MESSENGER's Hover Campaign

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ABSTRACT

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft achieved a number of technical milestones and successfully accomplished all of the planned science objectives for its nominal mission as well as the first two mission extensions, termed XM1 and XM2. The orbital phase of the mission through XM2 lasted 4 years, a duration four times as long as that of the baseline mission. Key to the success of the mission was a robust vehicle design that defied the designed mission lifetime and a creative team that developed operational concepts and science collection methods that allowed the continued collection of novel science data products. The mission culminated in one final mission extension, termed XM2′, during which the spacecraft periapsis altitude ranged over unprecedentedly low values. This vantage point allowed novel studies of Mercury, but it forced an elevated cadence of propulsive maneuvers, the last few using helium pressurant to impart velocity corrections to the spacecraft. On 30 April 2015, with the vehicle nearly out of pressurant and the XM2′ observation campaign complete, MESSENGER ended the flight phase of the mission by impacting the surface of Mercury.

INTRODUCTION

Late into the second mission extension (XM2) of the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, the MESSENGER spacecraft's orbit about Mercury was such that solar gravity pulled the orbit periapsis progressively closer to the planet. This decay in the minimum orbit altitude was countered by performing periapsis-raising maneuvers, but by the end of XM2, MESSENGER had used nearly all the remaining propellant required to delay the inevitable impact onto Mercury's surface. Despite the nearly empty fuel tanks, the team devised a plan to operate the spacecraft with the orbit periapsis altitude at values less than 40 km, thereby offering a unique vantage point for further study of the planet. The team operated the vehicle from this orbit through a final 6-week mission extension, termed XM2′, constrained mainly by the remaining onboard propellant. After having downlinked the last of the critical science observations, the mission ended on 30 April 2015 as MESSENGER impacted Mercury's surface at nearly 4 km/s.

MESSENGER was allowed to continue into XM2′ for two primary reasons: (*i*) the science campaigns conducted during the primary mission and XM1 and XM2 were successful (see Grant and Winters, this issue), and (*ii*) the spacecraft and payload remained healthy and operable. MESSENGER had met or exceeded all of the scientific objectives laid out for the first three of the mission's orbital segments. The solid history of exceeding sponsor expectations positioned the team to make a final attempt to collect unique science observations. In addition, the health of the spacecraft enabled MESSENGER to continue into XM2′. Despite operating in the hostile thermal and radiation environment near Mercury for a duration four times as long as that of design lifetime, the mission had nearly full use of all of its components and payload. The only noteworthy issue with the payload was that the cryogenic cooler on the Gamma-Ray Spectrometer sensor on the Gamma-Ray and Neutron Spectrometer instrument had failed, despite outliving its expected operational lifetime. However, the sensor was repurposed by converting its large-area anti-coincidence scintillator as a high-time-resolution detector of energetic electron bursts in Mercury's magnetosphere. The spacecraft itself proved to be even more robust than the nearly flawless payload; there were no notable component failures, and in all cases the spacecraft components remained healthy (and with nearly all of the as-launched redundancy available). In addition to the health of the flight system, the team was very comfortable operating the vehicle. The analysis capability of the planning team allowed operation of the vehicle with minimal risk despite the continued reduction in margins, particularly in the thermal and power subsystems.

