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ORBIT DESIGN AND NAVIGATION THROUGH THE END OF MESSENGER'S EXTENDED MISSION AT MERCURY

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MESSENGER became the first orbiter of Mercury on 18 March 2011 and spent one year in a near-polar, 12-h orbit with six orbit-correction maneuvers (OCMs) to keep periapsis altitude between 200 and 500 km and maintain orbit period. MESSENGER's first extended mission, which included two mid-April 2012 OCMs that lowered the orbit period to 8 h, lasted until 17 March 2013. MESSENGER's second extended mission began on 18 March 2013, included observations of comets Encke and ISON during the fall of 2013, and will include four OCMs to target periods with little variation from 25-km and 15-km periapsis altitude until Mercury impact in March 2015.

INTRODUCTION

Designed and operated by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in Laurel, Maryland, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft became the first orbiter of the planet Mercury in mid-March of 2011. Supported by NASA's Discovery Program, the spacecraft successfully completed its 7.6-year primary mission on 18 March 2012. Working with the mission design team at JHU/APL and the navigation team at KinetX Aerospace, the MESSENGER flight operations team is preparing to conduct a series of mission-extending, periapsis-raising maneuvers during the mission's second and final extended mission phase. The primary mission phases for MESSENGER have included: (1) a 6.6-year interplanetary cruise from a 3 August 2004 launch to one Earth flyby, two Venus flybys, and three Mercury flybys, culminating in Mercury orbit insertion on 18 March 2011, and (2) one year in a near-polar, high-eccentricity orbit with 200–500-km periapsis altitude, 12-h orbit period, and six orbit-correction maneuvers (OCMs) [1],[2]. Flight operations for the extended mission phases included: (1) a first extended mission (XM1) from 18 March 2012 through 17 March 2013, with two OCMs that together lowered the orbit period to 8 h for the final 11 months of XM1, and (2) a second extended mission (XM2) from 18 March 2013 through four OCMs until impact onto Mercury's surface on 28 March 2015.

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During the primary mission's Mercury orbital phase, engineering feasibility, operational safety, and scientific assessment of XM1 design options resulted in a maneuver sequence that maximized propulsion system performance while lowering the spacecraft orbit period to 8 hours[3]. Two OCMs four days apart in mid-April 2012 were designed to maximize utilization of onboard velocity change (ΔV) capability by expending all the usable oxidizer and safely utilizing all accessible fuel from one of the two main fuel tanks[4]. During XM1, solar gravity dominated orbit perturbations by more than doubling orbit periapsis altitude to about 450 km and shifting the sub-spacecraft Mercury latitude to its northernmost point (84.1°N). Throughout XM1, improvements to estimates of Mercury's gravity field and fine-tuning of solar and planetary radiation pressure helped to improve the precision of orbit determination and prediction for both the mission design and navigation teams.

Accurate trajectory estimation and prediction has enabled precise planning of science observations and accurate OCM design. These calculations depend on such factors as force modeling, observation modeling and weighting, relative location and velocity of objects in space and ground-based antennas, and parameter estimation strategy. One of the biggest challenges of trajectory estimation for a spacecraft in Mercury orbit involves modeling and estimating the radiation environment, including solar and planetary radiation pressure, particularly near periapsis. The MESSENGER navigation team has modeled and estimated these forces, determined modeling limitations, and continued to improve a priori force values and their uncertainties during XM2. The navigation team has also estimated and used operationally a spherical harmonic Mercury gravity field expanded to degree and order 20. As periapsis altitude decreases below 200 km during XM2, there may be an opportunity to fine-tune this gravity field and possibly to determine and implement higher-order terms than currently used. In support of XM2 planning, the results of four 6-to-12-week-long trajectory calculations, generated with navigation software and force models for each of four OCMs, are compared with similar independent trajectory determinations conducted with mission design software.

During XM1 the MESSENGER team evaluated the XM2 options that efficiently utilized remaining propellant to extend mission duration sufficiently to achieve all proposed scientific objectives. Propellant management, selection of intervals of nearly steady periapsis altitude, spacecraft thermal management, timing of communication-disrupting solar conjunctions, the extent of solar maximum, the visibility of Earth near periapsis, and surface lighting during lower altitudes and over selected regions were considered in selecting the XM2 trajectory. In November 2013, MESSENGER became the first spacecraft to observe short-period comet 2P/Encke near its perihelion from distances as close as 0.0249 AU. The MESSENGER spacecraft also observed hyperbolic-orbit comet C/2012 S1 (ISON) shortly before its 28 November perihelion from distances as close as 0.2420 AU. The timing of periapsis-raising OCMs 9 to 12 targets times before the next OCM when periapsis altitude settles with little variation over many orbits to altitudes of 25 km three times and 15 km once. The spacecraft orbit near periapsis will not be visible from Earth at the time of Mercury impact in March 2015.

FIRST EXTENDED MISSION – CLOSER TO MERCURY AT APOAPSIS

Options for the First Extended Mission

Multiple options for extending the mission one year beyond the yearlong orbital phase of the primary mission were designed, presented at a November 2011 MESSENGER science team meeting, and evaluated soon thereafter. These extended mission options, first summarized by Moessner[2], were variations of one of two low-periapsis-altitude science orbits, an 8-h orbit and a 12-h orbit. Each extended mission option included OCM-6, which lowered periapsis altitude in early March 2012, when the spacecraft maneuver attitude placed the spacecraft bus in the shadowed region behind the sunshade at <0.31 AU from the Sun. For the extended mission options with an 8-h orbit, either one or two OCMs at periapsis would reduce the orbit period to 8 h about one month after the end of the primary mission on 17 March 2012. Another variation of the 8-h orbit option planned two additional OCMs in October 2012 in order to reduce periapsis altitude by 50% and reset orbit period to 8 h for the remainder of the mission. The single-OCM option for lowering orbit period to 8 h was not selected in favor of a two-OCM plan that would use each OCM to deplete the remaining usable propellant from the oxidizer tank and one of the two main fuel tanks. Analyses by engineering and flight operations teams determined the safety and high likelihood of success for the data collection and data downlink strategies for the selected XM1 8-h orbit option. Thorough evaluation of spacecraft safety for the 8-h orbit options focused on enhancing software tools for spacecraft thermal management. The science benefit of being able to image Mercury's southern hemisphere from one-third closer than the primary mission's 12-h orbit had an associated challenge of having one-third less time for the spacecraft to dissipate heat absorbed into the battery and heat-sensitive instruments subject to low-altitude reflected solar radiation. Transition to an 8-h orbit provided new science potential not available with a continuation of an orbit with a period near 12 h, including the latest estimated date at which solar gravity perturbations would lead to Mercury impact in late August of 2014. Another extended mission option considered would have begun with a 200-km periapsis altitude by 12.2-h orbit period in early March 2012 followed by a periapsis-lowering OCM every 44–88 days for the next eight months. This maneuver plan would have kept the orbit period within 0.2 h of 12 h and would have left the spacecraft in an 11.8-h orbit two years after Mercury orbit insertion (MOI) [5]. At the end of the primary mission, one year after MOI, mission resources had not yet been allocated to study any plan to continue flight operations after XM1.

Tools and Resources for Orbit Design

Assumptions involving Mercury parameters, spacecraft physical characteristics, spacecraft attitude, solar radiation pressure (SRP), and engine performance provide the basis for designing the orbit-phase trajectory. The Mercury gravity models used by the mission design team for estimation of the reference spacecraft trajectory included 20 × 20 models developed by the MESSENGER navigation and science teams, and 50 × 50 models created by the science team. 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 according to the recommendation of the MESSENGER configuration control board to use the revised planetary constants kernel, pck00009_MSGR_v10.tpc.

The Mercury orbit-phase design relied on STK (Systems Tool Kit)/Astrogator software, with an orbit estimation procedure that accounted for SRP, general relativity, and the gravitational attraction of Mercury, all seven other planets, the Moon, Pluto, and the Sun (DE423 ephemerides). Small-force trajectory perturbations from planetary radiation pressure and thermal radiation are computed only by the navigation team[6]. The navigation team provides a short-term predicted ephemeris that extends about one month from the release date, 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 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[7], which defines spacecraft bus attitude and guidance and control, 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 at which the merge between short-term and long-term ephemerides occurs. Trajectory calculation accounts for frequent decrements of propellant mass at a rate of 8 g/week during XM1 and 6 g/week for XM2, as an accurate means of predicting spacecraft mass changes due to commanded momentum dump (CMD) propulsive events that keep spacecraft angular momentum well below limits designed to maintain spacecraft stability.

