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# MESSENGER – SIX PRIMARY MANEUVERS, SIX PLANETARY FLYBYS, AND 6.6 YEARS TO MERCURY ORBIT

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On 18 March 2011, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft became the first probe to orbit Mercury. The spacecraft's 6.6-year journey to Mercury orbit included six large trajectory-correction maneuvers and six planetary flybys. These planetary gravity assists imparted the vast majority of velocity change required to transform the spacecraft trajectory from Earth orbit departure to Mercury arrival. This paper summarizes the design and performance of all planetary flybys and course-correction maneuvers through orbit insertion, as well as the results of targeting the planetary-flyby aim points using the acceleration on the spacecraft imparted by solar radiation pressure.

## INTRODUCTION

On 18 March 2011, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft became the first probe to orbit the planet Mercury. Designed and operated by The Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, MESSENGER is led by the Carnegie Institution of Washington with key flight and science operation contributions from KinetX, Inc., NASA's Jet Propulsion Laboratory (JPL) and Goddard Space Flight Center, and numerous universities, research institutions, and subcontractors. Supported by NASA's Discovery Program, the spacecraft successfully launched from Cape Canaveral, Florida, aboard a Delta II 7925H-9.5 launch vehicle on 3 August 2004. Seven years after launch, the spacecraft has completed one Earth flyby, two Venus flybys, three Mercury flybys, five deep-space maneuvers (DSMs), and Mercury orbit insertion (MOI). A comparison of final results with final design targets for MESSENGER's heliocentric trajectory-correction maneuvers (TCMs), Earth flyby, Venus flybys, Mercury flybys, and Mercury orbit insertion indicates a successful and adaptable mission that overcame early minor deficiencies. The dynamic aspect of mission design and navigation is apparent by examining post-launch updates to these mission-critical events. Trajectory profiles for each planetary flyby and MOI reveal trajectory adjustments imparted by the planetary gravity assists and orbit insertion maneuver.

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An overview of propulsive maneuver options and operational constraints provides context for understanding the baseline mission trajectory and maneuver plan. The primary operational constraint considered for each TCM is aligning the thrust direction with the spacecraft velocity change (ΔV) direction such that the spacecraft sunshade protects the temperature-sensitive spacecraft bus. Because propulsion system operational constraints limit the ΔV component near the spacecraft-Sun direction, careful consideration is required in order to choose the best propulsive option and spacecraft orientation for each TCM. Beginning with the first Mercury flyby, a solar sailing method was developed and refined to clean up TCM execution errors and direct the spacecraft toward the next Mercury encounter target. This solar sailing method used timed sequences of sunshade orientation and solar panel tilt to adjust the trajectory via solar radiation pressure (SRP) perturbations while also managing spacecraft momentum. Solar sailing helped refine MESSENGER's trajectory such that, after accounting for high-accuracy, large TCMs that would have led to statistical TCM cancellations, solar sail targeting eliminated the need for 8 to 10 TCMs during the final 3.25 years before MOI. Cancellation of TCMs reduced operational risk and saved a small amount of propellant.

Twenty-three MESSENGER TCMs (counting TCM components as distinct maneuvers) performed from launch through MOI have exercised every thruster group and nearly every propulsive option available. Performance assessment of these TCMs helped flight team members to modify procedures and software, thereby improving TCM performance. Improvements in trajectory optimization since launch have lowered ΔVs for several TCMs by up to 6 m/s. For instance, the orbit insertion final design was 862.2 m/s vs. the 868.1 m/s design just after launch. Other TCM ΔVs increased slightly during preparation of a robust contingency plan that would enable constraint-compliant completion of a delayed TCM. The performance of each TCM, including MOI, compares well with the TCM design goal and resulting planetary encounter target offset. Other propulsive events, such as spacecraft momentum adjustments, that are not intended to adjust the spacecraft trajectory also were conducted.

The MESSENGER mission has accomplished highly accurate targeting at each planetary flyby. Five of the six completed planetary flybys, excluding only the solar-conjunction-obscured first Venus flyby, achieved periapsis altitudes within 1.5 km of the target altitude. Trajectory profiles of each planetary flyby and Mercury orbit insertion indicate changes in the spacecraft trajectory at each Mercury encounter. Primary changes in spacecraft orbit, including equivalent ΔV imparted, the largest of which was 6.94 km/s for the second Venus flyby, are documented for each planetary gravity-assist flyby.

## SPACECRAFT OPERATIONAL CONSTRAINTS

Although science objectives[1] play a major role in determining the desired spacecraft orbit and spacecraft attitude at Mercury, spacecraft safety and operational limitations are key for planning TCMs before MOI. During MESSENGER's early design phase the spacecraft orbit location and TCM thrust attitude relative to Earth, Mercury, and the Sun affected design and operational limitations of certain spacecraft subsystem components. Figure 1 sets the context for spacecraft operational constraints by depicting the location and orientation of major spacecraft components, and by showing spacecraft body axes. Components of the spacecraft having the largest surface area include the sunshade and two rotatable solar panels. Early in the cruise phase, for TCMs more than 0.85 AU from the Sun, the sunshade was pointed away from the Sun so that sunlight could help warm fuel tanks and lessen the demand for power from the solar panels. For TCMs closer than 0.85 AU from the Sun, when solar power is plentiful, the sunshade pointed to the Sun.

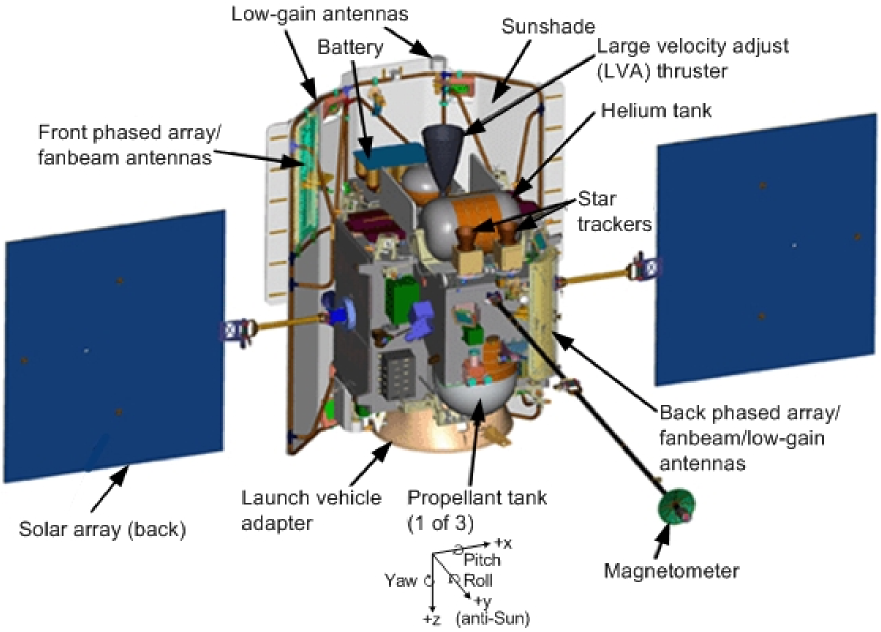
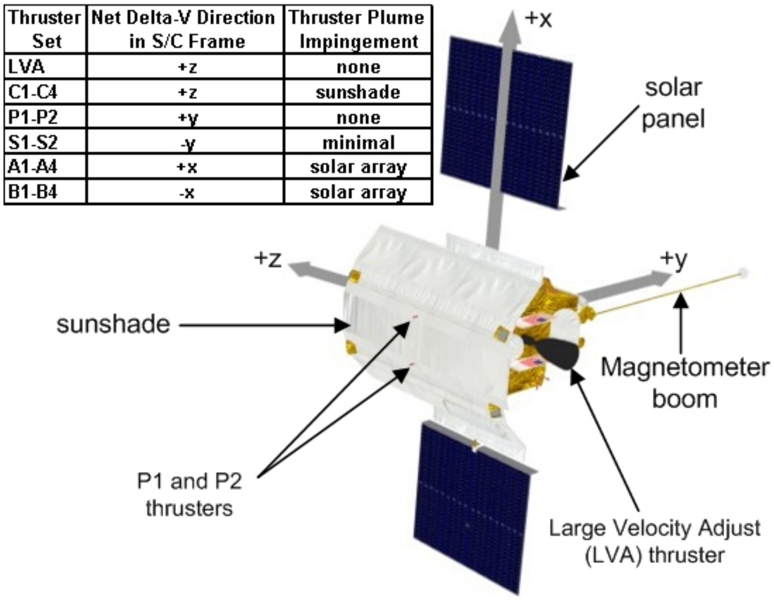


**Figure 1. Deployed configuration of the MESSENGER spacecraft.**

With the spacecraft as much as 70% closer to the Sun than Earth's average Sun distance during heliocentric cruise and Mercury orbit, the spacecraft's thermal subsystem had the greatest effect on TCM design. The increase in the Sun's radiation on the spacecraft between Earth and Mercury is 11.1 times at Mercury perihelion. The shape and orientation of the 200-km by 12-hour orbit at Mercury, along with argument of periapsis between 90º and 180º, are conducive to orbit stability (periapsis altitude increases and orbit period varies little) and thermal manageability. Results of design-phase thermal analysis helped produce the spacecraft orbit constraint on right ascension of the ascending node, i.e., throughout the orbital phase the right ascension of the ascending node must lie between 169º and 354º. This constraint effectively places the spacecraft orbit periapsis near the day/night terminator or on Mercury's night side when Mercury is closest to the Sun. These constraints help determine the number of Mercury flybys prior to MOI, as well as orbit targets used with MOI.