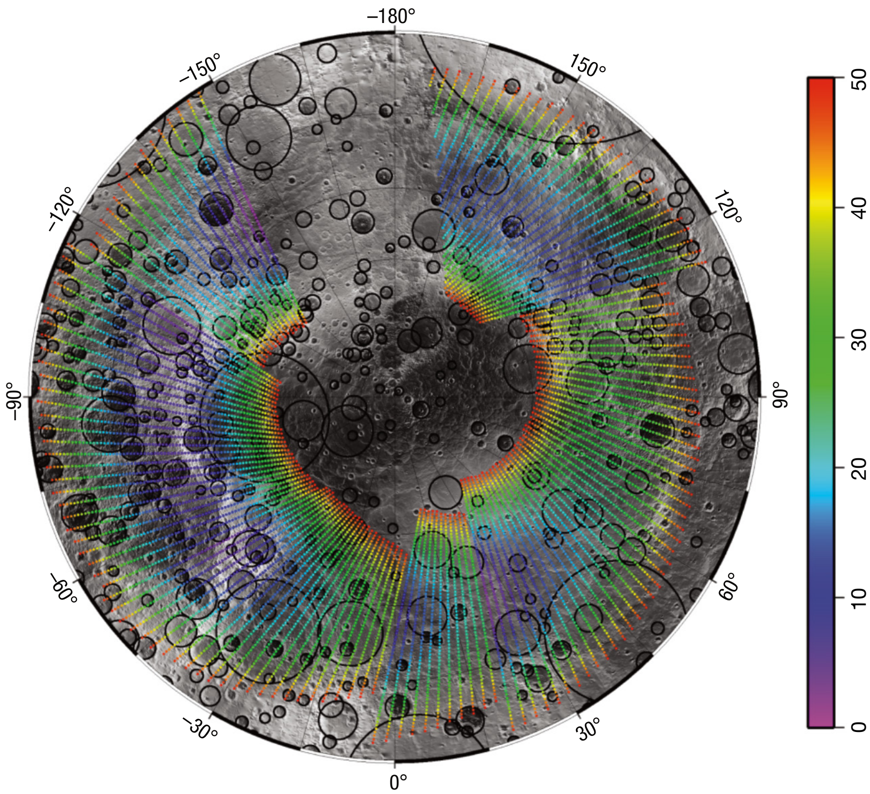

Figure 1. North-pole view of Mercury showing MESSENGER's ground tracks when the altitude was <40 km. Nearly complete longitudinal coverage was achieved during XM2′.

A healthy spacecraft and instrument suite was necessary to ensure continued operation beyond XM2, but it was essential to have a novel and compelling science observation plan to justify XM2′. Although it might seem that an additional 6 weeks of operation would not offer compelling science observations beyond what was achieved previously through the primary mission, XM1, and XM2, the extremely low periapsis altitudes possible late in the mission allowed enhanced spatial fidelity of some characteristics of Mercury that were detected but not well resolved from observations at higher altitudes.[1,2] This final campaign offered an opportunity for observations with resolution that could provide insight in two key areas. First, it offered a chance for observations of radar-bright craters in Mercury's northern hemisphere with enhanced spatial resolution. Second, XM2′ offered a chance for refined measurements of Mercury's magnetic field in the northern hemisphere, providing a sustained glimpse of the field at altitudes of <200 km. These magnetic observations were used to improve the characterization of anomalies in the magnetic field attributable to crustal paleomagnetism, helping to extend the temporal baseline of the magnetic field from decades to billions of years. To achieve the magnetic field observations, the goal was to provide as much longitudinal coverage at low altitude as possible, which meant that XM2′ was to be as long as practical. To achieve the proposed longitudinal coverage, as shown in Fig. 1, and ensure opportunities to observe three radar-bright craters of interest, the mission end date of 30 April 2015 was adopted.

HOVER CAMPAIGN DESIGN

The design of the spacecraft trajectory and the orbit-correction maneuvers (OCMs) needed to balance achievement of science goals with acceptable implementation risk.[3] The primary science goals that were directly linked to trajectory design included a desire to keep the spacecraft's minimum altitude at ~15 km

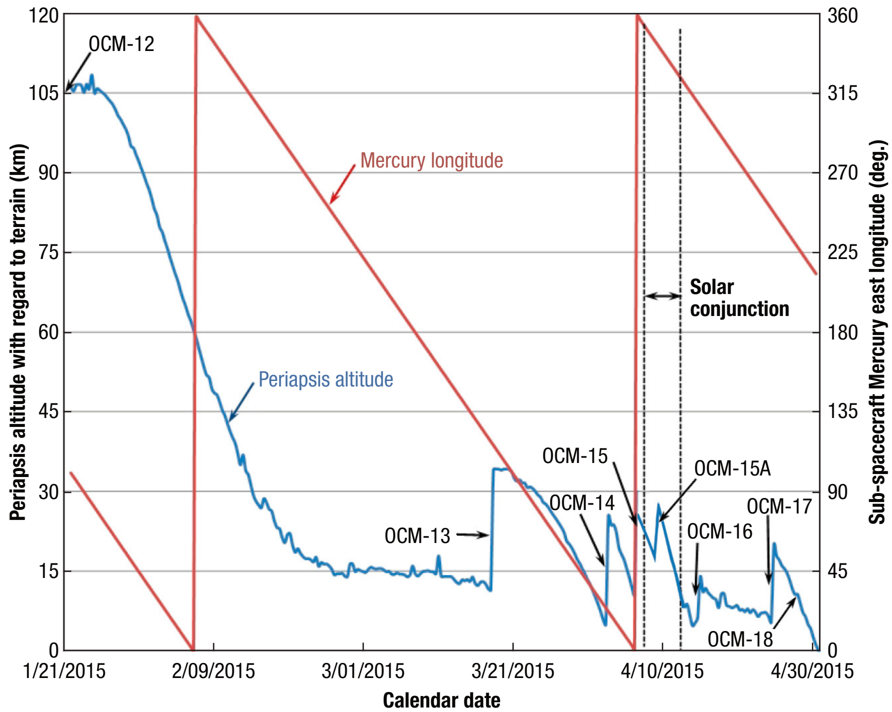

Figure 2. Periapsis altitude and OCM placement through the hover campaign.