Operational Constraints for XM1 Maneuver Design

In addition to the operational constraints that were in place throughout much of the interplanetary cruise phase and the first year of Mercury orbital operations, low levels of remaining usable oxidizer and hydrazine fuel and the presence of baffles in both main fuel tanks made implementation of a revised propellant management strategy[4] essential during both mission extensions. Mission-long constraints include keeping maneuvers outside of solar conjunctions (i.e., the Sun-Earth-probe angle should exceed 3˚), ensuring real-time observability with Earth-based tracking antennas, avoiding communication obstruction by either Mercury or Earth's Moon, and maintaining the Sun-spacecraft-ΔV angle between 78° and 102° throughout each maneuver so that the sunshade can continue to shield the spacecraft bus from direct sunlight. The choice of primary thruster set, number of active primary thrusters, and the number and duration of propulsive maneuver segments were carefully chosen for each OCM to minimize risk while utilizing remaining usable propellant. The term "primary thruster" indicates the thrusters used to impart the maneuver's desired ΔV, in distinction from the attitude control thrusters that minimize pointing error. Implementation of the propellant management strategy for low tank-fill fractions resulted in mission-unique aspects for both OCMs during XM1.

Design and Implementation of XM1 Propulsive Maneuvers

The start of XM1, the least active mission phase in terms of spacecraft-directed orbit-correction maneuvers, marked a seminal point in the Mercury orbital phase. Two propulsive maneuvers four days apart, OCM-7 and OCM-8, completed the transition from an 11.6-h orbit to an 8.0-h orbit. The mission's final bipropellant maneuver, OCM-7, accounted for substantial uncertainty in the amount of usable oxidizer (thrust duration could vary from 3.0 to 6.6 minutes as noted in Table 1) and extracted close to the maximum amount of remaining usable oxidizer. Four days and four hours after OCM-7, OCM-8 completed with no change in initial thrust time and a 0.13% in target ΔV reduction compared with the pre-OCM-7 design of OCM-8. This 100-h separation between course-correction maneuvers represents the MESSENGER mission's minimum time between maneuvers for which the outcome of the first maneuver changed the final design of the second maneuver. As shown by McAdams et al.[3], the success of OCM-7 and OCM-8 is evident in the attainment of the $3^h\ 36^m$ orbit-period reduction within less than 2 s of offset. Table 1 lists timing, ΔV, and other details for both the final design and reconstruction of OCM-7 and OCM-8. Figure 1 shows the orbit locations and orbit period changes for OCM-7 and OCM-8.

Table 1. Final Design and Reconstructed Results for First Extended Mission Maneuvers.

Correction Maneuver, Date, and Objective		Start Time (UTC)	ΔV (m/s)	Pointing Error (°)	Duration (s)	Propellant Mass (kg)
OCM-7 on 16 Apr 2012; lower orbit period and deplete oxidizer tank	Final Design	19:13:06	53.260	Not applicable	179.00-378.10	10.797
	Reconstruction	19:13:07	53.257	0.076	187.76	11.153
OCM-8 on 20 Apr 2012; lower orbit period to 8 h and deplete fuel tank 1	Final Design	23:05:35	31.444	Not applicable	238.10	7.854
	Reconstruction	23:05:35	31.420	0.060	240.18	7.942

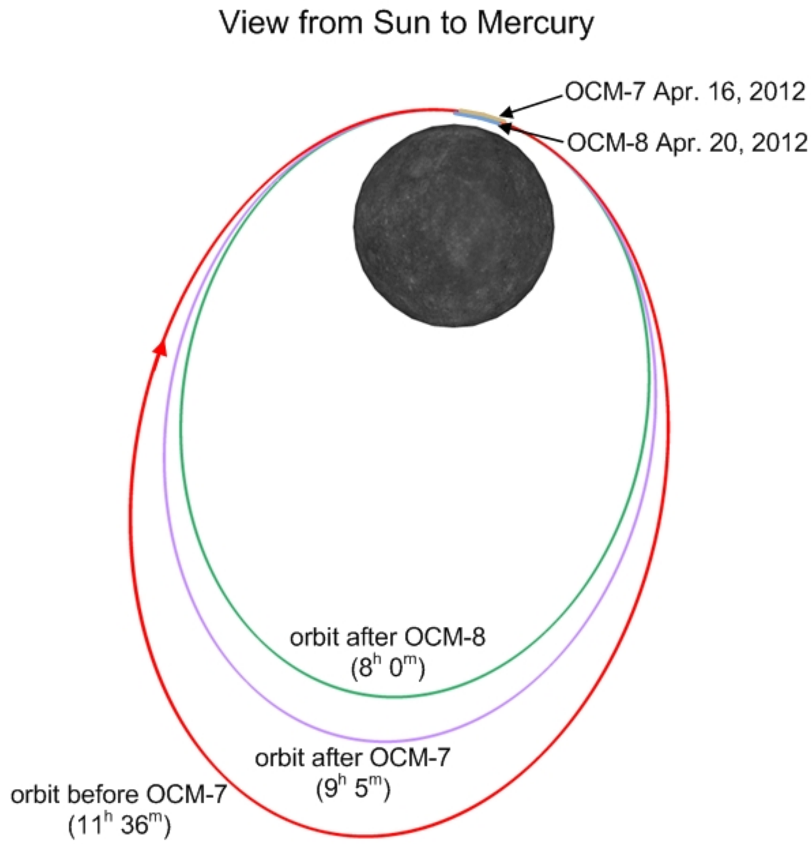

Figure 1. Orbits and OCMs for MESSENGER's Transition to an 8-h Orbit Period.

Orbit Progression During the Orbital Phase

To provide sufficient perspective on MESSENGER's extended-mission trajectory, it is instructive to summarize the changes in spacecraft trajectory through the full time in orbit. During the orbital phase of the primary mission, which ended one year after orbit insertion, six OCMs alternated between lowering periapsis altitude to 200 km and returning orbit period to 12 h. About one month into the yearlong XM1, OCMs 7 and 8 lowered the orbit period to 8 h. Less than two weeks before the end of XM1, the sub-spacecraft periapsis latitude reached its mission maximum value of 84.1° N, coincident with attainment of the maximum orbit inclination of 84.1° (up from the 82.5° inclination at MOI). This "orbit rollover" at the end of XM1 also coincided with a reversal in the sign of the change in periapsis altitude between successive orbits, leading to a progressive decrease in periapsis altitude until eventual Mercury surface impact. During the final year of the two-year-long XM2, four periapsis-altitude-raising OCMs are timed to enhance the achievement of science objectives and maximize propellant utilization to extend the mission. The progression of periapsis altitude, the relative location and effect of all 12 OCMs, and a representation of approximate sub-spacecraft Mercury latitude appears in Figure 2. Figure 2 also shows that periapsis altitude remained between 200 km and just over 500 km for more than three years after MOI, including a local maximum of just over 450 km at two years after MOI. The upward progression of the periapsis altitude was due primarily to solar gravity perturbations when the spacecraft orbit argument of periapsis was between 90˚ and 119˚. Conversely, the downward progression of periapsis altitude occurs when the argument of periapsis is < 90˚.

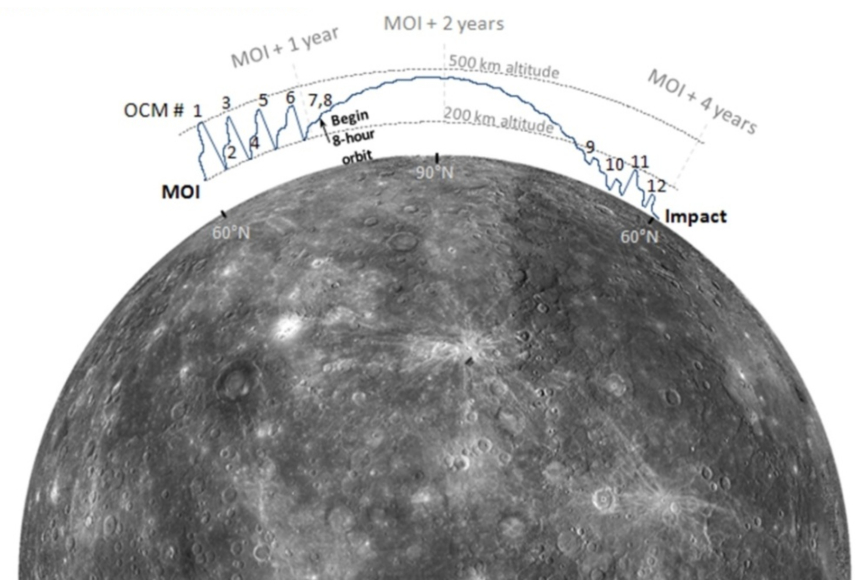

Figure 2. MESSENGER Periapsis Altitude during the Primary, XM1, and XM2 Orbital Phases. Periapsis Latitude Started at 60.0°N, Moved Northward to Peak at 84.1°N, and Then Moves Southward to 58.1°N at Mission End.