Another thermal requirement on spacecraft orientation relative to the Sun direction ensures that the sunshade protects the spacecraft bus from direct sunlight exposure during propulsive maneuvers closer than 0.85 AU from the Sun. All deterministic (those with pre-launch knowledge of spacecraft attitude requirements) ΔVs use either the large velocity adjust (LVA) bipropellant thruster and/or two to four of the "C" thrusters mounted on the same deck as the LVA thruster. Figure 2 clearly shows a ~90º orientation offset between the LVA thruster and the –y direction toward the Sun. Spacecraft rotations in yaw of ±15º and +13.5º to –12.4º in pitch define the operational zone where direct sunlight never reaches any part of the spacecraft protected by the sunshade. A greater margin of safety during TCMs limits these rotation angles to ±12º (a Sun-spacecraft-ΔV or "Sun elevation" angle between 78º and 102º including variance during any TCM that uses the C thrusters as the primary thrusters). After the first DSM in December 2005, spacecraft operators determined that the LVA thruster alignment was 0.69º off the –z-axis. This difference in alignment required an adjusted definition of the Sun elevation angle equal to Sun-spacecraft-ΔV + 0.69º for LVA thruster bipropellant TCMs. An operational Sun keep-in (SKI) constraint, defined by a maximum Sun elevation angle < 12.0º during any part of a TCM led to a conservative guideline not to exceed a Sun elevation angle of 9.5º for a nominal TCM design.



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

**Figure 2. MESSENGER spacecraft (S/C) drawing with body-frame axes and thruster sets.**

Another thermal requirement affecting spacecraft orbit prediction is the tilt of the solar arrays with respect to the Sun direction. In order to accurately predict solar pressure perturbations on the spacecraft's orbit, the orientation of the sunshade and solar arrays must be accurately known relative to the spacecraft-Sun line. Mission design and navigation software uses predicted spacecraft attitude and solar array tilt, along with solar distance, to compute the net solar pressure force acting on the spacecraft. This procedure reduces the uncertainty in future spacecraft position and velocity. The thermal rationale for solar array rotation is to keep the solar array surface, populated with 30% solar cells and 70% optical surface reflectors, at or below 135ºC, a normal array temperature for Earth-orbiting spacecraft. Figure 3 shows a preliminary plan over the 200 days leading up to MOI for the off-Sun tilt angle of the +x-axis-directed and –x-axis-directed solar panels. A small offset in the tilt angle between each solar panel is used to lessen solar radiation pressure torques on the spacecraft, effectively helping onboard momentum wheels to effectively manage spacecraft angular momentum. Figure 3 shows an additional constraint of maintaining solar arrays oriented such that at least 600 W of power is available at any solar distance late in the cruise phase.

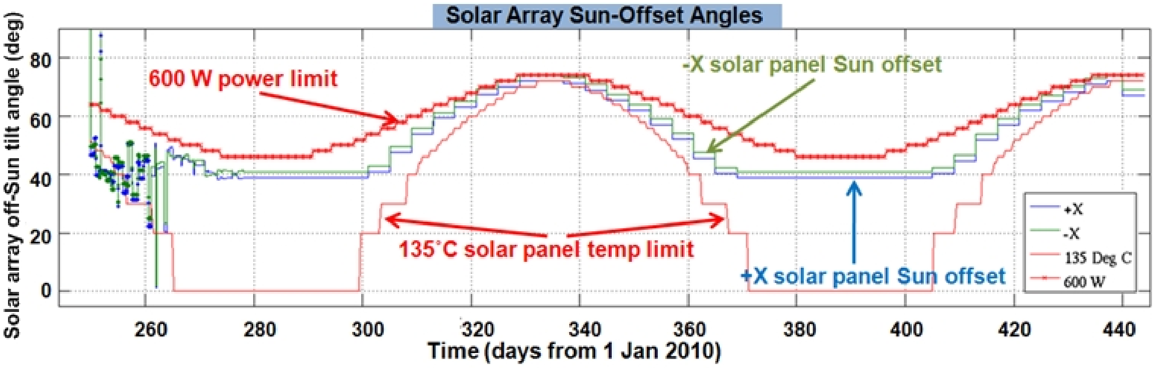


**Figure 3. MESSENGER solar array tilt angles (array normal vector to spacecraft-Sun direction).**

The number, location, orientation, and performance of the spacecraft's thrusters[2] affects maneuver design for each TCM performed en route to Mercury orbit insertion. The locations and orientation of the spacecraft's one 680-N LVA thruster, four 25-N thrusters, and 12 4.4-N thrusters are shown in Figure 4. The LVA thruster operates at 316-s specific impulse with thrust levels from 665 to 704 N (steady state of 679 to 684 N). The other thrusters operate at specific impulse typical of efficient hydrazine thrusters. Aerojet Corporation built the MESSENGER spacecraft's dual-mode propulsion system, which uses bipropellant (fuel and oxidizer) for TCMs with ΔV > about 10 m/s, and monopropellant (fuel) for smaller (and larger as needed) maneuvers. The spacecraft's five propulsion system tanks include two large fuel tanks, one large oxidizer tank, one small auxiliary fuel tank (small ΔVs), and a helium tank for main tank pressurization. Table 1 briefly describes each maneuver design option available at launch. In order to simplify Table 1, the ΔV component directions shown refer to TCMs performed when the sunshade is pointed toward the Sun. The spacecraft's sunshade has pointed toward the Sun (within SKI limits) continuously since 21 June 2006. All DSMs and the MOI maneuver utilized the bipropellant burn mode 3. Mode-3 TCMs have a fuel settling burn, an auxiliary tank refill burn, a main LVA burn, and a short trim burn with all four of 25-N thrusters to finish the ΔV more precisely than with the high-thrust LVA cutoff. The 4.4-N attitude control thrusters maintain ΔV direction during each TCM. Except during MOI, when fuel efficiency requires variable thrust direction, TCMs use a fixed inertial spacecraft attitude.

Another operational constraint affecting TCM design is the requirement for real-time visibility throughout each TCM. During heliocentric TCMs far from any planet, maneuver timing ensured that one or more Earth-based Deep Space Network (DSN) tracking antennas would view the MESSENGER spacecraft at more than 30º above the local horizon. Mission designers adjusted the MOI start time to coincide with the spacecraft being visible at more than 30º above the local horizon by two widely separated DSN antenna complexes. Periods when solar interference prevents or degrades reliable spacecraft communication, known as superior solar conjunction, occur when the Sun-Earth-spacecraft angle drops below 3º and approaches 2º and the spacecraft is on the opposite side of the Sun from Earth. All TCMs were planned to avoid these conditions associated with superior solar conjunction. In fact, DSM-2 was moved over 1.5 weeks earlier than its optimal time during solar conjunction. Finally, no TCM or science activity was planned during one of two cruise-phase or one Mercury orbital-phase lunar occultations – when Earth's moon passes between a DSN antenna and the spacecraft during communication with the spacecraft.

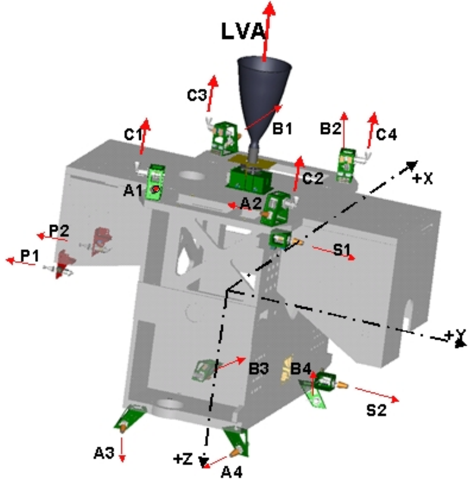


**Figure 4. Thruster locations and directions.**

Table 1. MESSENGER maneuver types available for heliocentric cruise.

| Propulsive mode(s) | Primary thruster set(s) | ΔV component direction(s) | Sun-S/C-ΔV angle range | Implementation notes |
|---|---|---|---|---|
| 1 | S1-S2 | sunward | <12° | DSM cleanup, flyby target/approach |
| 1 | P1-P2 | anti-Sun | >168° | DSM cleanup, flyby target/approach |
| 1 | A1-A4 or B1-B4 | lateral | 78°-102° | plume impingement varies with array tilt |
| 2 | C1-C4 | lateral | 78°-102° | 104-N total thrust for ΔV 3-20 m/s |
| 3 | LVA | lateral | 78°-102° | 672-N bi-prop thruster for ΔV > 20 m/s |
| 3/1 | LVA/S1-S2 | lateral/sunward | 12°-78° | ΔV cost too high unless near SKI limit |
| 3/1 | LVA/P1-P2 | lateral/anti-Sun | 102°-168° | ΔV cost too high unless near SKI limit |
| 2/1 | C1-C4/S1-S2 | lateral/sunward | 12°-78° | medium ΔV cost far from SKI limit |
| 2/1 | C1-C4/P1-P2 | lateral/anti-Sun | 102°-168° | medium ΔV cost far from SKI limit |
| 1/1 | S1-S2/A or B | sunward/lateral | 12°-78° | for DSM cleanup ΔV < 10 m/s |
| 1/1 | P1-P2/A or B | anti-sun/lateral | 102°-168° | for DSM cleanup ΔV < 10 m/s |

Trajectory selection is also affected by the spacecraft's power subsystem in that the battery must supply needed power during solar eclipse passage. Mass margin concerns early in the development phase limited the battery size such that the maximum time the spacecraft could be without power from the solar arrays is 65 minutes. The longest eclipse during cruise phase lasted 56 minutes just after the first Venus flyby, and a 62-minute eclipse in early June 2011 was the longest during the Mercury orbital phase.