and to delay Mercury impact as long as possible to enable low-altitude scientific measurements over a greater range of Mercury longitudes. During XM2, MESSENGER's altitude dipped as low as 12 km, but altitudes of <50 km were visited only briefly because the risk of an untimely surface impact was too great. The team adopted a strategy for XM2′ whereby the periapsis altitude would hover around the targeted value of 15 km; as a result, the operations team referred to this final mission extension as the hover campaign. Achieving a static periapsis altitude for MESSENGER was impossible from a practical standpoint. To affect a constant periapsis altitude, MESSENGER would have had to execute periapsis-raising maneuvers as many as three times per day to counteract the effect of the Sun's gravity on MESSENGER's orbit. This rate would have required far too many maneuvers to plan and execute given that the shortest interval between maneuvers to date had been 3 months. Instead, the team maintained the periapsis altitude near a target value of 15 km but allowed altitudes as low as ~7 and as high as 45 km. Adopting this range reduced the cadence of maneuvers to approximately one per week, which was viewed as challenging but manageable for the experienced team. The proposed periapsis altitude profile over the expected 6-week hover campaign is shown in Fig. 1.

Numerous issues affected the number and placement of OCMs during the hover campaign, including mission design constraints, propulsion subsystem performance, science objectives, and mission operations constraints. The key objective was defined by the science team's desire to maintain the periapsis altitude as low as possible, but this goal had to be balanced against the risk of early surface impact inherent in low-altitude operations. The mission design team and spacecraft navigators were concerned about uncertainty in the orbit predictions through an unmapped region of Mercury's gravity field and about unmapped surface features that might have acted to end the mission earlier than planned. However, the science team had developed a high-resolution elevation map throughout the prior 4 years of Mercury orbital operations via the use of the laser altimeter and stereoscopic images of Mercury's surface. The fidelity of this map, particularly in the critical northern hemisphere, provided confidence that there were no unmapped terrain features that might end the mission earlier than planned. So, although the navigators advised maintaining the altitude above 10 km, the team elected to push the minimum planned periapsis altitude just below 7 km in an attempt to improve the science return. The periapsis altitude and placement of OCMs 13–17 during XM2′ are shown in Fig 2.

A second trajectory design issue was a 6-day superior solar conjunction, when the spacecraft was on the opposite side of the Sun from Earth, during the hover campaign. The timing of this conjunction is indicated by the dashed vertical lines in Fig. 2. Although the conjunction did not affect the ability of the spacecraft to make the necessary measurements of Mercury, it did pose an issue for downlinking those observations to the ground because the spacecraft was unable to communicate with ground stations when the Sun–Earth–spacecraft angle was less than ~3°. Not only does such a conjunction eliminate communication altogether for several days, but the spacecraft communications link to the ground was degraded in the days before and after the conjunction because the vehicle was at a nearly maximum Earth range. The degraded downlink rates meant that the vehicle needed to survive for several weeks beyond the end of conjunction to ensure that all of the necessary science observations could be transmitted to the ground. A strategy that would end even a week earlier could greatly diminish the value of the hover campaign; although such a scenario would have allowed collection of the desired science observations by the spacecraft, there would be no opportunity to transmit all of the data to the ground. In addition to the downlink issues presented by the conjunction, ground operators would be unable to communicate with the spacecraft, and for that reason, no periapsis-raising maneuvers were planned during the communication outage. The conjunction coincided with an aggressive drop in the periapsis altitude, which meant that maneuvers had to be planned at both ends of conjunction to offset this altitude loss. It also meant that the team was under a very tight timeline to correct issues with the maneuver inbound to conjunction. If the planned maneuver was not completed fully before conjunction, it was possible that the spacecraft could have impacted Mercury before it was able to reestablish communication with Earth.

Perhaps the most substantial issue with regard to the design and execution of the hover campaign was the uncertainty about the remaining onboard propellant. MESSENGER was launched with nearly 600 kg of propellant for performing adjustments to its trajectory, and entering the hover campaign, the vehicle was predicted to have 6.6 kg of propellant remaining. This propellant, together with the 2.5 kg of remaining helium pressurant, was spread across four tanks, with varying degrees of uncertainty as to its accessibility, as shown in Table 1. To survive conjunction and ensure that all of the planned XM2′ observations would be telemetered safely and in full, a trajectory design was created that made use of all of the credibly accessible propellant. The propellant in main fuel tanks 1 and 2 presented accessibility issues, mostly as a result of the physical configuration of the tank baffles, which served to hold unknown amounts of propellant in pools and fillets. The planned hover campaign maneuvers almost exclusively relied on the propellant in the auxiliary fuel tank, because the hydrazine in that tank was believed to be both easily accessible and well known in quantity. Overall, the planned hover campaign required ~90 km of periapsis-raising capability, which meant that the vehicle would need to rely in part on using the helium pressurant to provide ΔV. Moreover, there was very little accessible pressurant left to correct any maneuver execution errors, trajectory estimation errors, or unexpected anomalies in the gravity field.