The end of XM1 in March 2013 marked changes in the spacecraft orbit that required adjustments to spacecraft pointing to ensure safe flight operations. From MOI to the March 2013 orbit orientation for which the line of apsides is closest to Mercury's rotation axis (see Figure 3),

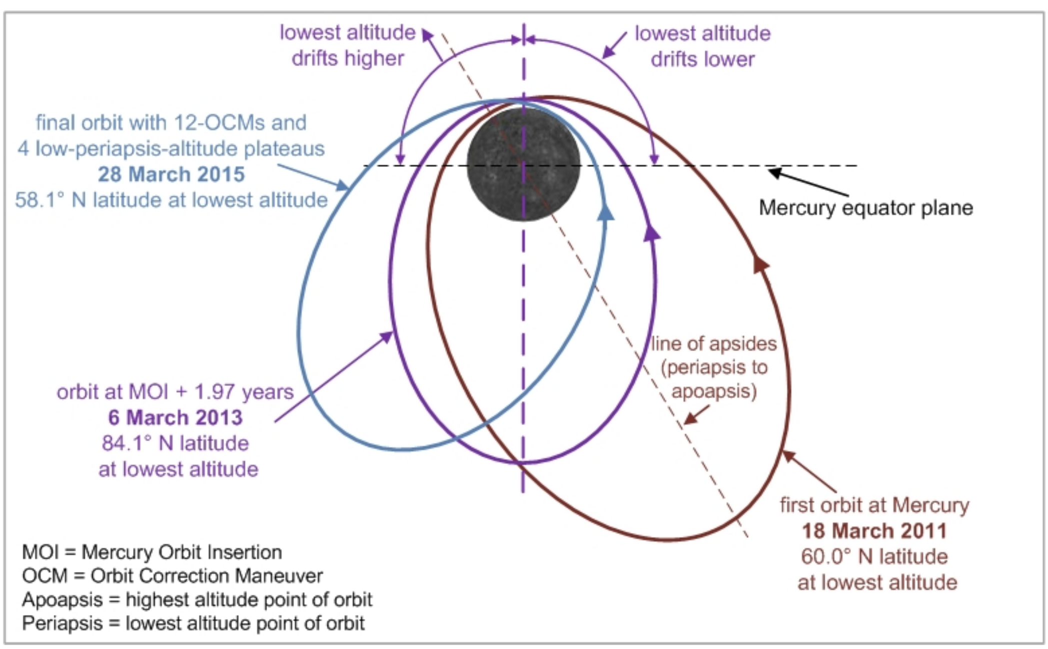

Figure 3. MESSENGER Orbit Orientation and Relative Dimensions during the Primary, XM1, and XM2 Orbital Phases.

the spacecraft experienced lower thermal gradients as the spacecraft descended from north to south in a noon-midnight orbit toward a low-altitude Sun-side periapsis, since higher thermal input onto the planet-facing spacecraft bus occurred after a lengthy solar eclipse (see left side of Figure 4). After March 2013, in contrast, the spacecraft experienced higher thermal gradients as the spacecraft ascended from south to north in a noon-midnight orbit toward a low-altitude Sun-side periapsis, since higher thermal input onto the planet-facing spacecraft bus occurred after a moderate altitude fly over of the southern hemisphere (see right side of Figure 4). The data points in Figure 4 each represent the longest solar eclipse duration, when Mercury obstructed either all or some sunlight from reaching the spacecraft.

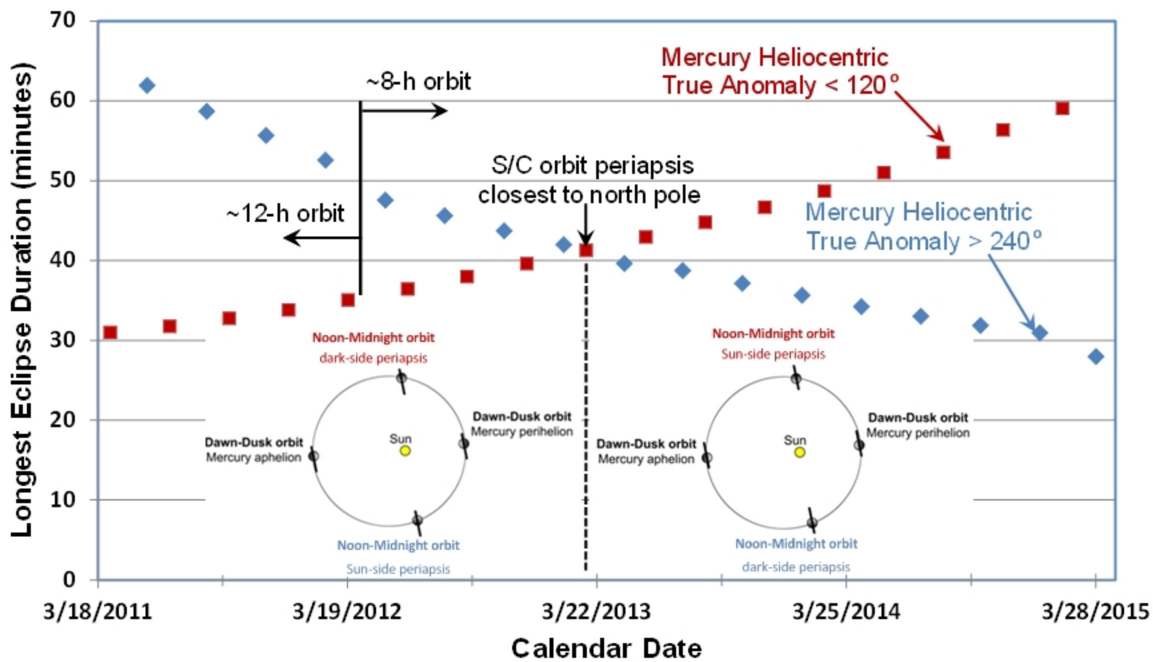

Figure 4. Longest Eclipse Duration of Each Eclipse Season. S/C Denotes Spacecraft.

SECOND EXTENDED MISSION – CLOSER TO MERCURY AT PERIAPSIS

Options for the Second Extended Mission

The MESSENGER team considered four options for extending the mission beyond XM1. The lowest-cost alternative used a mid-December 2013 OCM-9 to force Mercury impact to occur about 15 months before the latest possible impact and efficiently utilized OCMs while consuming all usable propellant. This "forced early-impact" option would have targeted a January 2014 impact after about five weeks of operations with periapsis altitude below 15 km. The next lowest-cost option would involve no OCMs, thereby allowing the spacecraft to coast until Mercury impact in late August of 2014. A "thermal-safe" option would have placed periapsis-altitude-raising OCMs near the spacecraft orbit's apoapsis in March, June, and September of 2014, followed by a late-October 2014 OCM that would lower orbit period to 8 h until Mercury impact in mid-March of 2015. This thermal-safe option would expend nearly all usable propellant to establish mid-November of 2014 as the latest date for periapsis altitude to remain above 200 km.

A fourth option coordinated the effective utilization of remaining propellant with spacecraft pointing strategies that balance new highs of spacecraft bus thermal input with unique opportunities for low-altitude and targeted science observations and improved resolution of higher-order Mercury gravity field terms. Figure 5, which depicts both periapsis altitude and sub-spacecraft Mercury latitude at periapsis, also shows when "hot seasons" (i.e., the noon-midnight Sun-side periapsis on the lower right of Figure 4) and a key superior solar conjunction occur. Four OCMs each increase periapsis altitude enough to target periapsis altitudes of 25 km (three times) or 15 km (once). Each OCM must occur when the spacecraft's sunshade will protect the spacecraft bus from direct sunlight, a condition that is met near the middle of periods when periapsis altitude changes little over many consecutive orbits. Communications disruption due to solar interference during the December 2014 solar conjunction, when the Sun-Earth-probe angle will be < 3°, led OCM-11 to be sufficiently large to target the next acceptable time for OCMs in late January of 2015. The significance of solar incidence angle being > 84° in Figure 5 is that periapsis is either near or over portions of Mercury's surface that are not illuminated by sunlight. Therefore, the red colored periapsis times in Figure 5 represent times where imaging is not planned at or near periapsis. Note also that image smear cannot be minimized to an acceptable level at altitudes below about 80 km, where image resolutions of non-contiguous surface regions can approach 2 m/pixel.