## LAUNCH AND THE FIRST TWO YEARS OF OPERATION

The MESSENGER spacecraft launched on 3 August 2004, the fifth day of the third of three launch opportunities[3] in 2004. This launch option had a heliocentric trip time of about 1.5 years longer than the previous two options because of an additional Mercury flyby and subsequent DSM and two extra DSMs to adjust for non-optimal phasing in the Earth-Venus and Venus-Mercury transfers. Excluding the addition of the initial Earth flyby early in March 2000, Chen-wan Yen[4] first identified the MESSENGER heliocentric trajectory strategy that combines two to three Venus flybys with v-infinity leveraging[5] (repeat sequences of a Mercury flyby followed by near-aphelion DSM to lower orbit period and perihelion distance to lower the spacecraft's Mercury-velocity or v-infinity, $V_\infty$, at the next Mercury encounter). Despite having the lowest post-launch ΔV of all three launch opportunities in 2004, the heliocentric trajectory, shown in Figure 5, had features that increased mission risk. These elevated-risk features included the largest number (6) of large, deterministic maneuvers through MOI, the largest number of planetary flybys (6), a Venus flyby with minimum altitude near 3000 km during solar conjunction, and a long-duration solar conjunction between a DSM and six weeks before the first Mercury flyby. The final pre-launch MESSENGER trajectory for the 3 August 2004 launch date had minimum altitudes at planetary flybys close to the final results shown in Figure 5 – 2289 km at Earth, 3347 km at Venus flyby 1, 300 km at Venus flyby 2, and 200 km at all three Mercury flybys. This final pre-launch trajectory had 0.867 km/s for the MOI ΔV. A high-level comparison of the course-correction ΔV budget plan a few months after launch[1] with the results and plan a few months after MOI appears in Table 2. Changes in DSM ΔV resulted from DSM date shifts with contingency DSM planning and from offsets in planetary flyby target attained. The largest increase in deterministic ΔV came from shifting DSM-2 more than two weeks before its optimal date in order to provide more than an eight-day buffer to the start of the mission's longest superior solar conjunction. An overall reduction in ΔV capability resulted from changes in documented propulsion system performance, cruise-phase analysis of usable propellant, and other factors.

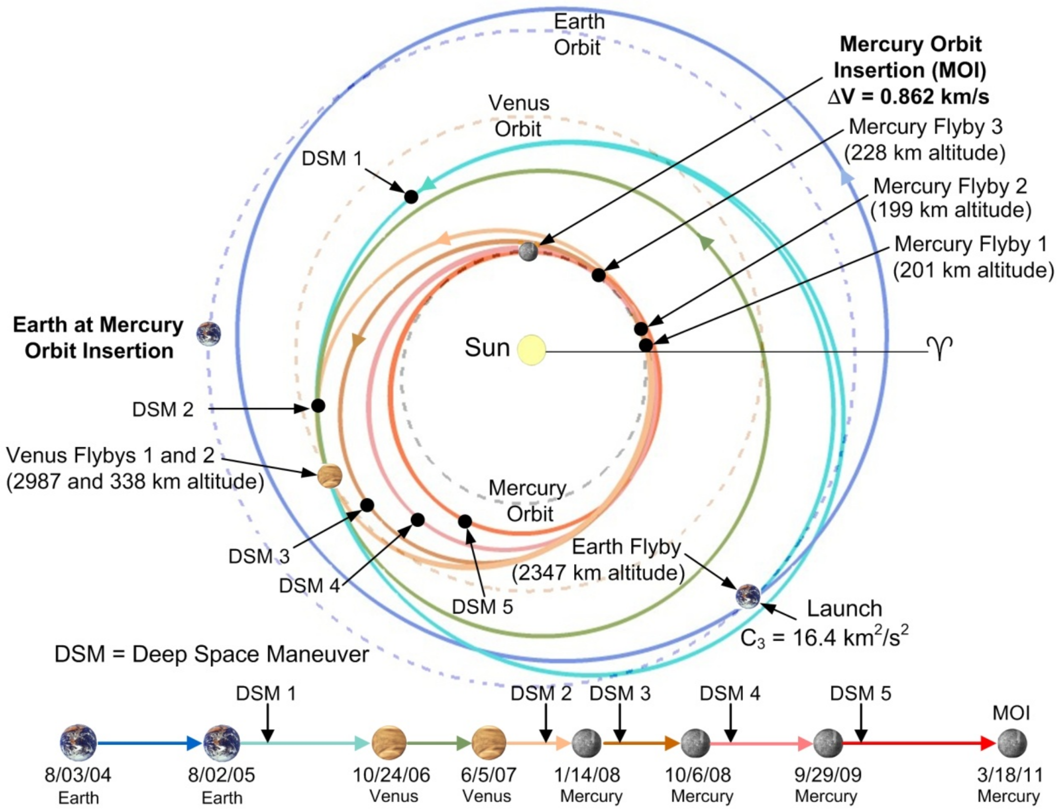


**Figure 5. North ecliptic pole view of the MESSENGER heliocentric transfer trajectory.**

**Table 2. ΔV allocation 4 months after launch and 4 months after Mercury orbit insertion.**

| **Maneuver Category** | **Launch + 4 months** | **MOI + 4 months** |
|---|---|---|
| | **ΔV (m/s)** | **ΔV (m/s)** |
| Deep space maneuvers | 1008 | 1023 |
| Launch vehicle, navigation errors (99%) | 121 | 85 |
| Mercury orbit insertion | 868 | 862 |
| Mercury orbit correction maneuvers, momentum adjust | 85 | 84 |
| Contingency | 169 | 144 |
| **Total** | 2251 | 2198 |

On August 3, 2004, at 06:15:56.5 UTC, MESSENGER launched aboard a Delta II 7925H launch vehicle from Cape Canaveral Air Force Station. The 1107.25-kg spacecraft departed Earth orbit with a 16.388 $km^2/s^2$ launch energy at a -32.66° declination of launch asymptote (DLA) relative to the Earth mean equator at the standard J2000 epoch. While the first hour after launch closely followed the planned trajectory, the larger-than-average 2.0-standard-deviation underburn produced a deviation from the targeted 16.513 $km^2/s^2$ launch energy. Shortly after Earth orbit departure the flight team began planning TCM-1, which would be the first TCM to target the Earth flyby one year after launch.

The first two years of orbital operations after launch, illustrated in Figure 6, included an Earth flyby, seven TCMs, and two commanded momentum dumps (CMDs). During this early portion of the cruise phase all three propulsive modes were utilized at least once. A brief summary of TCM performance and timing appears with information about the Earth flyby in Table 3. Even at this early point in the mission, mission planners verified from the maneuver-execution error-model prediction that mode 3 bipropellant maneuvers would be the most accurate type of maneuver. The 9% underburn during TCM-10 resulted upon reaching a thruster time cut-off limit with higher than expected B-thruster plume impingement on a solar panel. A final reconstruction of the Earth flyby trajectory (Figure 7) reveals the absence of an eclipse near the perigee location over Mongolia. The first tests to reduce spacecraft angular momentum occurred on 10 January 2006 and 15 May 2006 and had residual ΔVs of 0.020 and 0.036 m/s.