In addition to the driving design considerations described above, numerous other constraints were considered when developing the hover campaign. The propulsive maneuver efficiency, measured in terms of kilometers of periapsis rise per kilogram of propellant, changed as a function of date. Furthermore, the date of each maneuver could also dictate the thruster set used (because of the changing Sun–spacecraft–DV angle). One thruster set that was needed for XM2′, the P thrusters, had long been dormant, and these thrusters had been avoided for years because a prior use had shown issues in achieving precision in the targeted DV. Because of the limited hydrazine resources for XM2′, the team planned to use the gaseous helium (GHe) pressurant should the liquid propellant be depleted earlier than expected. Although the helium gas was theoretically a useful (and even a reasonably efficient) propellant, pressurant had never been used as a primary propellant.[4] Furthermore, the use of helium could not be flight tested easily, and special onboard autonomy rules had to be developed to detect the transition from liquid to gas to allow DV maneuvers in progress to continue to completion. All of these constraints fed into the trajectory design process and the preparations for XM2′.

With regard to the many constraints that had to be considered when developing the hover campaign, one of the most unexpected developments was that the trajectory and science plans largely were unaffected by the dominant vehicle design constraints: the allowable thermal, radiation, and power limits. MESSENGER operations were carefully planned to accommodate these three constraints derived from the spacecraft design (see Bedini, this issue). XM2′ happened to cover a portion of the Mercury year when these constraints did not have a substantial impact on payload operations. Some spacecraft components were very sensitive to vehicle orientations, which could strongly influence the component temperatures, especially during portions of the Mercury year when the back side of the spacecraft was exposed to the reflected infrared radiation from Mercury.[5] For the hover campaign, however, these thermal issues were mitigated because the primary sci-

Table 1. Predicted propellant resources for XM2′

Resource	Mass (kg)	Accessibility	Utilization Risk	Approximate Periapsis Altitude Raise (km)
Hydrazine in auxiliary fuel tank	2.8	Very high	Very low	80
GHe in main fuel tank 1	0.7	High	Medium	15
GHe in main fuel tank 2	0.6	High	Medium	15
GHe in helium tank	0.6	High	Medium	15
Hydrazine in lines/manifold	0.3	Low	Medium	10
Hydrazine in main fuel tank 1	1.6	Low	High	40
Hydrazine in main fuel tank 2	0.0	Low	High	0
GHe in oxidizer tank	0.6	Low	Very high	15
Oxidizer in oxidizer tank	1.9	Very low	Very high	N/A

ence objective during the bulk of the hover campaign was the acquisition of magnetometer observations, and that instrument did not require specific vehicle attitudes, so thermal considerations did not impact science data collection.

IMPLEMENTATION

The cadence of maneuvers during the hover campaign made it impossible to plan, simulate, test, build, and upload commands to the spacecraft following the same rigorous process that had been used for prior maneuvers (see McAdams et al., this issue). Instead, a series of commands were developed with a reduced set of changeable parameters to enable quicker build, test, and upload times. With this framework, the number of detailed reviews and simulations required for each hover campaign maneuver was reduced substantially with minimal increase in risk. A propulsion model developed during MESSENGER's flight was used to calculate propellant consumption from all tanks as a function of on time, feed pressure, and duty cycle using subsystem telemetry and thruster performance curves. However, the model was ill-equipped to handle GHe flow, and updating legacy MATLAB and Simulink code originally designed to evaluate bipropellant maneuvers was considered an inefficient use of project resources. Therefore, starting with OCM-12, which was intended to evaluate thruster performance using GHe, a special model was developed that allowed modification of the propellant type mid-maneuver, as needed, on the basis of observed thruster performance. The propulsion team was able to use the new model to quickly iterate predicted feed pressure, thrust, and specific impulse, and the model was refined as the guidance and control team provided thrust estimates from the onboard accelerometer data during GHe propellant use.

Although the specialized commanding simplified certain elements of the maneuver design process, it also added constraints that limited the flexibility of each maneuver design. First, all burns in the hover campaign were designed as single-segment burns using only one set of thrusters and no tank changes, except when opened or closed by autonomy rules. Changes were also made to the attitude thruster control parameters. Before the hover campaign, the attitude-control deadbands for the spacecraft were chosen for each specific burn type to optimize burn performance. P thruster, C thruster, and commanded momentum desaturation burns all used different parameters. For the hover campaign, limitations on command space required that the attitude-control deadbands provide acceptable limits for all maneuver and commanded momentum desaturation configurations. The single set of parameters also had to perform acceptably across varying thrust scenarios of hydrazine, GHe, or some combination of the two. Creating a default set of universal thruster control parameters introduced slightly more error than was seen previously but at a level that was within the tolerance of the burn design. Because the science conducted during the hover campaign was designed to be compatible with a wide range of achieved trajectories, maneuver-execution pointing error was less important during the hover campaign than for previous OCMs. Typical earlier burns had pointing errors of <1° for the resultant ΔV, whereas the hover OCMs were expected to have pointing errors up to 4°.