This fourth option was summarized and proposed to NASA in late February 2013.

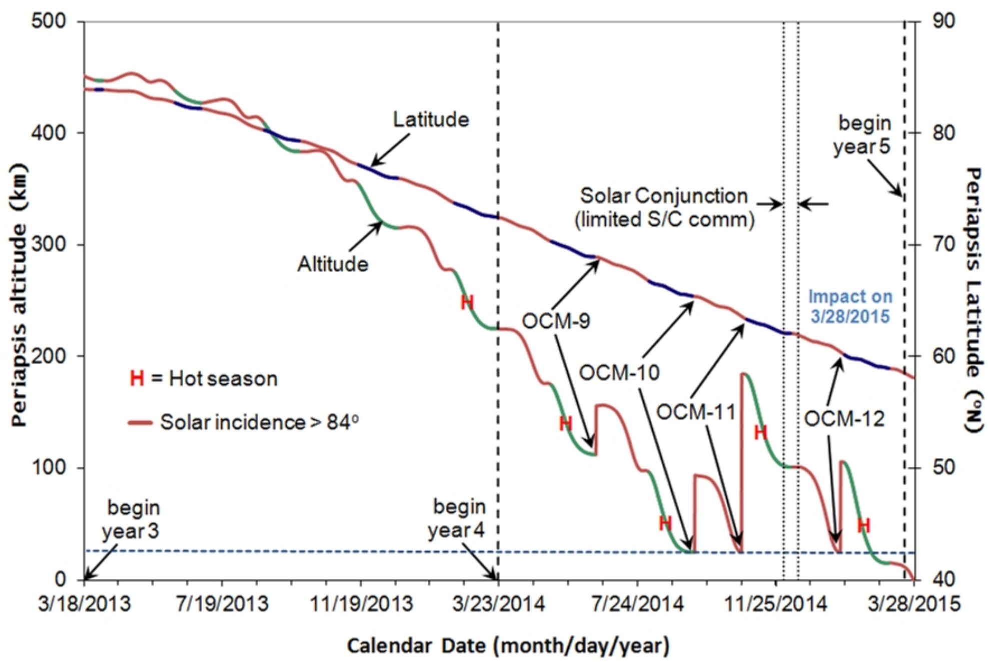

Figure 5. Periapsis Evolution during the Second Extended Mission.

Coordination of Comet Observations

A most unusual convergence of events in November of 2013 gave MESSENGER scientists the opportunity to observe short-period comet Encke and hyperbolic-orbit comet ISON. 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. Encke's closest approach of 0.0249 AU, only 9.7 times the average Earth-Moon distance, occurred a few days before the comet's perihelion, and less than 1.5 days before a 0.2420 AU closest approach by ISON (Figure 6). Note that comet ISON's post-perihelion orbit marks where the comet would have gone had it remained intact after its 0.0125 AU perihelion on 28 November 2013. Figure 7 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 late October to early December 2013, with Mercury Dual Imaging System (MDIS) images of ISON (280 images) and Encke (431 images) returned to Earth, as well as other science data from the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) and X-Ray Spectrometer (XRS) instruments.

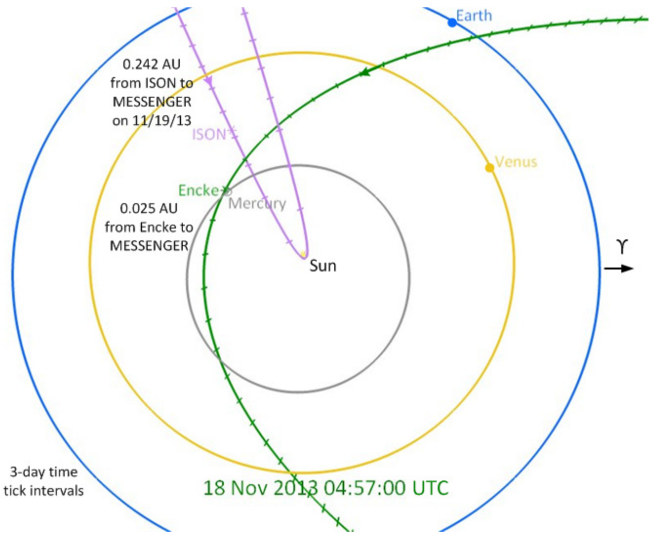

Figure 6. North Ecliptic Pole View of Orbits of Comets Observed by MESSENGER.

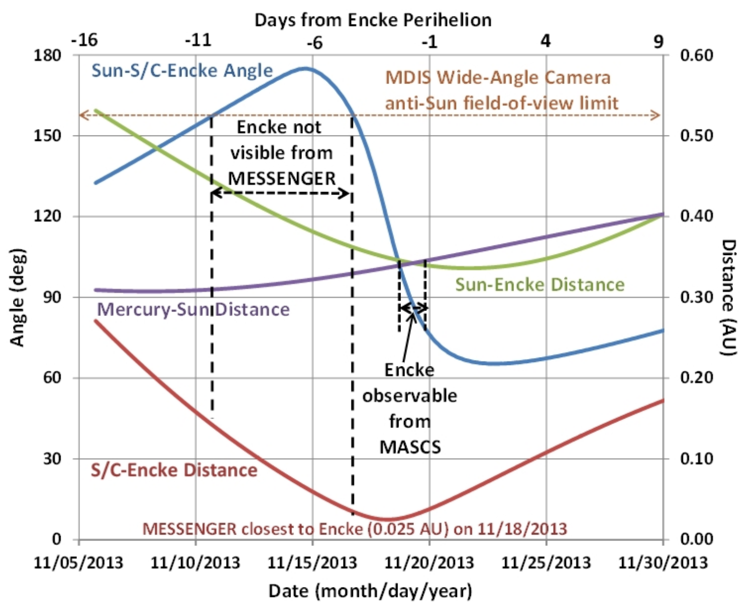

Figure 7. Observability of Comet Encke by MESSENGER.

Design and Implementation of XM2 Propulsive Maneuvers

The timing, duration, predicted performance, and purpose of the four maneuvers required for the low-periapsis-altitude campaign appear in Table 2. This OCM summary is current as of mid-January 2014 but is likely to change slightly given nominal OCM performance. At the start of these final OCMs, the MESSENGER propulsion system will have imparted 2158.1 m/s of ΔV to the spacecraft. Another 42.5 m/s of ΔV will cover OCM-9 through OCM-12 and remaining commanded momentum-dump maneuvers. Each OCM design is updated every six weeks as part of a trajectory re-optimization process, with the new maneuver times and accompanying spacecraft ephemeris to Mercury impact delivered to the SciBox software team.

Table 2. Mercury Orbital Phase XM2 Maneuver Summary.