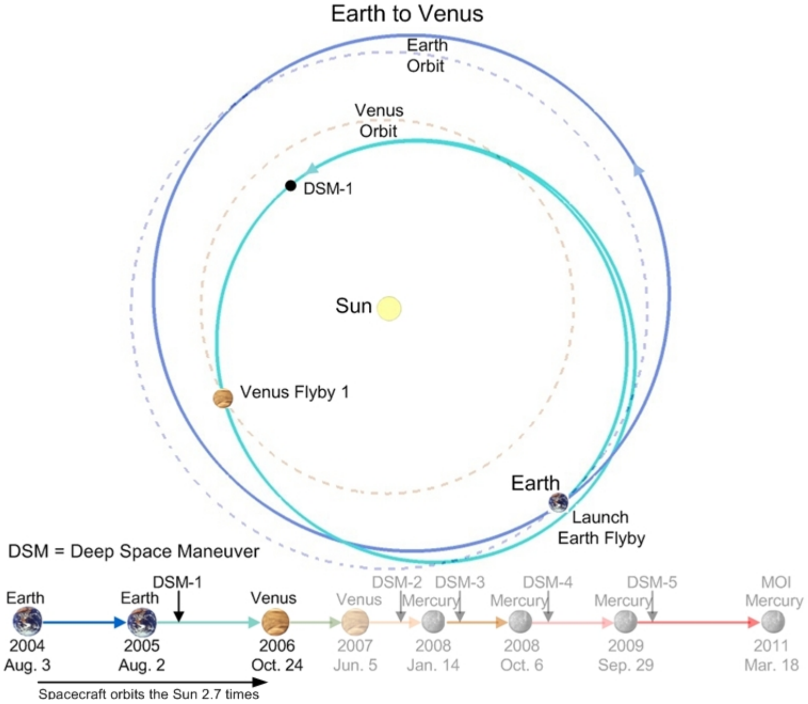


**Figure 6. North ecliptic pole view of MESSENGER's launch to Venus flyby 1 trajectory.**

**Table 3. TCM performance for the first two years of the MESSENGER mission.**

| TCM (DSM) | Date and initial thrust time (UTC) | Maneuver segment | Thruster set (mode) | Sun-S/C dist. (AU) | ΔV magnitude (m/s) | | | Sun-S/C-ΔV (°) | Pointing offset (°) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Design | Result | % Error | | |
| | | | | | | | | design | |
| 1 | 24 Aug 04-21:00:07 | - | C(2) | 1.040448 | 18.000 | 17.901 | -0.551 | 93.2 | 0.309 |
| 2 | 24 Sep 04-18:00:00 | - | C(2) | 1.066747 | 4.590 | 4.589 | -0.030 | 92.8 | 0.274 |
| 3 | 18 Nov 04-19:30:00 | - | C(2) | 1.071266 | 3.236 | 3.247 | 0.333 | 88.6 | 0.342 |
| 4 | 05 May 05-17:00:00 | cancelled | | | | | | | |
| 5 | 23 Jun 05-14:30:00 | - | S(1) | 0.962319 | 1.145 | 1.103 | -3.650 | 133.2 | 0.374 |
| 6 | 21 Jul 05-18:00:01 | - | P(1) | 0.998575 | 0.147 | 0.150 | 2.513 | 145.8 | 4.577 |
| 7 | 29 Jul 05-18:00:00 | cancelled | | | | | | | |
| Earth Flyby (2 Aug 2005 19:13:08 UTC at 2348 km altitude) | | | | | | | | | |
| 8 | 12 Aug 05-18:00:00 | cancelled | | | | | | | |
| 9 (1) | 12 Dec 05-11:30:00 | - | LVA(3) | 0.603974 | 315.720 | 315.633 | -0.027 | 86.9 | 0.026 |
| 10 | 22 Feb 06-16:00:00 | - | B(1) | 0.887902 | 1.407 | 1.281 | -8.977 | 90.0 | 2.556 |

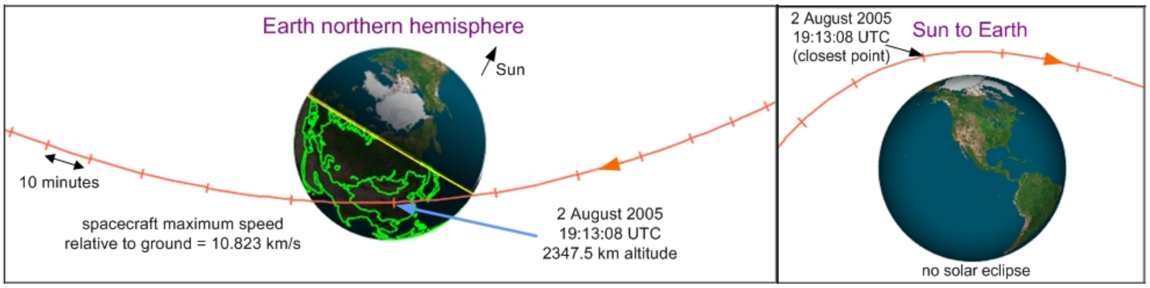


**Figure 7. Views of the Earth flyby trajectory from above northern Asia and from the Sun.**

## VENUS FLYBYS

After DSM-1 and its clean-up maneuver, TCM-10, two Venus flybys provided large trajectory changes as the journey to the spacecraft's first Mercury encounter continued. The heliocentric trajectory between the Venus flybys and leading to the first Mercury encounter, shown in Figure 8, reveals a 1:1 resonant transfer with the spacecraft encountering Venus at about the same point in the Venus orbit around the Sun one revolution apart. About one orbit after Venus flyby 2, DSM-2 (also called TCM-18) targeted Mercury flyby 1 three months later.

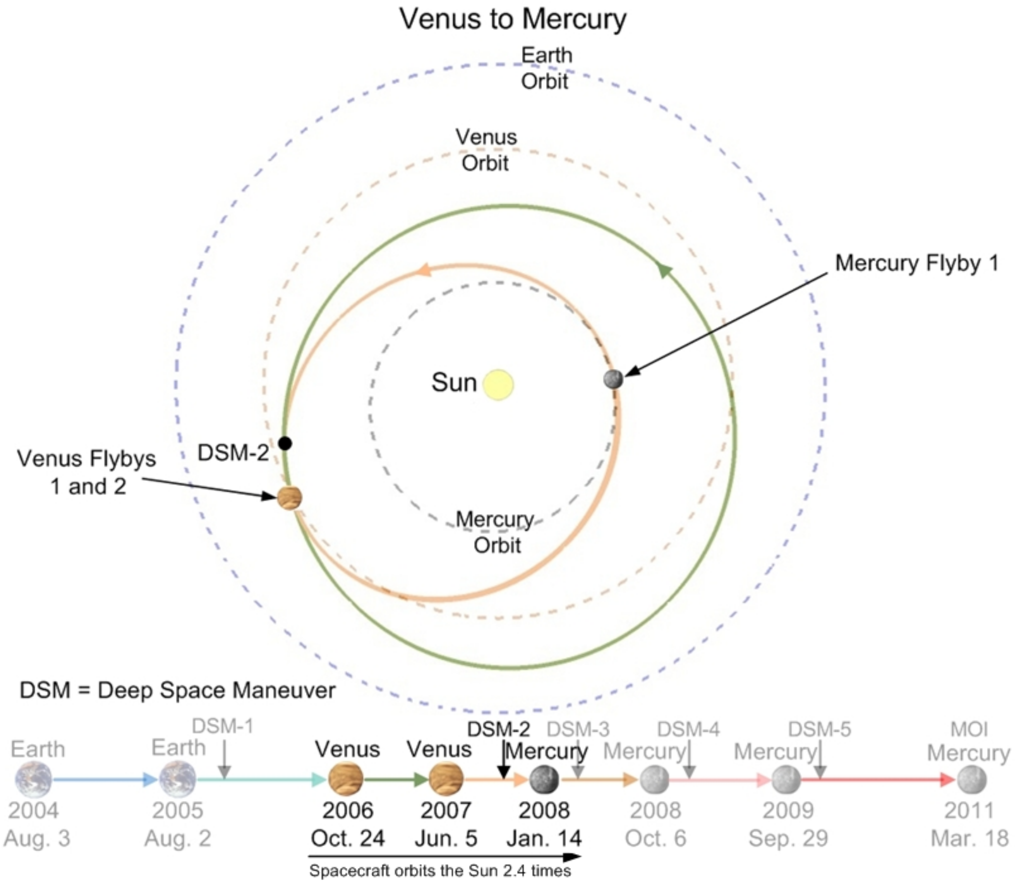


**Figure 8. North ecliptic pole view of MESSENGER's trajectory from Venus to Mercury.**

Planning for the 24 October 2006 Venus flyby 1 brought unique challenges to mission planners. With Venus closest approach during superior solar conjunction at a Sun-Earth-spacecraft angle of 1.37°, it was not known if transmissions from the spacecraft would be possible close to Venus. With no encounter science planned for Venus flyby 1, mission planners instead focused on planning for no TCMs when the Sun-Earth-spacecraft angle was less than 3°, a span from one week before until 18 days after Venus flyby 1. Multiple tests involving the spacecraft and ground-based simulations helped ease concern regarding the first eclipse, the cruise phase's longest at 56-minute duration, occurring at a time when commands could not be transmitted to the spacecraft. One factor that lessened risk with Venus flyby 1 during solar conjunction was a moderate periapsis altitude of about 3000 km.

The performance of the final two TCMs before Venus flyby 1 is shown in Table 4 with the periapsis final results for each Venus flyby and all remaining TCMs before Mercury flyby 1. With a ΔV direction about 159° from the spacecraft-Sun direction, TCM-11 was the first mode-2/mode-1 component maneuver. After TCM-12 final design the incorporation of delta differential one-way ranging (ΔDOR) data into the orbit solution by the navigation team led to a substantial reduction in the predicted upcoming Venus flyby altitude and a corresponding 40 m/s ΔV correction cost after the Venus flyby. On 3 October 2006 the mission design team designed a 0.74 m/s contingency TCM-12C2 maneuver for implementation on 12 October. Although this contingency TCM would have saved almost 40 m/s of statistical ΔV, the short cycle for TCM-12C2 implementation, testing, and uploading to the spacecraft was deemed too risky to attempt.