For C-thruster burns, the updated parameters were also chosen to reduce the on time of the A and B thrusters, which are less efficient than the C thrusters when using the same propellant type. Forcing the control system to maintain attitude control primarily using the C thrusters during maneuvers of this type helped save propellant because the C thrusters are pointed such that their pulsing contributes to the desired ΔV, whereas the A and B thrusters are approximately orthogonal to the desired ΔV. To improve efficiency during the P-thruster burns, only four of the eight attitude-control thrusters were enabled (A2, A4, B2, and B4). When fired for attitude control, these four thrusters contributed a ΔV component in the desired direction, whereas the disabled thrusters would have contributed in the opposing direction, working against thrust from the P thrusters. However, any A2, A4, B2, and B4 on-pulsing for attitude control contributed to maneuver-execution direction errors because of the 15° cant angle of the four thrusters and the fact that they were not paired with their oppositely offset counterparts.

A summary of the hover campaign maneuver performance is shown in Table 2, and the periapsis altitude

Table 2. XM2′ maneuver summary

OCM	Date	Propellant Usage (kg) N_2H_4	Propellant Usage (kg) GHe	Duration (s)	Total ΔV (m/s)	No-OCM Impact Date	Maneuver Purpose
13	18 Mar	0.73		32.96	3.07	28 Mar	Planned OCM
14	2 Apr	0.93		401.24	2.96	4 Apr	Planned OCM
15	6 Apr	0.43	0.07	600.00[a]	1.73	10 Apr	Planned OCM
15A	8 Apr	0.05	0.49	303.00[a]	1.92	13 Apr	Cleanup OCM-15
16	14 Apr		0.29	201.92	0.99	24 Apr	Planned OCM
17	24 Apr		0.43	469.22	1.53	27 Apr	Planned OCM
18	28 Apr		0.11	181.02	0.45	30 Apr	Ensured desired impact time

[a] OCM-15 and OCM-15A terminated because of a maximum burn duration timeout.

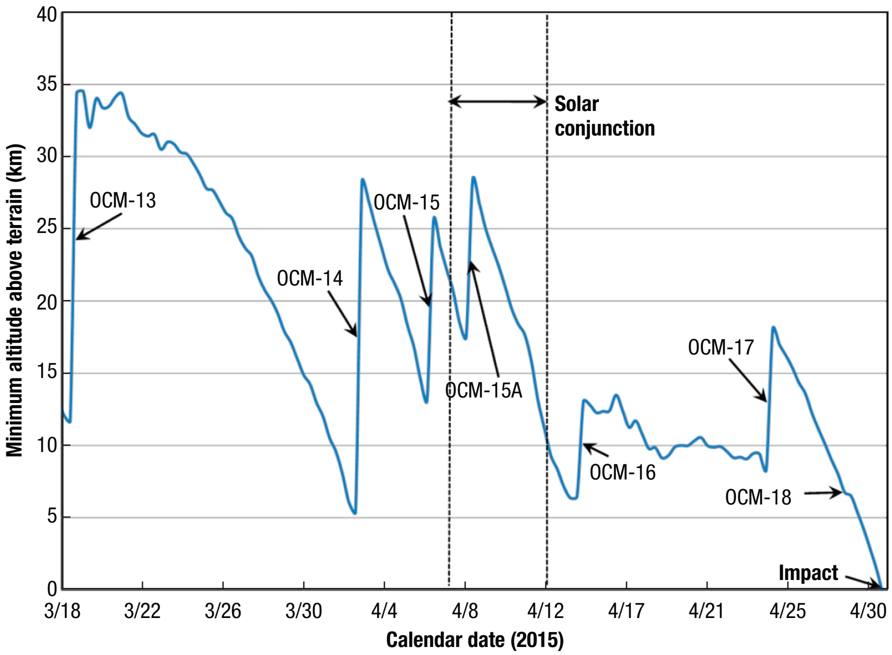

Figure 3. Minimum altitude relative to Mercury surface topography during XM2′.

throughout XM2′ is shown in Fig. 3. It is immediately obvious when comparing Figs. 2 and 3 that the flight execution of XM2′ added two maneuvers, OCM-15A and OCM-18, compared with the planned trajectory. The additional maneuvers were the result of responding to anomalies in the OCM-15 execution and trajectory prediction errors, respectively. With the exception of OCM-15, the control system maintained low maneuver execution errors despite variations in active thrusters, propellant source, propellant availability, and planning horizons.