Maneuver and Purpose	OCM Segment – Fuel Source	Calendar Date (day month year)	Start UTC (hh:mm:ss)	Sun Elevation (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 – auxiliary tank	17 Jun 2014	14:54:00	5.60	60.0	0.439
	2C main – auxiliary tank	17 Jun 2014	14:55:00	----	51.0	4.307
	A/B trim – auxiliary tank	17 Jun 2014	14:55:51	----	56.8	0.349
	Post-OCM-9 usable fuel = 9.954 kg (1.798 kg used) 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 – auxiliary tank	13 Sep 2014	16:15:00	7.00	60.0	0.355
	2C settle – auxiliary tank	13 Sep 2014	16:16:00	-----	36.0	2.580
	4C main – main fuel tank 2	13 Sep 2014	16:16:36	-----	15.0	2.869
	4C main – auxiliary tank	13 Sep 2014	16:16:51	-----	15.9	2.663
	Post-OCM-10 usable fuel = 7.622 kg (2.260 kg used) 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 – auxiliary tank	25 Oct 2014	19:23:00	-2.88	150.2	19.208
	Post-OCM-11 usable fuel = 3.073 kg (4.519 kg used) OCM-11 total ΔV = 19.208 m/s					
OCM-12 raises periapsis such that periapsis altitude levels off at 15 km before descending to surface impact.	4C main – auxiliary tank	21 Jan 2015	18:11:00	-4.04	98.7	9.744
	Post-OCM-12 usable fuel = 0.718 kg (2.289 kg used) OCM-12 total ΔV = 9.744 m/s					

Although OCM-9 will be performed using fuel only from the auxiliary fuel tank, propellant management procedures will be followed to prevent usable fuel from migrating and becoming trapped above the main fuel tank baffles. To prevent usable fuel from becoming unusable, OCM-9 will use a fuel-settle segment with four 4.4-N A/B thrusters, a main segment with two (of four onboard) 22-N C thrusters [8], and a trim segment that uses four 4.4-N A/B thrusters. This apoapsis-centered maneuver, designed to raise periapsis altitude such that the orbiter comes no closer than

25 km above Mercury's terrain when periapsis altitude changes little for many consecutive orbits just before OCM-10 on 13 September 2014, is planned on 17 June 2014. The mission design team identifies terrain-based altitudes for OCM targeting by applying a northern-hemisphere digital elevation model supplied by the MESSENGER Science Team and derived from the Mercury Laser Altimeter (MLA) instrument. An example of how terrain-based altitude differs from altitude relative to a 2440-km Mercury reference radius is presented in Figure 8.

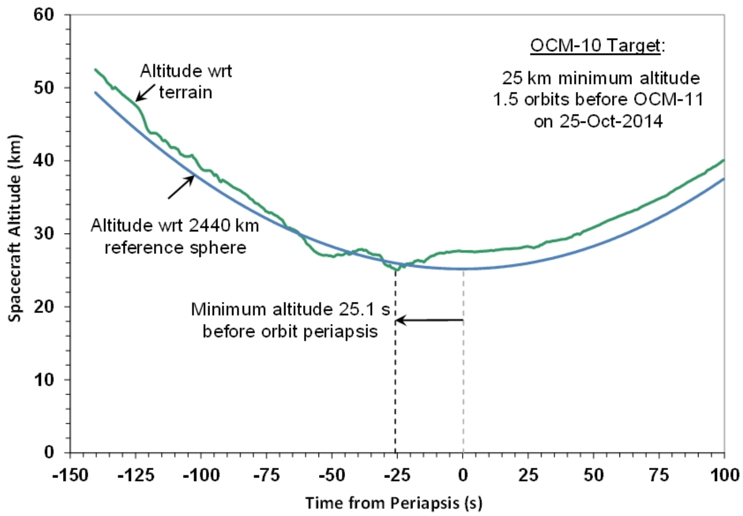

Figure 8. Effect on Altitude of Mercury's Topography from a Digital Elevation Model.

About one Mercury year after OCM-9, the apoapsis-centered OCM-10 will raise the periapsis altitude enough to target a minimum altitude of 25 km above Mercury's terrain about one-half Mercury year later, when periapsis altitude reaches a local minimum about 1.5 orbits before the 25 October 2014 OCM-11. A secondary design aspect of OCM-10 is to consume nearly all usable fuel contained in the only main fuel tank with usable fuel remaining. This objective requires a four-segment design that begins with an A/B-thruster fuel settle and a fuel-settle firing of two C thrusters, both using fuel only from the auxiliary tank. The settle segments will be followed by a main-segment burn with four C thrusters that draws fuel from the main fuel tank. A conservative estimate is that the usable fuel in the main fuel tanks will be consumed after 15 s. Then, a main-segment burn using four C thrusters drawing fuel only from the auxiliary fuel tank will complete the maneuver. Should there be less than 15 s of fuel remaining in the main tanks for the third maneuver segment, onboard autonomy will shift the maneuver into the final auxiliary tank segment early.

The next maneuver, OCM-11, will occur at apoapsis in order to raise periapsis altitude enough to target a minimum altitude of 25 km above Mercury's terrain about one Mercury year later, when periapsis altitude reaches a local minimum about 1.5 orbits before the 21 January 2015 OCM-12. Since there is no longer a need to conserve usable fuel in the main fuel tanks, OCM-11 does not require any lower-thrust settling or trim maneuvers. The maneuver will be performed using a single four-C-thruster segment that draws fuel only from the auxiliary tank.

The final maneuver planned for MESSENGER, OCM-12, will raise periapsis altitude to target a local minimum of 15 km above Mercury's terrain during the final time before Mercury impact during which periapsis altitude changes by less than 2 km within 1.5 weeks. This objective is accomplished by performing OCM-12 at apoapsis and using a single four-C-thruster segment drawing fuel from the auxiliary tank. After OCM-12 is completed, there will be about 0.7 kg of usable fuel remaining in the auxiliary tank, which is more than ten times the amount estimated for all remaining CMDs.

Contingency Preparedness for XM2 Propulsive Maneuvers

With three of four XM2 OCMs to be performed while periapsis altitudes are near 25 km, a postponed OCM or substantial under burn could lead to Mercury impact before the next maneuver opportunity at which all constraints are met, typically 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 (likely a 3–5 day delay) that completes the full objective of the missed or anomalous OCM with an out-of-orbit-plane, single-component OCM or a two-component OCM using two primary thruster sets with net thrust directions that are orthogonal. A third level of contingency for longer delays until safe spacecraft operation is certified would be completing just enough of the periapsis raise with a two-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, extra fuel may be pursued from main fuel tank 2, as unusable propellant estimates for this tank have been shown to be conservative.

Orbit Evolution During XM2

During MESSENGER's second extended mission, trends in spacecraft orbit seen during the primary and XM1 orbital phases are reversed in direction. Figure 9 depicts two changes affecting the orientation of the spacecraft orbit plane, right ascension of the ascending node in the Mercury J2000 frame and orbit inclination relative to Mercury's equator, with orbit inclination reversing its upward trend from 82.5 to 84.0° during the previous two years and the ascending node direction continuing at the same rate of decline since MOI. For the 26 months from OCM-8 to OCM-9, orbit period varied between 28,801 s and 28,809 s. The periapsis-raising OCMs 9–12 increased orbit period from $8^{h}\ 0^{m}$ to $8^{h}\ 17^{m}$. Figure 10 provides a Mercury north polar view of the clockwise progression of the northernmost sub-spacecraft Mercury surface point for the final year of XM2. Additional aspects of the spacecraft XM2 orbit evolution are evident in Figures 3–5.

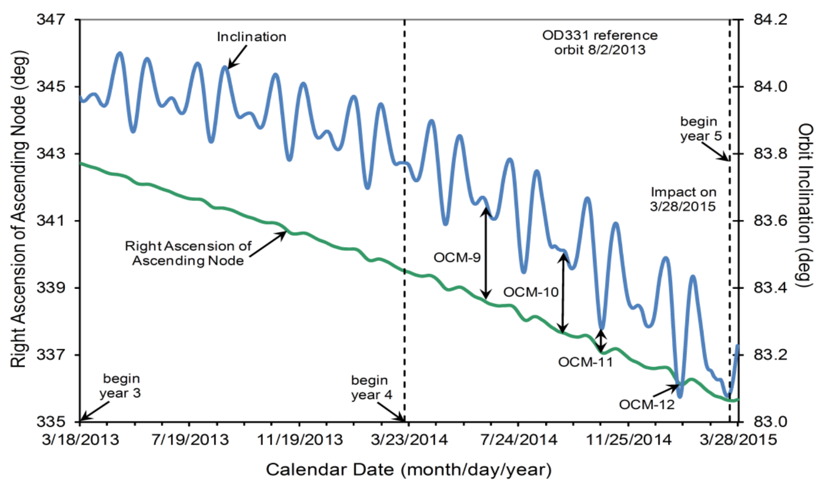

Figure 9. Examples of Orbit Plane Rotation during XM2.