**Table 4. Trajectory correction maneuver performance near the Venus flybys.**

| TCM (DSM) | Date and initial thrust time (UTC) | Maneuver segment | Thruster set (mode) | Sun-S/C dist. (AU) | ΔV magnitude (m/s) | | | Sun-S/C-ΔV (°) design | Pointing offset (°) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Design | Result | % Error | | |
| 11 | 12 Sep 06-23:00:00 | A | C(2) | 0.605094 | 0.830 | 0.835 | 0.599 | 81.0 | 0.638 |
| | 12 Sep 06-23:10:00 | B | S(1) | 0.605087 | 1.460 | 1.444 | -1.040 | 81.0 | 11.105 |
| 12 | 05 Oct 06-22:30:00 | - | B(1) | 0.637723 | 0.497 | 0.501 | 0.963 | 90.0 | 1.840 |
| Venus Flyby 1 (24 Oct 2006 08:34:00 UTC at 2987 km altitude) | | | | | | | | | |
| 13 | 02 Dec 06-21:00:00 | A | P(1) | 0.870826 | 8.131 | 7.591 | -6.638 | 99.0 | 1.151 |
| | 02 Dec 06-22:00:00 | B | LVA(3) | 0.870919 | 19.810 | 20.251 | 2.223 | 99.0 | 1.723 |
| | 03 Dec 06-03:00:00 | C | P(1) | 0.871385 | 8.131 | 7.867 | -3.243 | 99.0 | 2.280 |
| 14 | 24 Jan 07-22:30:00 | cancelled | | | | | | | |
| 15 | 25 Apr 07-17:30:00 | - | B(1) | 0.550991 | 0.767 | 0.572 | -25.357 | 90.0 | 0.322 |
| 16 | 25 May 07-16:00:00 | - | B(1) | 0.664989 | 0.212 | 0.213 | 0.236 | 90.0 | 2.015 |
| Venus Flyby 2 (5 Jun 2007 23:08:19 UTC at 338 km altitude) | | | | | | | | | |
| 17 | 15 Jun 07-20:00:00 | cancelled | | | | | | | |
| 18 (2) | 17 Oct 07-22:00:00 | A | LVA(3) | 0.679218 | 226.017 | 225.992 | -0.011 | 96.9 | 0.221 |
| | 17 Oct 07-22:30:00 | B | B(1) | 0.679328 | 1.421 | 1.421 | -0.042 | 90.0 | 2.642 |
| 19 | 19 Dec 07-22:00:00 | - | B(1) | 0.589260 | 1.104 | 1.104 | -0.056 | 90.0 | 0.215 |

About two weeks after the end of the solar conjunction TCM-13 accomplished most of the correction needed to place the spacecraft back on course to encounter Venus a second time. The mission's only mode-1/mode-3/mode-1 component maneuver, TCM-13 consumed about 50% of the total auxiliary fuel tank fuel capacity during each of the mode-1 monopropellant components. These maneuvers, 33 and 31 minutes in duration, revealed valuable information regarding the reliability of one of the four onboard accelerometers. This new understanding helped enhance the accuracy of some future TCMs. Investigation of the 25% underburn of TCM-15 revealed omission of a key acceleration term. A resulting procedural change by the guidance and control

(G&C) team led to improved maneuver performance at TCM-16 and TCM-19. At 0.551 AU from the Sun, TCM-15 was the closest to the Sun of any TCM until MOI in March 2011. The Venus flyby 2 B-plane aim point was biased off the minimum ΔV solution in order to ensure sunshade protection of the spacecraft via SKI compliance for the upcoming 17 October 2007 DSM-2 (TCM-18). As mentioned earlier, the approach of a long 47-day solar conjunction between DSM-2 and Mercury flyby 1 led to a decision to increase total mission ΔV by about 19.5 m/s as an 8.3-day buffer was set between DSM-2 and the start of solar conjunction. In addition to targeting Mercury flyby 1, DSM-2 was designed as a mode-3/mode-1 component maneuver in order to complete two goals with the small mode-1 component. The mode-1 component would shift the propellant location in the tanks to enable passive angular momentum management (by planned changes in spacecraft attitude without thruster activity). A second goal was to characterize thruster plume impingement using a 72° off-Sun solar array tilt angle, similar to that needed for mode-1 maneuvers either just before Mercury flybys or during Mercury orbital phase near Mercury perihelion. The final mode-1 maneuver of the cruise phase, TCM-19, occurred one week after solar conjunction exit and successfully targeted Mercury flyby 1.

Views of each Venus flyby trajectory (Figure 9) indicate that the spacecraft approached Venus from the direction of the Sun. The near pole-to-pole nature of the first Venus flyby is consistent with a large change in heliocentric orbit inclination. Eclipse entry and exit labels have two times to mark the extent of the penumbra, when the cloud-enveloped Venus obscures only a portion of the solar disk. The second Venus flyby marked a key halfway milestone with the completion of three of the six planned planetary gravity-assist flybys.

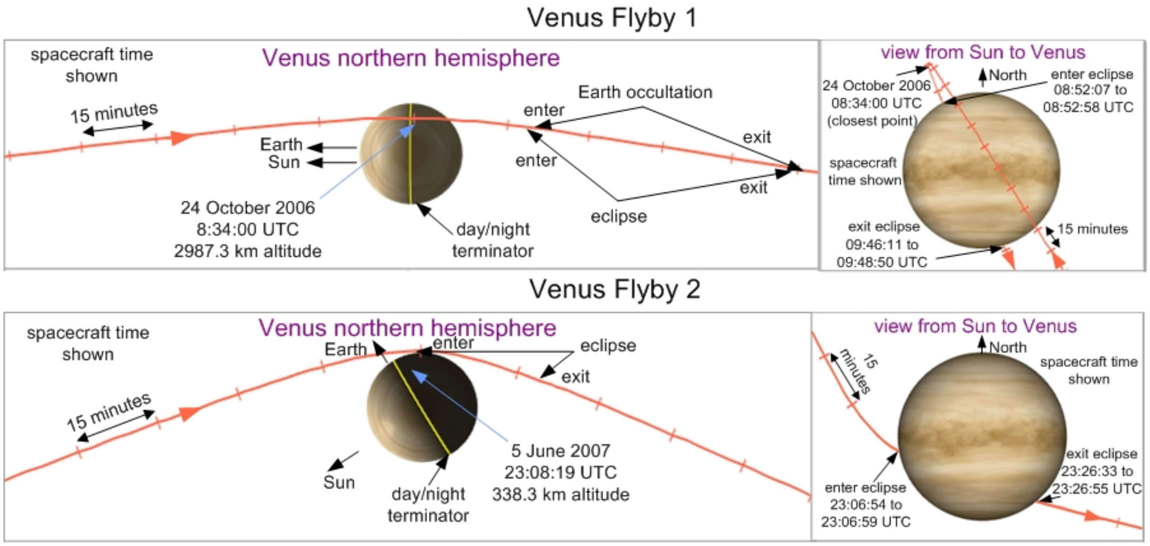


**Figure 9. Views of each Venus flyby trajectory from above Venus' north pole and the Sun.**

The effect of each of the mission's six planetary gravity-assist flybys may be measured in several ways. The equivalent ΔV imparted to the spacecraft trajectory during each planetary gravity assist[6] is the following:

$$\Delta V = 2V_\infty /(1 + r_p V_\infty{}^2 / \mu_p) \tag{1}$$

where $V_\infty$ is approach hyperbolic excess velocity, $r_\mathrm{p}$ is periapsis distance from the planet's center, and $\mu_p$ is the planet's effective gravitational parameter. Unlike missions that utilize planetary gravity assists to reach the outer planets, each of MESSENGER's gravity-assist flybys decelerates the spacecraft relative to its motion around the Sun. This immediate effect at the point where the gravity assist occurs should not be confused with the overall effect of the gravity assists, which increase the spacecraft's Sun-relative speed by nearly 60% (average orbital speeds relative to the Sun are 29.8 km/s for Earth and 47.9 km/s for Mercury). Table 5 shows how each major trajectory adjustment (primarily the planetary gravity-assist flybys) contributed toward the goal of reducing the spacecraft's velocity relative to Mercury at orbit insertion. The table lists orbital parameters that most affect the velocity difference that the spacecraft's propulsion system must correct in order to enter into orbit around Mercury. By minimizing the difference in these parameters between the spacecraft's orbit and Mercury's orbit, the velocity change required for the spacecraft at orbit insertion is reduced. Equivalent $\Delta V$ comes from equation (1) for each planetary flyby and from the actual spacecraft velocity change for each DSM and for MOI. Longitude of perihelion is measured as positive counterclockwise from the Sun-Earth direction at the autumnal equinox to the Sun-spacecraft direction at perihelion. The values in Table 5 apply to the spacecraft orbit after completion of the listed event.