OCM-15 failed to complete the targeted altitude change because this maneuver depleted the remaining accessible hydrazine propellant and transitioned to GHe use earlier than expected. The initial thrust at OCM-15 was similar to the thrust level seen at OCM-14, but ~150 s into the burn the thrust began to decline slowly as the pressure in the auxiliary tank decreased. Onboard fault protection opened main fuel tanks 1 and 2 at 215 s into the burn, as designed, when the pressure in the fuel manifold dropped to <50 psi. Approximately 11 s after the main tanks were opened, the propulsion system had established a steady-state gas flow, resulting in ~0.15 N of thrust per P thruster, just 8% of the nominal thrust using hydrazine. Helium gas produced insufficient thrust to complete the ΔV within the maximum allowed duration of 600 s, and the maneuver terminated upon timing out. Introduction of GHe into the auxiliary tank during OCM-10 and OCM-12 proved to have a longer-lasting impact than originally expected. Thruster performance data suggested that remaining GHe had been fully vacated from the auxiliary tank during the final segments of those two maneuvers as well as during OCM-13 and OCM-14, which saw >1.6 kg of hydrazine consumed from the auxiliary tank without any evident helium bubbles. Going into OCM-15, the possibility of hydrazine exhaustion was well known, and the expectation was that the cessation of propellant flow would be abrupt, with the line pressure dropping to the vapor pressure of hydrazine (~1 psi). Instead of a sudden decline, however, there was an unanticipated gradual decline in feed pressure. The observed slow decline in the auxiliary tank pressure suggests that the previously introduced GHe remained in the auxiliary tank as hydrazine froth or foam that was slowly expelled as the diaphragm lowered. This helium masquerading as hydrazine resulted in an ~0.7-kg overestimation of remaining hydrazine propellant in the auxiliary tank, as shown in Table 1.

The total periapsis altitude change achieved with OCM-15 was approximately half of that needed to survive the ensuing solar conjunction. If no further action had been taken after OCM-15, the spacecraft would have impacted the surface of Mercury before OCM-16, cutting the hover campaign short by more than 2 weeks. An emergency maneuver, OCM-15A, was designed, tested, loaded to the spacecraft, and executed in less than 48 h. For OCM-15A, all three fuel tanks were opened, and four C thrusters were used with helium gas to impart the remaining ΔV to put the spacecraft back on the desired trajectory. The observed thrust level during OCM-15A is shown in Fig. 4. After an initial burst of thrust from hydrazine that remained trapped in the propellant lines, the average total thrust through the burn was ~3 N, far less than the observed thrust level of 10 N seen in the helium test performed during OCM-12.[6] However, the test use of GHe during OCM-12 was recognized as being of limited utility because sustained cold gas flow was never fully established. Although the ΔV for OCM-15A through OCM-18 was delivered using GHe via the C thrusters, attitude-control thruster activity via the A and B thrusters was accomplished via residual hydrazine remaining in the thruster feed lines. The elevated attitude-control thrust level is shown in the bottom portion of Fig. 4; very short thruster pulses contributed to relatively large changes in the spacecraft angular rates, and these changes in vehicle rates were consistent with the historical performance of the atti-

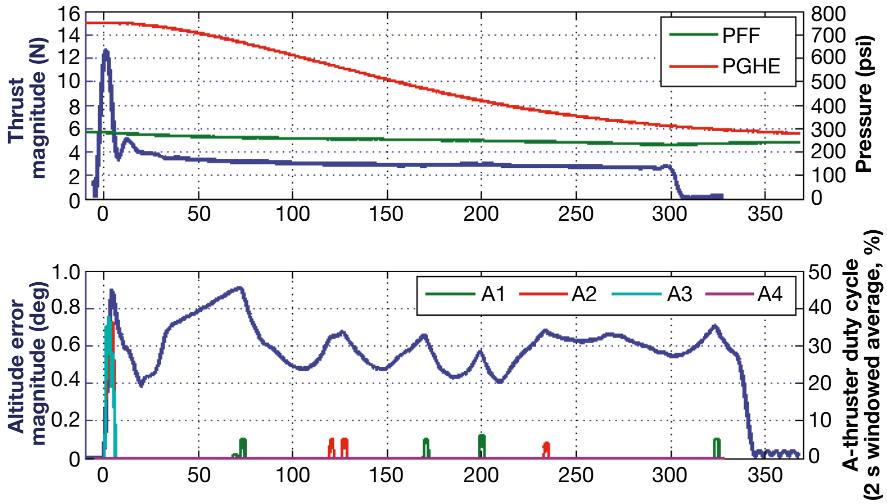

Figure 4. OCM-15A flight performance. Top, Thrust magnitude, propulsion system feed pressure (PFF), and gaseous helium pressure (PGHE). Bottom, Attitude control error magnitude and average A-thruster duty cycles.

tude-control system when using hydrazine. The elevated thrust for A and B thrusters measured at OCM-15A persisted throughout the remainder of the mission.