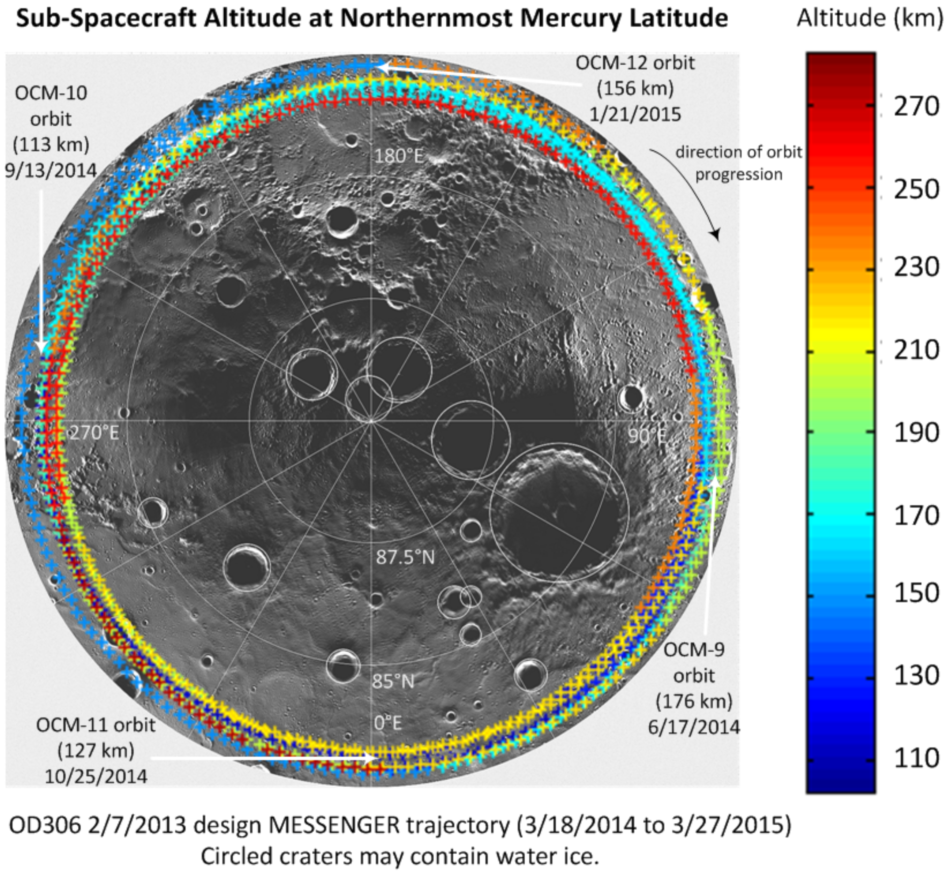

Figure 10. Altitude at Northernmost Sub-Spacecraft Latitude for the Final Year of XM2.

OVERVIEW OF NAVIGATION OPERATIONS

The KinetX Aerospace navigation team is responsible for processing NASA Deep Space Network (DSN) radiometric tracking data to produce the current and projected best estimate of the spacecraft trajectory for use in mission operations, science planning, and DSN tracking. In addition, the KinetX navigation team works closely with the mission design team at JHU/APL to validate and model OCMs. KinetX uses the MIRAGE suite of software tools to perform high-precision orbit estimation and maneuver design validation for the MESSENGER spacecraft and other deep-space missions.

Throughout XM1, improvements to estimates of Mercury's gravity field and fine-tuning of solar and planetary radiation pressure have helped to improve the accuracy of orbit determination (OD) and prediction for both the mission design and navigation teams. Accurate trajectory estimation and prediction has enabled precise planning of science observations and accurate OCM design, but these calculations depend on such factors as force modeling, observation modeling and weighting, relative location and velocity of objects in space and ground-based antennas, and parameter estimation strategy. Table 3 summarizes the estimated and considered model parameters used by the navigation team during the MESSENGER orbital operations phase. Estimated parameters are explicitly determined as part of the solution for spacecraft "state vector." Considered parameters are only used in the determination of formal uncertainties associated with estimated parameters.

Table 3. Summary of Estimated and Considered Model Parameters for OD Solutions.

Estimated Parameters	Considered Parameters
Position and velocity	Station locations
SRP specular and diffuse reflectivity coefficients	Troposphere model parameters
PRP specular and diffuse reflectivity coefficients	Ionosphere model parameters
Mercury albedo specular and diffuse reflectivity coefficients	Earth pole, UT1
ΔV due to commanded momentum dumps	Earth ephemeris
Orbit correction maneuvers	
Mercury ephemeris	
Mercury gravity field (20×20 spherical harmonic expansion)	

Orbit determination for the orbital phase utilizes the following DSN radiometric data types (abbreviations shown are standard DSN designations): two-way coherent Doppler (F2), three-way coherent Doppler (F3), and two-way ranging (SRA). Although delta differential one-way ranging (ΔDOR) was used during the mission cruise phase, it is not required for orbital phase navigation.

The navigation team delivers an OD solution and corresponding trajectory to the project nominally once per week. Data arcs are typically seven to nine days long. The project generally performs a CMD once per week, so there are usually one or two CMDs in the OD fit span. The predicted trajectory generated and delivered to the project ends 30-35 days after the tracking data cutoff to support near-term science sequence planning and also for DSN tracking. There is no *a priori* knowledge of the magnitude and direction of the future commanded momentum dumps, so they are not modeled in the predicted trajectory.

Primary Modeling Challenges

Superior solar conjunctions (when the planet Mercury passes behind the Sun as viewed from Earth) occur several times per year. The Doppler and ranging data signals can be degraded markedly as they pass through the solar plasma. During such periods, the tracking data weights are manually adjusted to reflect the increased noise, generally set approximately to the inverse square of the observed one-standard-deviation noise level.

For modeling the forces on the spacecraft due to radiation pressure, the spacecraft is approximated as ten flat plates. Specular and diffuse reflectivity coefficients and over-all scale factors are filter parameters to be determined in the solar radiation pressure (SRP), planetary (infrared) radiation pressure (PRP), and planetary albedo models. Modeling and estimating these forces due to the radiation environment near the planet Mercury is a substantial challenge and will be even more so as periapsis altitude decreases during XM2.

Another modeling challenge during the orbital phase has been estimation of the gravitational field of Mercury. To determine an *a priori* Mercury gravitational model after MOI and into the orbital phase, navigation used a method implemented by A. H. Taylor of the MESSENGER navigation team. This method is based on square root information (SRI) filter theory, as described by Bierman[9]. During the primary mission MESSENGER's periapsis altitude was no less than 200 km. From that minimum altitude, the navigation team determined that spherical harmonic coefficients to degree and order 20 could be determined (although the resolution of the shorter-wavelength components are much poorer in the southern hemisphere). To date, three Mercury navigation gravity (MNG) solutions have been delivered to the project, labeled sequentially MNG01, MNG02, and MNG03. As discussed in more detail below, MNG02 and MNG03 are similar, and both have been shown to meet the needs of navigation operations. Minor variations in these a priori field coefficients are estimated by the navigation team as part of the weekly orbit solutions, and are tightly constrained by appropriate uncertainties in each coefficient.

To mitigate the propagation of trajectory errors resulting from force modeling uncertainties during MESSENGER's orbital phase, the navigation team provides to the mission operations team a table of ephemeris time-tag biases. These time biases are calculated from the differences between predicted periapsis passages from the latest estimated trajectory and the previous four weekly trajectory deliveries. Since by far the largest component of trajectory error propagation tends to be along-track, application of a time bias can remove the vast majority of propagation errors. These time biases are uploaded to the spacecraft by the mission operations team and applied to on-board command loads in order to facilitate more accurate timing of science observations.

ANALYSIS OF NAVIGATION FORCE MODELS

The MESSENGER navigation team is preparing for what promises to be perhaps the most challenging period of the orbital phase, the controlled descent sequence of low-altitude periapsis passages prior to planetary impact. In late April 2014 spacecraft periapsis altitudes will descend below 200 km for the remainder of the mission (Figure 2). This altitude regime will place new demands on modeling and state estimation beyond those experienced to date. Gravitational harmonics of higher degree and order are likely to become increasingly important at low altitudes, and planetary radiation pressure perturbations will become more intense. The modeling of infrared radiation from Mercury's surface in particular will be more difficult at low altitudes, especially during eclipses when limitations on the adopted surface temperature model could potentially affect other estimation parameters. Trajectory accuracy feeds into the quality of science observations as well as the guidance design that will be used to control the sequence of altitude-raising maneuvers to extend the mission through late March 2015. Ongoing navigation analyses provide continuing process improvements that mitigate operational difficulties and provide a basis for successful completion of MESSENGER's second extended mission[10].

We next discuss navigation team efforts to validate and/or improve force models before the start of the XM2 OCM campaign and low-periapsis-altitude operations.

