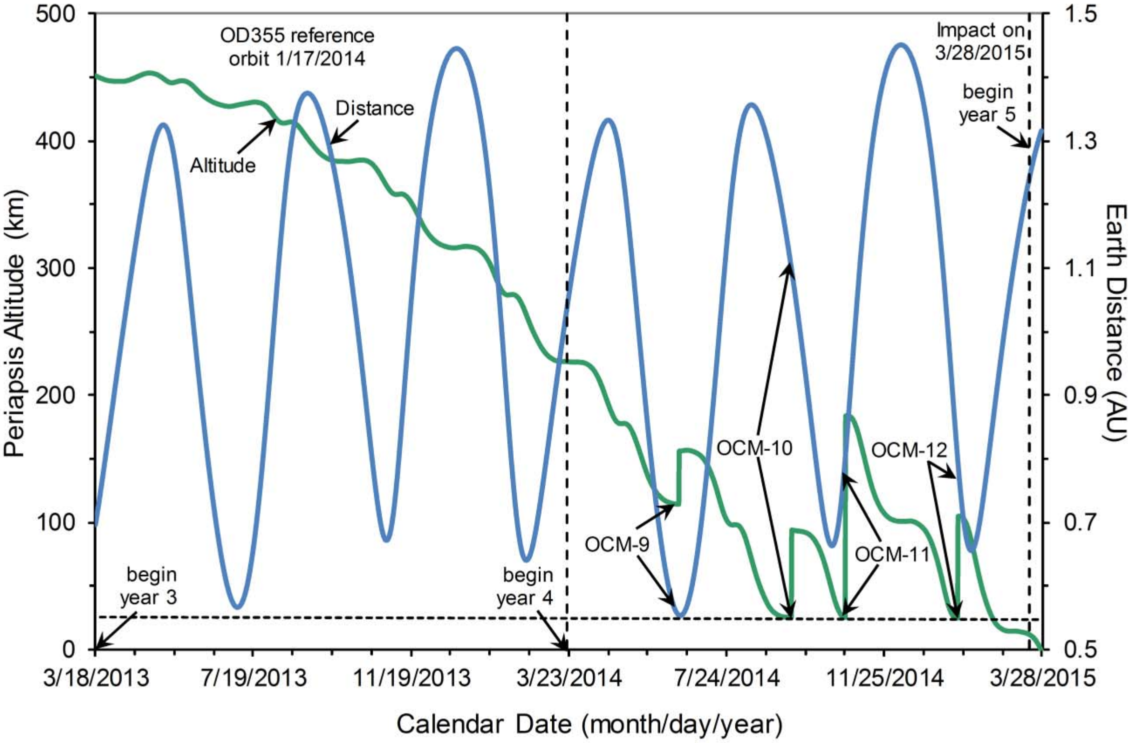


Figure 17. Periapsis altitude and Earth distance during XM2

8. Summary

MESSENGER's second and final extended mission began on 18 March 2013 and will continue until the spacecraft impacts Mercury on or about 28 March 2015. The first 15 months of XM2 are spent in the current 8-h orbit as perturbations dominated by solar gravity, decrease the orbit's periapsis altitude by more than 335 km. During this time of a near-constant orbit period, MESSENGER also acquired and returned images of two nearby comets, Encke and ISON, in November 2013. Between mid-June 2014 and the end of the mission, four orbit correction maneuvers (OCMs 9–12) will enable a planned low-periapsis-altitude campaign. The target of each of the first three OCMs is a 25-km minimum altitude when periapsis altitude has minimal variation just prior to the next OCM. The target of the final OCM is a 15-km minimum altitude during the last period prior to impact when periapsis altitude has little variation. Furthermore, the combined effect of all four upcoming OCMs will delay the spacecraft's impact with Mercury from late August 2014 until late March 2015. During the last eight months of the mission, the low-periapsis-altitude campaign will result in approximately 190 days of spacecraft operation while in an orbit with periapsis altitude at or below 100 km and about 200 orbits with periapsis altitudes at or below 30 km, thus providing unprecedented observational opportunities and helping to further refine Mercury's gravity field.

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