RISK MANAGEMENT

The hover campaign offered the team a unique opportunity to observe the planet Mercury from very low altitude. Operating MESSENGER so near to the surface carried elevated risk because of uncertainty in the navigation state of the spacecraft, poorly known gravity perturbations at the lowest altitudes, uncertainty in the maneuver performance, and a communication blackout through solar conjunction. These risks meant that the science objectives of the hover campaign might only be partially satisfied or might not be satisfied at all; however, the operations and science teams worked to mitigate risks to ensure that the hover campaign was a complete success. Aside from the value of the hover campaign science data to the international planetary community, it would have been unfortunate to end the highly successful MESSENGER mission with an untimely impact, thereby leaving an impression that despite 4 years of successful operations about Mercury the mission had not been fully successful.

It was widely recognized by the team that the cadence of operations throughout the hover campaign was going to exceed that experienced during the prior 4 years of orbital operations. It was not practical to increase staffing for such a short (~6 week) mission extension, so the team had to make simplifications to ensure that the trajectory was executed successfully and the spacecraft remained completely healthy until the planned impact time. Key simplifications were made that allowed the team to approach XM2′ with the same level of rigor as all prior mission phases despite the increased cadence of XM2′ critical events.

Before the hover campaign, each planned maneuver carried with it one backup opportunity in the schedule. These backup maneuvers were fully planned, tested, and loaded to the spacecraft in the event that the primary burn did not execute as planned. For the hover campaign, the team executed a tabletop planning exercise to decide how long it might take to scramble to correct a failed maneuver. On the basis of this exercise, the team was confident that any failed burn or partial burn could be corrected within 24 h. With this information, each hover campaign OCM was placed to allow a minimum of 24 h before impact (or loss of communication) should the planned OCM fail to execute. This margin gave the team confidence that any failed or partial maneuver could be corrected, and they did not plan any contingency maneuvers *a priori*. True to their assessment, the team demonstrated with both OCM-15A and OCM-18 the ability to plan, design, and load a contingency maneuver to the spacecraft in ~24 h. Elimination

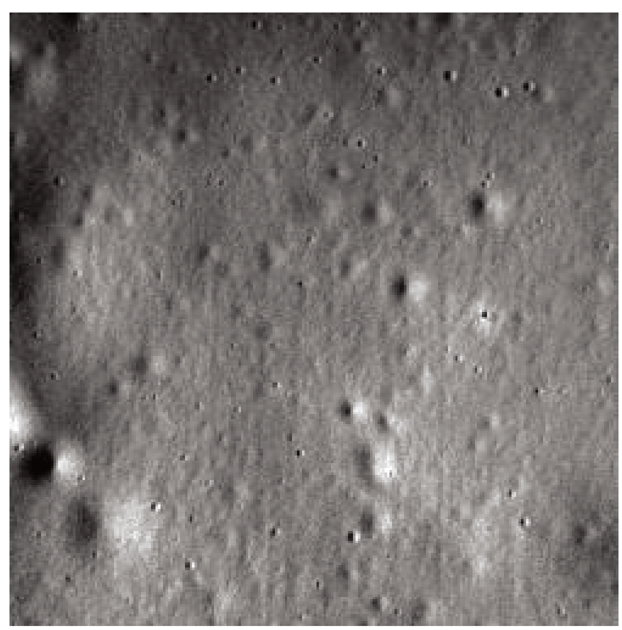

Figure 5. The final telemetered image of Mercury from MESSENGER was acquired ~25 min before impact. The scene in the image is located within the floor of the 93-km-diameter crater Jokai, is at a resolution of 2.1 m/pixel, and shows a region ~1 km across.

of the contingency planning helped reduce the team's workload, allowing the team to focus only on contingency plans that were actually needed.

Perhaps the biggest concern going into the hover campaign was the uncertain environment the spacecraft faced when passing over the planet at low altitude. To help mitigate the risk of operating at low altitude, the engineering team turned to the science team for help. With the assistance of the Mercury Laser Altimeter team, a procedure was established whereby ranging data from the spacecraft to Mercury's surface were made a part of the high-priority downlinked data, and those data were immediately processed by the altimetry team at Goddard Space Flight Center to estimate the sensed (terrain-relative) altitude. These estimates were compared with the orbit solution provided by the navigation team (derived from radiometric data) for consistency. This comparison provided confidence that the navigator's orbit solutions were correct and that predictions of the evolution of the periapsis altitude in the future would unfold as expected. In the end, the orbit predictions were always within ~1 km (over a 7-day prediction horizon) of the true periapsis altitude as seen in the altimetry data. This feedback helped with decision-making throughout the hover campaign and was instrumental in adding OCM-18 to achieve the proper impact time, thereby ensuring that all hover campaign science observations were safely downlinked to Earth.