Analysis of Mercury Gravity Models

As discussed above, the latest Mercury gravity field models produced by the navigation team are the 20×20 harmonic fields MNG02 and MNG03. Over a period of several months, parallel weekly OD runs using MNG02 and MNG03 were produced by the navigation team, and it was determined that there is no significant difference in the resulting OD solutions and trajectory predictions. Since post-fit track data residuals were marginally smaller for MNG02 than for MNG03, MNG02 was adopted as the standard gravity field for operational OD deliveries.

The mission design ephemeris prediction software currently uses the HgM005 spherical harmonic gravity model developed by the MESSENGER Science Team. As of this writing, this 50x50 field is the latest Mercury gravity model produced by the Science Team[11].

As the MESSENGER flight operations team prepares for the XM2 OCM campaign and low-altitude operations, it is prudent to assess the consistency of current Mercury gravity models produced by the navigation and science teams. Analyses to date indicate that these gravity models are consistent with each other in that they produce similar results for OCM design, OCM verification, and long-term orbit prediction.

For OCM-9, the first maneuver of the upcoming low-altitude periapsis period, a preliminary design was produced in November 2013 by the mission design team using HgM005. The navigation team then verified this maneuver design through simulated maneuver execution and long-term ephemeris prediction with the MNG02 gravity model. The results of the OCM-9 preliminary maneuver design analysis are presented in Table 4. Also included in this analysis was an optimization of the final burn segment duration to achieve the desired target periapsis altitude at the next planned maneuver, OCM-10, on 13 September 2014. The results shown in Table 4 demonstrate close agreement between the solutions by the mission design and navigation teams, especially considering that the post-maneuver periapsis altitude target is almost three months after burn execution. Similar verification analyses were performed (with good agreement) on the preliminary maneuver interface files from the mission design team for OCM-10, OCM-11, and OCM-12, for which relative positioning within the mission timeline are depicted in Figure 2.

Table 4. OCM-9 Design Verification by the Navigation Team.

Mercury Gravity Models Used: HgM005 (Science Team) and MNG02 (Navigation Team)							
Burn Model/Event	Pre-burn periapsis		Post-burn periapsis		Burn target periapsis		
	Altitude (km)	Period (s)	Altitude (km)	Period (s)	Time (ET)	Altitude (km)	Period (s)
Design	114.245	28806.738	156.225	28924.042	09/13/14 04:01:29.292	25.948	28924.053
Verification	114.245	28806.738	156.216	28924.052	09/13/14 04:05:17.344	26.554	28924.370
Difference	N/A	N/A	-0.009	0.010	228.052	0.606	0.317

The maneuver design verification summarized in Table 4 was completed with completely independent software suites used by the mission design and navigation teams. For a direct comparison of Mercury gravity models, the navigation team conducted additional analysis on the preliminary OCM-9 maneuver design using only the MIRAGE navigation software and varying only the gravity field model. This analysis consisted of performing a long-term ephemeris prediction (including modeling the maneuver) with different gravity models as shown in Table 5. The results of trajectory comparisons between MNG02 and HgM005, the latter in both its full 50×50 spherical harmonic configuration and a truncated version limited to the first 20×20 terms (the same size as MNG02), show that the prediction from 2 December 2013 through OCM-9 on 17 June 2014 and past the OCM-10 epoch on 13 September 2014 produced only minor differences in the results between the different gravity models. This analysis confirms the validity of comparisons between the results generated by the mission design and navigation teams over extended time spans. It also provides assurance of consistency in ephemeris predictions across low-altitude periapsis passages, whichever gravitational model is used. This result is an important verification as the MESSENGER spacecraft prepares to undertake a controlled descent toward impact onto the surface of Mercury.

Table 5. Comparative Gravity Modeling Results (OCM-9, MIRAGE).

Gravity Model/Event		Pre-burn periapsis		Burn apoapsis	Post-burn periapsis		Burn target periapsis		
		Altitude (km)	Period (s)	Time (ET)*	Altitude (km)	Period (s)	Time (ET)	Altitude (km)	Period (s)
MNG02		113.669	28806.668	06/17/14 14:54:55.151	155.632	28923.974	09/13/14 04:01:49.633	24.728	28923.469
HGM005	20x20	113.995	28806.683	06/17/14 14:54:53.904	155.966	28923.996	09/13/14 04:01:54.682	25.475	28923.489
	50x50	113.887	28806.679	06/17/14 14:54:53.623	155.857	28923.991	09/13/14 04:01:52.720	25.197	28923.476

* ET = Ephemeris Time

Analysis of Radiation Pressure Models

The radiation pressure parameters estimated by the OD filter include specular and diffuse solar, planetary infrared, and planetary albedo coefficients for each of the ten plates in the spacecraft model (a total of 60 parameters). Two overall scale factors are also estimated, one each for the planetary infrared and visible-wavelength re-radiation models. As part of an ongoing statistical analysis of almost three years of OD solutions delivered once per week to the mission operations team since MOI, the navigation team has plotted the sequence of orbital solutions for specific estimation parameters, and an example is shown in Figure 11. In this example, the "delta solution" (difference between a current delivered OD parameter estimate and the previous week's estimate) of the solar radiation pressure specular reflectivity coefficient for one of three components of the spacecraft sunshade (SPEC01) is displayed as a function of time and is mapped to the numerical sequence of OD deliveries. The error bars denote ± one standard deviation (σ) estimated by the filter for that solution parameter. The legend displays the mean (weighted by each formal sigma) and 1-σ, 2-σ, and 3-σ multiples of the delta solutions (displayed as horizontal lines). The reflectivity coefficients have a range between zero and one. On rare occasions when physically unrealistic values (e.g., negative values) are produced by the filter, the OD analyst will adjust the *a priori* σ until the estimated value is in the proper range. The occasional occurrence of negative reflectivity coefficients is usually due to limitations in model fidelity and aliasing between force model parameters. Solution points that required OD analyst adjustment are included on the plot but are not included in the calculation of the weighted mean. Note that the formal errors shown on the plot are smaller than the week-to-week variability in the solution parameter, indicating that formal errors underestimate actual uncertainty.

The kind of statistical analysis represented by Figure 11 has been useful in tuning the OD filter and sometimes provides insights into hidden relationships and dependencies among model parameters and other variables, such as orbit geometry. From analyses such as these, nominal and *a priori* values have been updated in the OD filter for XM2, for which the planetary radiation environment will be more intense. These updates produced subtle but consistent improvements in subsequent OD solutions. The navigation team continually tests, in parallel with operational solutions, variations in estimation strategies in order to improve the delivered OD solutions. When a modification in the baseline setup improves the fit consistently, it may be incrementally incorporated into the baseline configuration. This procedure facilitates a rigorous analysis environment within which quality is continually improved through a competition between solutions.