**Table 5. Orbit changes resulting from MESSENGER's planetary flybys and DSMs.**

| Event | Equivalent $\Delta V$ (km/s) | Longitude of perihelion (LP) | LP to goal | Orbit inclination (OI) | OI to goal | Perihelion distance (PD) | PD to goal | Aphelion distance (AD) | AD to goal |
|---|---|---|---|---|---|---|---|---|---|
| Launch | - | 205° | **128°** | 6.3° | **0.7°** | 0.923 AU | **0.615** | 1.077 AU | **0.610** |
| Earth Flyby | 5.9963 | 132° | **55°** | 2.5° | **4.5°** | 0.603 AU | **0.295** | 1.015 AU | **0.548** |
| DSM-1 | 0.3156 | - | **-** | - | **-** | - | **-** | 1.054 AU | **0.587** |
| Venus Flyby 1 | 5.5225 | 104° | **27°** | 8.2° | **1.2°** | 0.547 AU | **0.239** | 0.900 AU | **0.433** |
| Venus Flyby 2 | 6.9378 | 47° | **30°** | 6.8° | **0.2°** | 0.332 AU | **0.024** | 0.745 AU | **0.278** |
| DSM-2 | 0.2274 | - | **-** | - | **-** | 0.325 AU | **0.017** | - | **-** |
| Mercury Flyby 1 | 2.3040 | 56° | **21°** | 6.9° | **0.1°** | 0.313 AU | **0.005** | 0.700 AU | **0.233** |
| DSM-3 | 0.0722 | - | **-** | - | **-** | 0.315 AU | **0.007** | - | **-** |
| Mercury Flyby 2 | 2.4526 | 68° | **9°** | 7.0° | **0.0°** | 0.302 AU | **0.006** | 0.630 AU | **0.163** |
| DSM-4 | 0.2467 | - | **-** | - | **-** | 0.310 AU | **0.002** | - | **-** |
| Mercury Flyby 3 | 2.8361 | 81° | **4°** | 7.0° | **0.0°** | 0.303 AU | **0.005** | 0.567 AU | **0.100** |
| DSM-5 | 0.1778 | - | **-** | - | **-** | 0.308 AU | **0.000** | - | **-** |
| **Mercury orbit (goal)** | **0.8617 (MOI)** | **77°** | **-** | **7.0°** | **-** | **0.308 AU** | **-** | **0.467 AU** | **-** |

## MERCURY FLYBYS

After DSM-2 and its clean-up maneuver, TCM-19, three Mercury flyby-DSM sequences imparted large trajectory changes as the spacecraft's orbit continued to draw closer in size and orientation to the orbit of Mercury. The larger the $\Delta V$ imparted to the spacecraft during the DSM, the closer the distance from the Sun the next time the spacecraft encountered Mercury. The Mercury gravity-assist flybys and subsequent course-correction maneuvers produced successive spacecraft:Mercury orbital resonance of about 2:3, 3:4, and 5:6 (i.e., the spacecraft orbited the Sun five times while Mercury orbited the Sun six times). Note from Table 5 that the third Mercury flyby rotated the orbit's longitude of perihelion to 81° (past the 77° value for Mercury's orbit). While this excess rotation seems non-optimal, this extra orbit rotation is required to achieve the aforementioned 5:6 spacecraft:Mercury orbital resonance. Without this resonance, Mercury would not be there when the spacecraft approaches perihelion for MOI. The heliocentric trajectory between the Mercury flybys and leading to Mercury orbit insertion, shown in Figure 10, shows the near-aphelion placement of each DSM followed by a progression of the subsequent Mercury encounter closer to the Sun than the previous Mercury encounter.

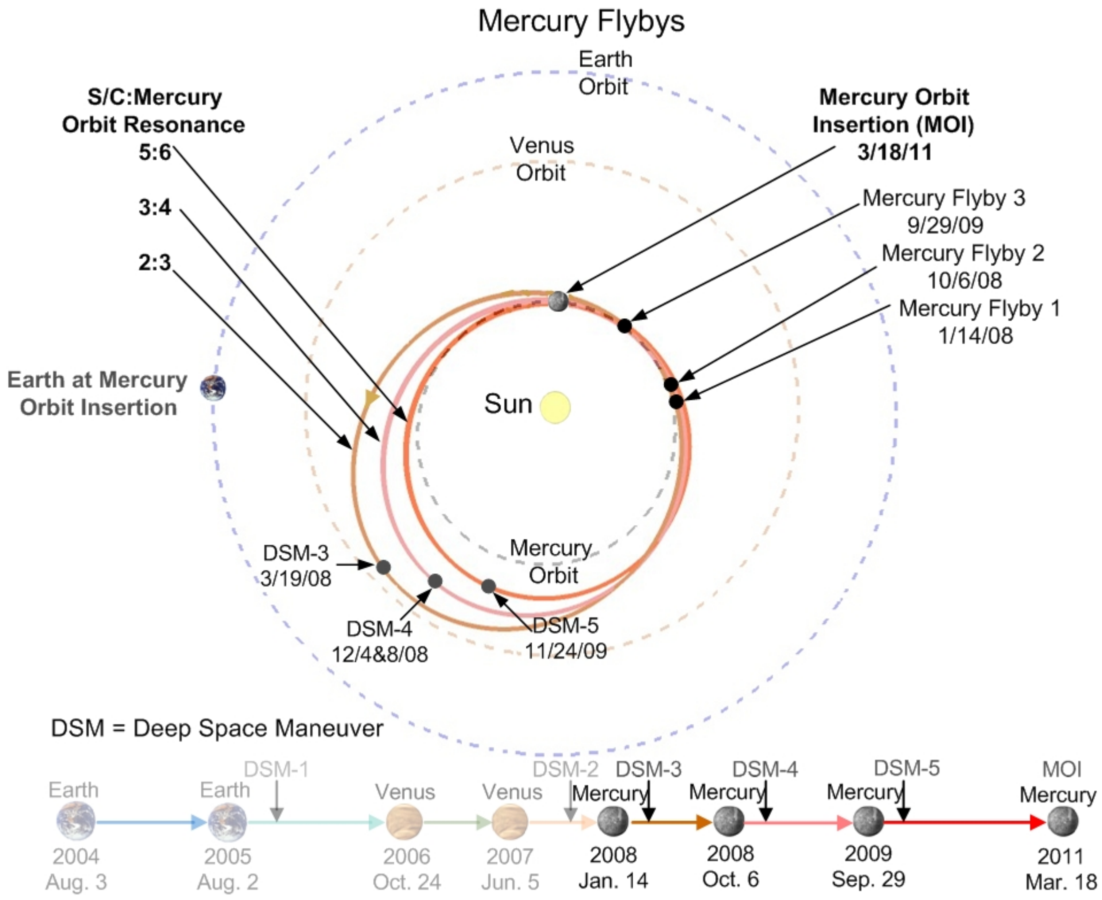


**Figure 10. North ecliptic pole view of MESSENGER's trajectory from Mercury flyby 1 to MOI.**

Upon final approach to the first Mercury flyby, the flight team had to decide between one of three options for refining the Mercury encounter aim point. Orbit determination following TCM-19 indicated that following the option to take no corrective action before Mercury flyby 1 would result in about a 5 m/s total corrective ΔV increase after the flyby. Another option involved implementing the smallest TCM since launch four days before the flyby, where the encounter science sequence would be minimally affected. Experience with higher relative errors for small TCMs plus the risk of adding a complex operation prior to a well-tested, high-profile initial Mercury flyby made this option undesirable. The G&C lead engineer provided analysis that supported a plan to change the solar panel orientation for a sufficiently long period to remove most of the aim-point offset. This strategy to utilize small changes in solar radiation pressure trajectory perturbations marked the beginning of the solar sailing[7,8] method of refining planetary encounter targeting. The solar sailing methodology combined a carefully planned sequence of sunshade rotation and tilt, along with changes in solar panel tilt to effect a gradual low-thrust trajectory correction.

A summary of DSM performance and Mercury flyby targeting accuracy testifies to the success of precision maneuver implementation and solar sail maneuver clean-up for MESSENGER. Table 6 shows the design goal and final results for each DSM, along with the preceding Mercury flyby closest approach altitude and time. DSM-3 provided a low-risk option to test the vital variable-thrust direction method that would be required for Mercury orbit insertion three years later.

Having the lowest ΔV of all five DSMs, DSM-3 was located long enough before MOI to allow time for software changes, reviews, and uploading to the spacecraft with a re-test opportunity using DSM-5 in November 2009. After a successful DSM-3 variable-thrust-direction test at the same turn rate as planned for MOI, refinements in the solar sail maneuver clean-up strategy were developed and implemented for targeting Mercury flyby 2. With all TCMs between DSM-3 and Mercury flyby 2 cancelled, the focus after Mercury flyby 2 became planning and implementing DSM-4 about one-half orbit later. DSM-4 was split 90%/10%, with the second part serving as an open-loop test (timed thrust cut-off as would be used if accelerometer data were not available) of the MOI variable-thrust direction. Continuation of the solar sailing after DSM-4 successfully targeted Mercury flyby 3 without need for additional TCMs. After highly accurate targeting at Mercury flyby 3, adjustments to DSM-5 became the final opportunity to make major changes in the pre-MOI Mercury arrival trajectory. Table 7 provides direct evidence of improvement in targeting accuracy (given the long time and vast distances between the final pre-flyby TCM and the planetary flyby) after implementation of solar sailing for TCM clean-up. Figure 11 includes trajectory profiles for all three Mercury flybys with final results for periapsis times and altitudes.