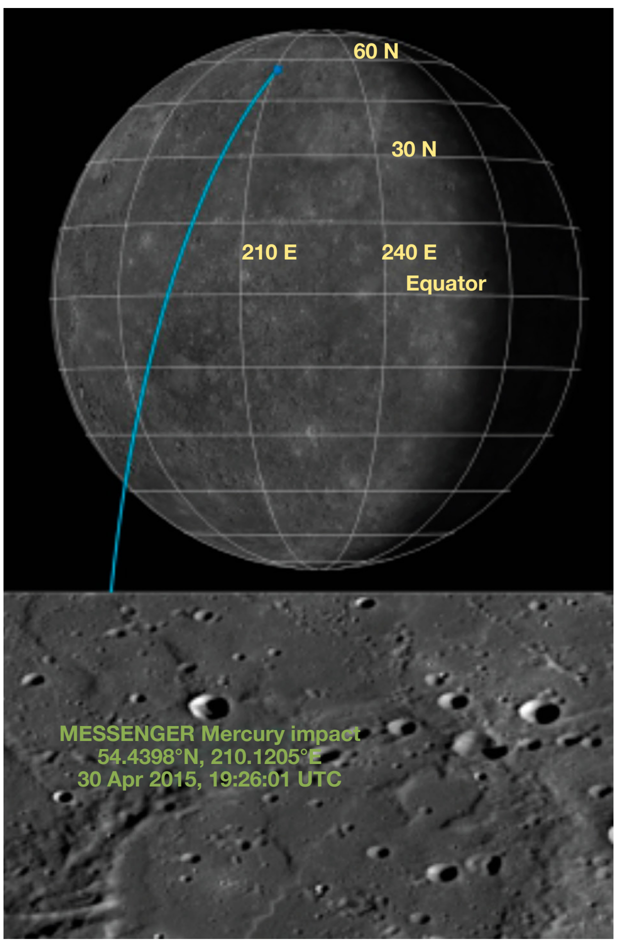

Figure 6. The spacecraft impacted onto a part of Mercury's surface that has a gradual incline with an approximate slope of 8.5°. Top, Spacecraft trajectory prior to impact. Bottom, The final estimate of the impact location is at 54.4398°N, 210.1205° E, 2438.790 km from the center of Mercury.

FINAL IMPACT

At 19:00 UTC on 30 April 2015, MESSENGER ended its final transmission of science data to Earth (Fig. 5). It turned its transmitter away from Earth so that its instruments could be pointed toward Mercury in the hopes that another orbit might be completed, although Mercury Laser Altimeter data from the prior periapsis pass indicated that another orbit was not expected. Four minutes later, the spacecraft passed behind the planet (as viewed from Earth) for a final time. Although not in view of Earth at the time of impact, on the basis of altimetry data from the prior periapsis pass and radiometric data up to the final occultation by Mercury, MESSENGER impacted the Mercury surface at 19:26:01 UTC. MESSENGER was finally unable to resist the perturbations to its orbit by the Sun's gravitational pull, and it slammed into Mercury's surface at 3.91 km/s (~8,750 miles per hour), creating a new crater estimated to be more than 15 m (50 ft) wide (Fig. 6).

CONCLUSION

The hover campaign ended with MESSENGER achieving a final engineering success, as it descended to surface impact on the planned orbit. This timing allowed for one last high-gain data transmission, providing a final orbital view of the innermost planet. Although the hover campaign marked the end of MESSENGER's flight mission, the data collected during these final 6 weeks rest safely on Earth for analysis. The success of the hover campaign and the flight mission as a whole was attributable to the tremendous creativity, dedication, and meticulousness of the hundreds of individuals who made up the MESSENGER team, as well as full NASA support and acceptance of the risk inherent in allowing this extraordinary campaign to yield exceptional science.

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Daniel O'Shaughnessy graduated from the University of Missouri with B.S. and M.S. degrees in mechanical and aerospace engineering. After graduation, he joined APL as a guidance and control engineer. He was involved with MESSENGER since joining APL in 2000, and he led the guidance and control team through cruise, Mercury orbit insertion, and the first year of orbit operations. Dan has also supported Near Earth Asteroid Rendezvous (NEAR), Solar TErrestrial RElations Observatory (STEREO), New Horizons, and Parker Solar Probe, in addition to working numerous research and flight projects in control systems, algorithm and software development, and autonomous on-orbit commissioning and calibration. During the final 2 years of the MESSENGER mission, he served as the Mission Systems Engineer, making him responsible for all technical aspects of the program. In 2014, Dan was awarded the inaugural Heinlein Award for Space Technology for his work supporting MESSENGER's inaugural flight demonstration of solar sailing. He is currently the Double Asteroid Redirect Test (DART) mission Guidance and Control Subsystem Lead Engineer. His e-mail address is daniel.oshaughnessy@jhuapl.edu.

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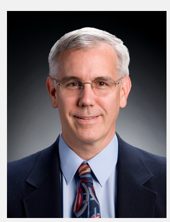

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James V. McAdams, now working for KinetX Aerospace, concluded his MESSENGER responsibilities as a member of the Principal Professional Staff in the Astrodynamics and Control Systems Group in APL's Space Exploration Sector. He led the MESSENGER mission design team throughout mission conceptual studies and all mission phases. His e-mail address is jim.mcadams@kinetx.com.