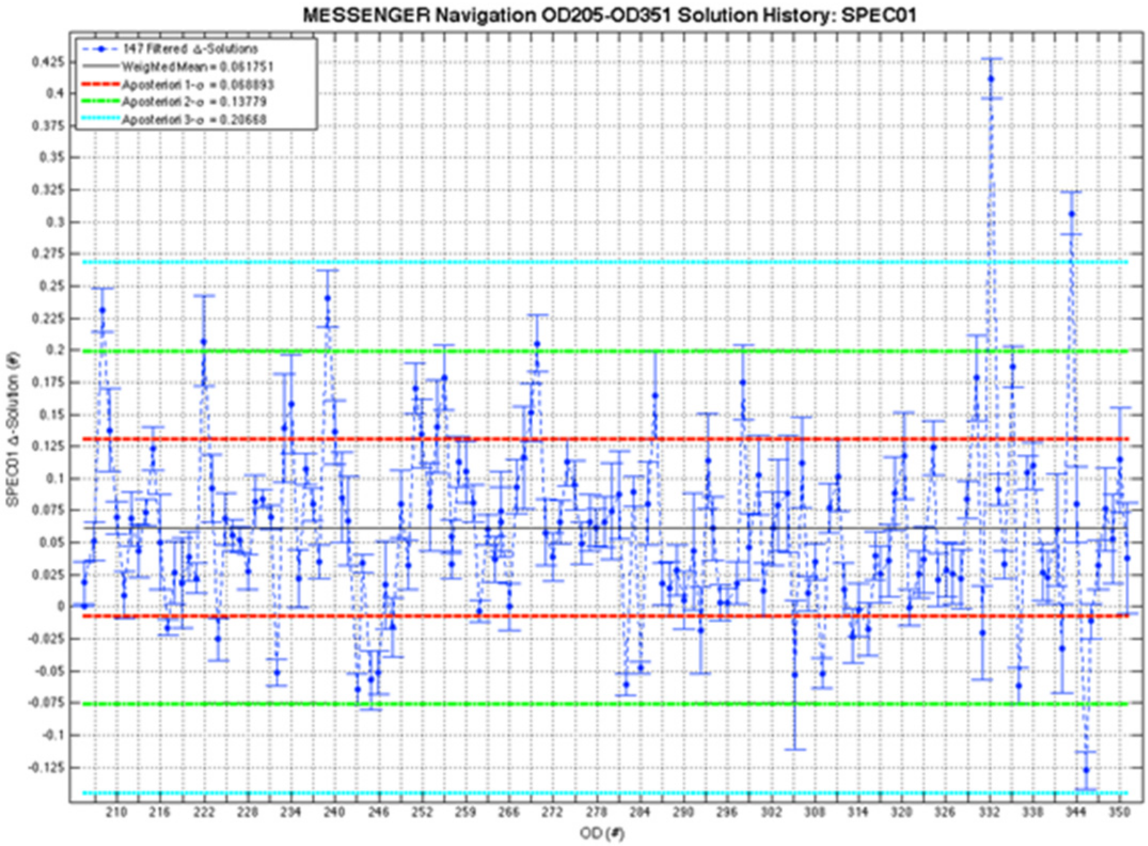

Figure 11. SPEC01 Solution History.

Often, valuable insight into the state estimation and modeling processes are acquired. For example, a variant OD strategy was attempted which involved removing the infrared and albedo overall scale factors from the estimation list. In the upper right of Figure 11, two "out of family" points (OD solutions 332 and 343) were the result of the propagation of errors in the infrared reflectivity coefficient estimates into other parameters during spacecraft solar eclipse seasons. There are two of these eclipse seasons during each orbit of Mercury about the Sun, one with periapsis on the sunlit side of the planet and one with periapsis on the night side. This effect is postulated to be a result of fidelity limitations in the Mercury surface temperature model for the specific geometry of nightside periapsis eclipse seasons. Acceleration perturbations from solar radiation pressure and planetary albedo are absent when the Sun is eclipsed by Mercury from the point of view of the spacecraft. When this occurs at low altitudes, as with night-side periapses, the OD filter has more difficulty finding other model parameters to match the observed accelerations. This analysis led to the determination that the infrared and albedo overall scale factors should be retained as estimated parameters, and this step in the analysis is likely to increase in importance during the low-altitude periapsis regime of XM2.

NAVIGATION PLANNING FOR OCMS AND LOW-ALTITUDE OPERATIONS

As discussed earlier, during XM2 the periapsis altitude will decrease below 200 km (Figure 2), which should enable more precise determination of the shorter-wavelength components in the gravity field than in the 20×20 harmonic models employed by the navigation team to date. For example, a sustained periapsis altitude at or below 130 km should yield tracking data that resolve (for the purpose of navigation operations) field coefficients up to degree and order 30. However, since each additional increment in the order, n, of spherical harmonics adds $2n+1$ terms to the model, such an increase in the number of estimated state parameters adds a computational burden on the filter, due primarily to the calculation of partial derivatives with respect to each state parameter. Therefore, consideration must be given to the extent to which the additional computations are justified given the time constraints of ongoing navigation operations.

For navigation contingency planning, fuel tank depletion could occur during one or more of OCMs 9 through 12. Therefore, the navigation team must prepare for the possibility of a substantial under-burn at any point. Testing performed by the navigation team prior to OCM-7 and OCM-8 indicated that the OD filter is able to converge to actual burn execution parameters even when the *a priori* target values are significantly different from the executed burn, as long as *a priori* errors are set wide enough. The navigation team plans to continue this analysis for a variety of under-burn scenarios in preparation for the XM2 OCM campaign. In addition, a small forces file derived from on-board guidance, navigation, and control sensor data collected during and after a burn can be helpful both for a “quick look” immediately after execution and also for burn parameter setup in the OD filter when solving for an off-nominal burn.

Improvements to the Mercury surface temperature model are also possible. The model uses a 10×10 spherical harmonic fit to pre-MOI values. More recent planetary temperature values and a model expanded to higher degree and order is currently under consideration given current time and resource constraints. However, the continued inclusion of the overall infrared scale factor in the estimation parameter list mitigates fidelity limitations of the planetary infrared re-radiation model.

SUMMARY

After a successful yearlong primary Mercury orbital phase that ended in March 2012, MESSENGER next completed a one-year first extended mission and then began its final (two-year) second extended mission in mid-March 2013. The high-eccentricity primary mission orbit had an orbit period near 12 h, a near-polar orbit (inclination 82.5°–84.0°), and a periapsis altitude between about 200 and 500 km. With full mission success recognized after the primary mission, mission planners lowered the orbit period to $8^h\ 0^m$ one month into XM1. With 50% more orbits per day and apoapsis nearly one-third closer to Mercury’s surface than during the primary mission, spacecraft operators were able to extend the mission’s scientific accomplishment in ways not possible during the primary mission. In February 2013, the MESSENGER project submitted to NASA its final plan for extending the mission into late March 2015 by using most of the propellant remaining to raise periapsis four times between June 2014 and January 2015. Each periapsis-raising OCM will 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 direction.

Strategic planning and close cooperation between the mission design and navigation teams has been a key element of the success of MESSENGER’s extended mission. Recent coordination between these two teams has refreshed maneuver design and verification procedures that have not been used since planning OCMs 7 and 8 in April 2012. Careful coordination with the Mission System Engineer and the Propulsion Lead Engineer have resulted in completed OCMs and future OCMs that effectively and safely utilize remaining propellant to the fullest extent possible and that contribute to the MESSENGER mission’s continued scientific success.

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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] D. P. Moessner, and J. V. McAdams, "The MESSENGER Spacecraft's Orbit-Phase Trajectory." *Astrodynamics 2011: Part III, Advances in the Astronautical Sciences,* 142, pp. 2211–2230, 2012.

[3] J. V. McAdams, S. C. Solomon, P. D. Bedini, E. J. Finnegan, R. L. McNutt, Jr., A. B. Calloway, D. P. Moessner, M. W. Wilson, D. T. Gallagher, C. J. Ercol, and S. H. Flanigan, "MESSENGER at Mercury: From Orbit Insertion to First Extended Mission," *63rd International Astronautical Congress*, paper IAC-12-C1.5.6, 11 pp., Naples, Italy, October 1-5, 2012.

[4] M. N. Wilson, C. S. Engelbrecht and D. E. Jaekle, Jr., "MESSENGER Propulsion System: Strategies for Orbit-Phase Propellant Extraction at Low Fill Fractions," *49th Joint Propulsion Conference and Exhibit*, American Institute of Aeronautics and Astronautics/American Society of Mechanical Engineers/Society of Automotive Engineers/American Society for Engineering Education, paper AIAA-2013-3757, 15 pp., San Jose, CA, July 14-17, 2013.

[5] 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.

[6] D. R. Stanbridge, K. E. Williams, A. H. Taylor, B. R. Page, C. G. Bryan, D. W. Dunham, P. J. Wolff, B. G. Williams, J. V. McAdams, and D. P. Moessner, "Achievable force model accuracies for MESSENGER in Mercury orbit," in *Astrodynamics 2011: Part III, Advances in the Astronautical Sciences*, 142, pp. 2231-2249, 2012.

[7] T. H. Choo, et al., "SciBox: An Automated End-to-End Science Planning and Commanding System," *Acta Astronautica,* 93, pp. 490-496, 2014.

[8] J. C. Leary, et al., "The MESSENGER Spacecraft," *Space Science Reviews*, 131, pp. 187-217, 2007.

[9] G. J. Bierman, "Factorization Methods for Discrete Sequential Estimation", Academic Press, New York, 241 pp., 1977.

[10] B. R. Page, C. G. Bryan, K. E. Williams, A. H. Taylor, D. R. Stanbridge, P. J. Wolff, and B. G. Williams, "MESSENGER Navigation Operations during the Mercury Orbital Mission Phase," *Spaceflight Mechanics 2013: Part III, Advances in the Astronautical Sciences*, 148, pp. 2825-2844, 2013.

[11] E. Mazarico, et al., "The Gravity Field of Mercury as Seen by MESSENGER after 2.5 Years in Orbit," abstract P11A-01, American Geophysical Union, San Francisco, CA, 9-13 December 2013.