**Table 6. Trajectory correction maneuver performance near MESSENGER's Mercury flybys.**

| TCM (DSM) | Date and initial thrust time (UTC) | Maneuver segment | Thruster set (mode) | Sun-S/C dist. (AU) | ΔV magnitude (m/s) | | | Sun-S/C-ΔV (°) | Pointing offset (°) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Design | Result | % Error | | |
| | | | | | | | | | |
| Mercury Flyby 1 (14 Jan 2008 19:04:39 UTC at 201.4 km altitude) | | | | | | | | | |
| 23 (3) | 19 Mar 08-19:30:00 | - | LVA(3) | 0.689589 | 72.231 | 72.226 | -0.007 | 81.7 | 0.046 |
| 24-27 | | cancelled | | | | | | | |
| Mercury Flyby 2 (6 Oct 2008 08:40:22 UTC at 199.2 km altitude) | | | | | | | | | |
| 28 | | cancelled | | | | | | | |
| 29 (4) | 04 Dec 08-20:30:00 | A | LVA(3) | 0.622602 | 222.148 | 222.069 | -0.035 | 87.2 | 0.014 |
| | 08 Dec 08-20:30:00 | B | LVA(3) | 0.628536 | 24.738 | 24.650 | -0.354 | 90.0 | 0.101 |
| 30-33 | | cancelled | | | | | | | |
| Mercury Flyby 3 (29 Sep 2009 21:54:56 UTC at 227.5 km altitude) | | | | | | | | | |
| 34 | | cancelled | | | | | | | |
| 35 (5) | 24 Nov 09-21:45:00 | - | LVA(3) | 0.566966 | 177.749 | 177.781 | 0.018 | 87.5 | 0.055 |
| 36-42 | | cancelled | | | | | | | |

**Table 7. Planetary encounter results illustrate improvement from solar sailing.**

| Flyby | Last TCM to flyby (days) | Last TCM to flyby dist. (AU) | Approach maneuver cost (m/s) | Departure Maneuver cost (m/s) | Total ΔV penalty (m/s) | B-plane target miss (km) | Periapse altitude offset (km) |
|---|---|---|---|---|---|---|---|
| Earth | 12.05 | 0.204 | 1.3 | 0.0 | 1.7 | 22.1 | +1.0 |
| Venus 1 | 18.42 | 0.419 | 2.8 | 35.7 | 40.0 | 36.0 | -52.8 |
| Venus 2 | 11.29 | 0.237 | 0.8 | 0.0 | 1.0 | 5.7 | +1.4 |
| **Transition to solar sailing for gradual trajectory correction** | | | | | | | |
| Mercury 1 | 25.88 | 0.695 | 0.9 | 0 | 2.4 | 10.4 | +1.4 |
| Mercury 2 | 200.55 | 4.511 | 0 | 0 | -0.7 | 2.6 | -0.8 |
| Mercury 3 | 295.06 | 7.131 | 0 | 0 | -0.5 | 3.5 | -0.5 |
| MOI Approach | 478.12 | 12.123 | 0 | n/a | n/a | 8.0 | +6.0 |

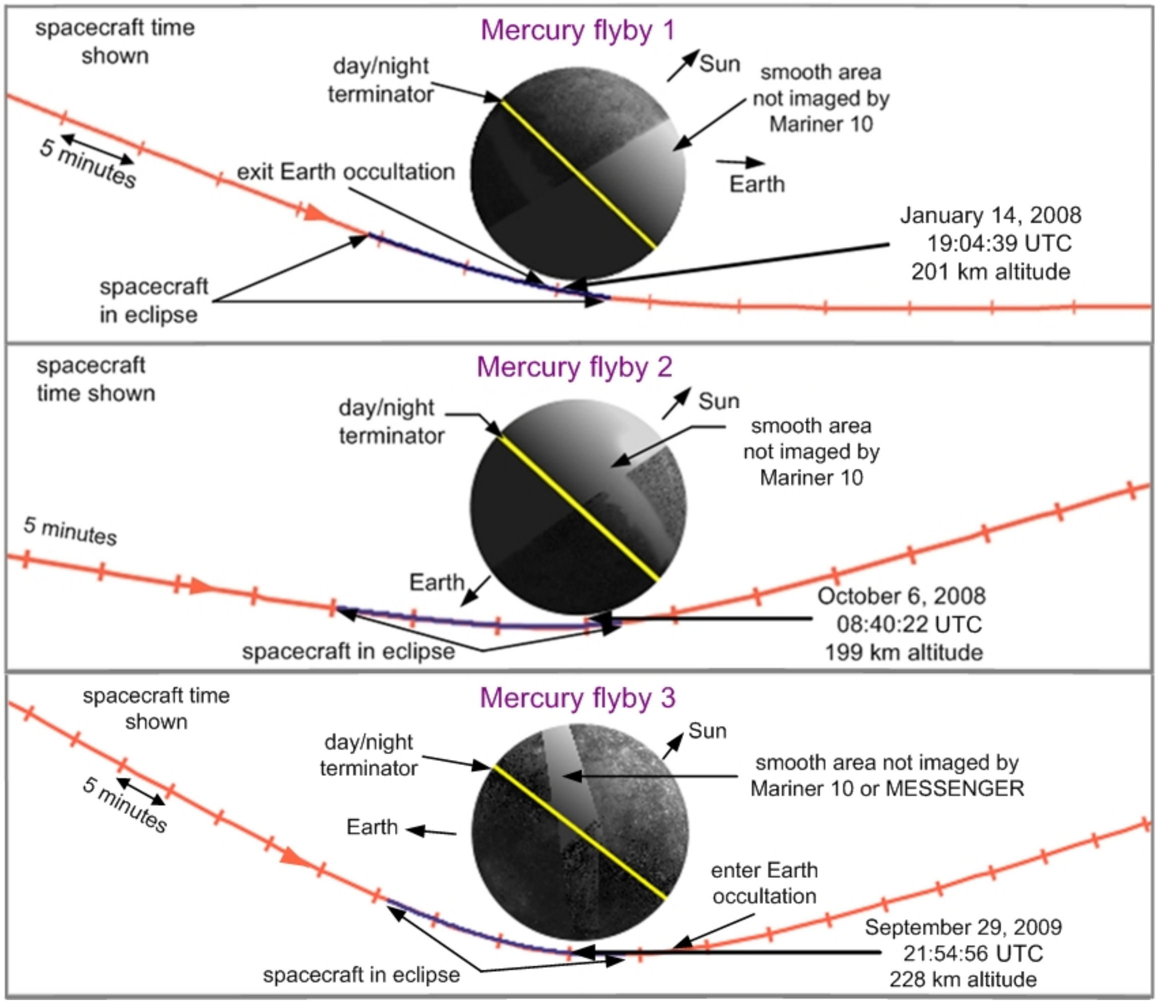


**Figure 11. Views of each Mercury flyby trajectory from above Mercury's north pole.**

## MERCURY ORBIT INSERTION

The transition from cruise phase to orbital phase occurred at the end of Mercury orbit insertion maneuver on 18 March 2011 at 01:00:00 UTC. The final requirements for the MESSENGER spacecraft's initial orbit were evaluated at the first periapsis after completion of MOI. These requirements and their corresponding tolerance included 200-km (125 km to 225 km) periapsis altitude, 12-hour (± 10 minutes) orbit period, 60º N (56ºN to 62ºN) periapsis latitude, 350º (169º to 354º) right ascension of ascending node, and 82.5º (±1º) orbit inclination. These requirements, shown in Mercury-centered inertial coordinates for epoch January 1.5, 2000, were defined from science and engineering requirements. Using the Mercury approach trajectory with MOI centered at Mercury periapsis would have resulted in a 49º N initial periapsis latitude. The MOI thrust start time and variable-thrust direction profile were optimized to achieve the remaining 11º N rotation of the line of apsides needed to achieve 60º N latitude at the first periapsis after MOI. Table 8, which lists the spacecraft's targeted and achieved classical orbital elements in the Mercury-centered inertial frame at the first periapsis after MOI, verifies the success of MOI.

**Table 8. Initial Mercury orbit periapsis orbital elements on 18 March 2011 (Mercury-centered inertial frame).**

| | Semi-major axis (km) | Orbit eccentricity | Orbit inclination (°) | Right ascension of ascending node (°) | Argument of periapsis (°) | Time, UTC (hh:mm:ss) |
|---|---|---|---|---|---|---|
| **Targeted** | 10135.12 | 0.73952 | 82.4994 | 350.1691 | 119.134 | 12:47:56.0 |
| **Achieved** | 10175.39 | 0.73990 | 82.5213 | 350.1652 | 119.168 | 12:52:19.9 |
| **Deviation** | 40.27 | 0.00038 | 0.0219 | -0.0039 | 0.034 | 263.9 s |

First presented by McAdams[9] in June of 2011, the final design strategy and results of MESSENGER's MOI maneuver are a testament to the team's adaptability and responsiveness to new information. The Mercury orbit insertion strategy used one maneuver in order to minimize both the time and propellant required to place the spacecraft into the primary science orbit defined earlier by MOI accuracy requirements. This strategy's "turn while burning" approach used variable-thrust-direction during the 834-s-duration, bipropellant segment operating with an average 680.8-N thrust, 316.1-s specific impulse, and 0.843 fuel-oxidizer mixture ratio. For most of the first two minutes of LVA thruster firing, before steady-state performance began, the final MOI maneuver design accounted for variable-thrust and variable-specific impulse. The start time, duration, and time-varying orientation of MOI were optimized to minimize propellant usage. The MOI maneuver decreased the spacecraft's Mercury-relative velocity by directing the thrust vector nearly opposite to the instantaneous spacecraft velocity vector. The trajectory during MOI and the subsequent first orbit around Mercury appear in Figure 12. A 17.3° Sun-Earth-spacecraft angle,

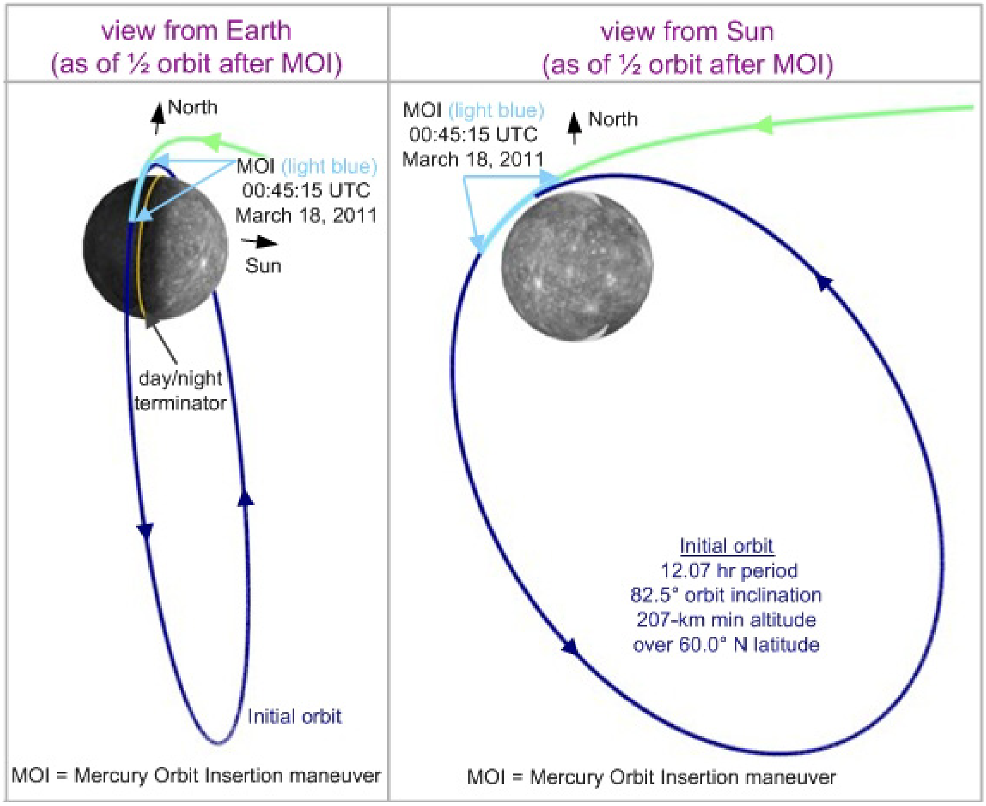


**Figure 12. Two views of MESSENGER's orbit insertion and Initial Orbit around Mercury.**

well above the 3° limit for superior solar conjunction, during MOI ensured that there would be no degradation in communications with the spacecraft during orbit insertion. The sunshade's protection of the spacecraft bus from direct sunlight was verified when MOI reconstruction analysis revealed a maximum Sun elevation angle of 9.52°, well below the 12° limit described above. The result of MOI was an orbit with initial 206.77-km periapsis altitude, 12.073-hour orbit period, and 59.98º N sub-spacecraft periapsis latitude. The time chosen for MOI provided that the spacecraft was more than 30° above the horizon (see Figure 13) at each of two widely separated DSN ground antennas. Goldstone, California, was the primary DSN location for monitoring MOI and Canberra, Australia, was the backup DSN tracking site. The alignment of the MOI $\Delta V$ direction with the spacecraft-Earth direction meant that 72.8% of the MOI maneuver $\Delta V$ was detectable via Doppler shift during real-time MOI monitoring.

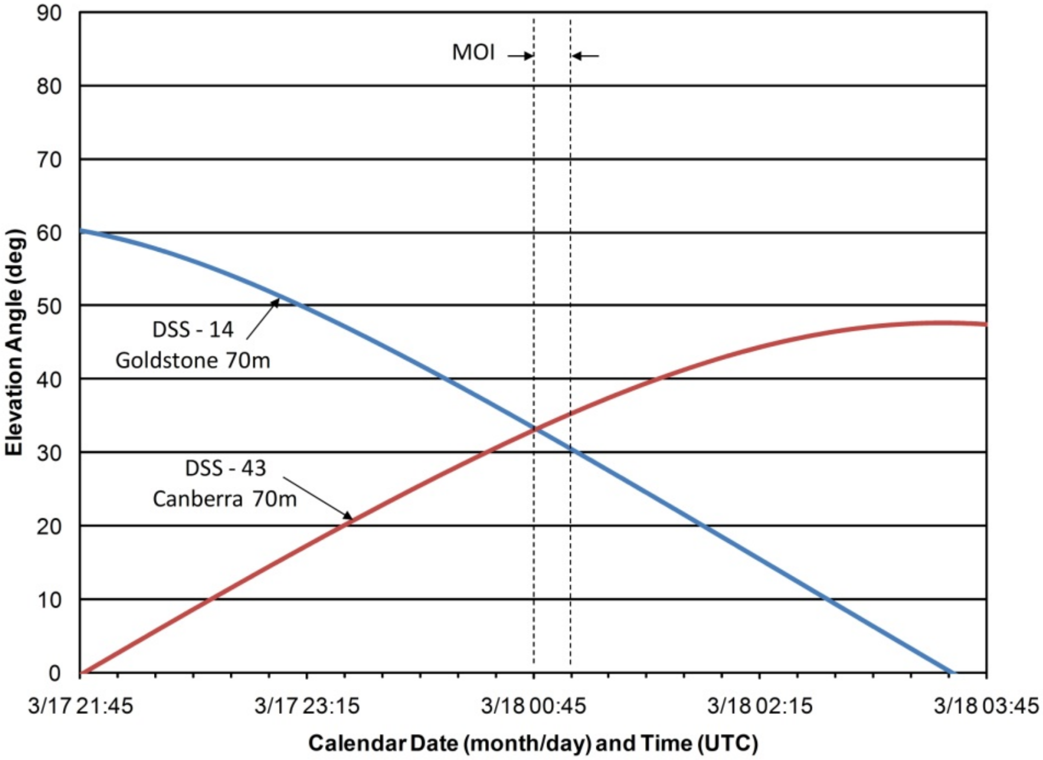


**Figure 13. Ground station visibility of MESSENGER during orbit insertion.**

The Mercury arrival trajectory and the performance of the Mercury orbit insertion maneuver differed slightly from the final design goals. Most of this difference came from an offset between the arrival B-plane location and the targeted Mercury arrival aim point, as well as from fuel pressures that were lower than those assumed for the final maneuver design (resulting in lower thrust during MOI). The arrival B-plane aim point, whose 2.8-standard-deviation error had the largest effect on the resulting orbit, was about 8.0 km from the target. This offset produced a 6.0-km increase in periapsis altitude, a condition reached 5.4 minutes after the MOI maneuver began. Except for a 30-s "tweak" segment that helped stabilize spacecraft attitude and propellant slosh after the spacecraft met its target $\Delta V$, the total thrust duration was 885 s, or 7 s longer than predicted. Completing MOI required an estimated 185.6 kg of propellant, about 31% of the total propellant loaded before launch. In order to maximize maneuver efficiency, a 0.038°/s thrust-direction turn rate occurred during the 834-s duration bipropellant segment. Given that the primary orbit-change objectives of MOI were a significant reduction in spacecraft velocity and a rotation in the line of apsides, the MOI $\Delta V$ direction was always within 4° of opposite to the spacecraft velocity direction. The MOI resultant $\Delta V$ of 851.056 m/s, as given by the guidance and control team using onboard accelerometer and thruster activity data, was 0.008 % less than the 851.124 m/s goal, and the pointing error was 0.003°. The navigation team estimated an MOI-integrated (along flight path) $\Delta V$ of 861.714 m/s, or 0.052% less than the 862.166 m/s final design, with 0.472° of pointing error. A more detailed account of MOI is available from Moessner and McAdams[10].

## SUMMARY

Launched on 3 August 2004 from central Florida's Cape Canaveral Air Force Station, the MESSENGER spacecraft became the first to complete six planetary gravity-assist flybys. The 6.6-year heliocentric transfer included six primary TCMs, including five DSMs and Mercury orbit insertion. The journey from launch to MOI included 15.6 revolutions of the Sun and traversed 7.9 billion kilometers as measured along the trajectory relative to the Sun. On 18 March 2011 the heliocentric cruise phase ended with a more significant first-time accomplishment in planetary exploration, insertion of the first spacecraft into orbit around the planet Mercury.

With the exception of one Venus flyby during solar conjunction, each planetary flyby came within 1.5 km of the planned periapsis altitude. This accurate flyby targeting was achieved using highly accurate TCMs and implementation of a new solar sailing technique for correcting maneuver errors. Without exception, only TCMs with relatively small $\Delta V$ had larger errors in $\Delta V$ magnitude or direction. Solar sailing combined spacecraft momentum management with timed alternation of downlink and trajectory-altering spacecraft attitude as defined by sunshade orientation and solar panel tilt angle. Even after accounting for accurate implementation of all large TCMs, solar sailing helped reduce mission risk by helping to cancel eight to 10 TCMs. The longest time between TCMs, the 478 days from DSM-5 to MOI, included about 4.6 revolutions around the Sun along over 1.813 billion kilometers of Sun-relative trajectory.

The Mercury orbit insertion maneuver met mission requirements such that no MOI clean-up maneuver was needed. After a 14.75-minute maneuver imparting 861.714 m/s $\Delta V$ along the flight path, the post-MOI orbit had an initial 206.77-km periapsis altitude, 12.073-hour orbit period, 82.52° orbit inclination, and 59.98° N sub-spacecraft periapsis latitude. Now that the MESSENGER spacecraft is well into the Mercury primary science mission, the scientific and engineering contributions continue as new discoveries help solve age-old mysteries about our solar system's closest planet to the Sun.

## ACKNOWLEDGEMENTS

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