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DESIGN, IMPLEMENTATION, AND OUTCOME OF MESSENGER'S TRAJECTORY FROM LAUNCH TO MERCURY IMPACT

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MESSENGER launched on 3 August 2004, entered orbit about Mercury on 18 March 2011 (UTC), and impacted Mercury's surface on 30 April 2015. After a 6.6-year cruise phase with one flyby of Earth, two of Venus, and three of Mercury, MESSENGER spent 4.1 years in orbit about the innermost planet. Initially in a 12-h orbit, MESSENGER maintained periapsis altitudes of 200–505 km before transferring to an 8-h orbit on 20 April 2012. MESSENGER's low-altitude campaign included periapsis altitudes between 15 and 200 km. In its final 44 days, MESSENGER maintained unprecedented minimum altitudes less than 38 km above Mercury's terrain before impact.

INTRODUCTION

Designed and operated by The Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission was led by Sean C. Solomon, of the Carnegie Institution of Washington and Columbia University, with key flight and operations contributions from KinetX Aerospace, the Jet Propulsion Laboratory (JPL), the NASA Goddard Space Flight Center, and numerous universities, research institutions, and subcontractors. Supported by NASA's Discovery Program, the spacecraft was successfully launched from Cape Canaveral, Florida, on 3 August 2004 during the third of three launch period in 2004.[1]

The first phase of MESSENGER's innovative trajectory was a 6.6-year interplanetary cruise that included six total flybys, one of Earth, two of Venus, and three of Mercury, as well as 17 maneuvers.[2] Each flyby lowered the spacecraft's speed relative to Mercury until the amount of onboard propellant was sufficient to attain the planned initial science orbit about Mercury. Five of the maneuvers during the interplanetary phase were major course corrections (termed deep-space maneuvers or DSMs) that imparted a total of 1040 m/s in velocity change (ΔV) and targeted subsequent planetary flybys and insertion into orbit about Mercury. The remaining trajectory-correction maneuvers (TCMs) totaled 69 m/s and consisted of small course corrections that substantially reduced targeting errors on approach to a planetary flyby. After December 2007, these small TCMs were no longer required because of the use of MESSENGER's solar-panel tilt and sunshade orientation as solar sail controls.[3, 4] This novel approach, led by Daniel J.

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O'Shaughnessy of the guidance and control team, resulted in precise targeting of the second and third Mercury flybys and Mercury orbit insertion (MOI), as well as propellant savings that enabled a final six-week mission extension. The interplanetary cruise phase ended with MOI on 18 March 2011 (UTC).

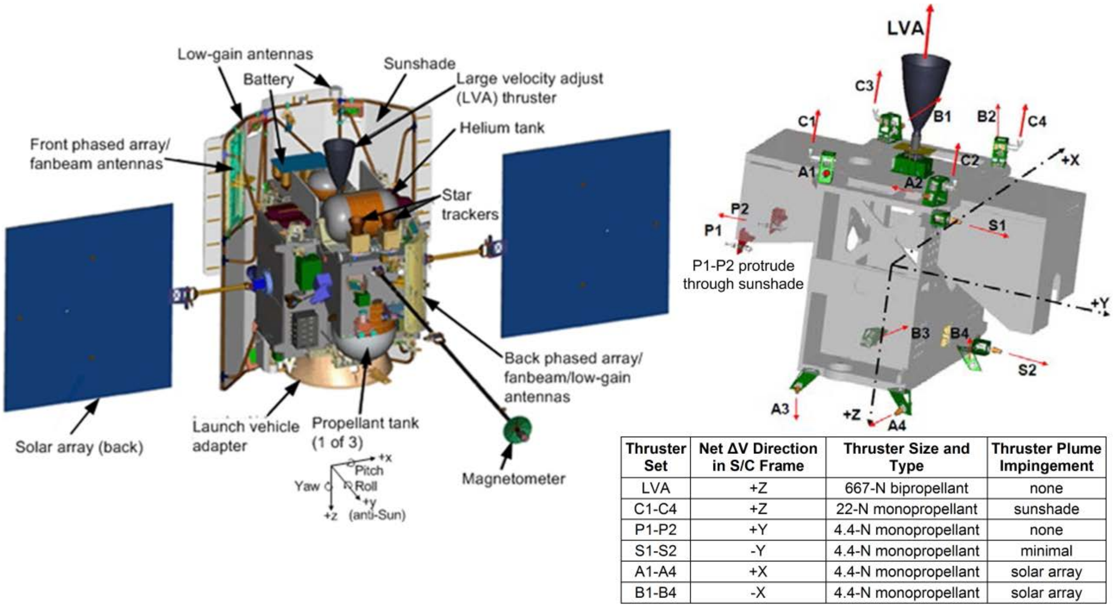
The orbital phase of the MESSENGER mission began with a single MOI maneuver on 18 March 2011 at 00:45:15 UTC.[5] Lasting approximately 15 minutes and imparting an 862-m/s velocity change (ΔV), the MOI maneuver slowed the spacecraft's Mercury-relative velocity by using variable-direction thrust with the thrust vector remaining nearly opposite to the instantaneous spacecraft velocity vector throughout the maneuver. MOI safely delivered the spacecraft into an orbit with a 207-km periapsis altitude, 12.07-h orbital period, 82.5° inclination, and 60.0º N sub-spacecraft periapsis latitude.

During MESSENGER's 4.1 years in orbit about Mercury, OCMs were required to adjust periapsis or minimum altitude and orbital period. During the first year in orbit, the primary orbital mission, MESSENGER performed six OCMs, counteracting the influence of a variety of trajectory perturbations, including those due to solar gravity, solar radiation pressure, planetary radiation pressure, and variations in Mercury's gravity field, to maintain the desired periapsis altitude range of 200–500 km. Beginning 91 days after MOI, the first five OCMs were executed about every 44 days either to return the spacecraft's periapsis altitude to 200 km or to adjust orbital period to an average of 12 h.[6, 7] The sixth OCM, conducted 88 days after OCM-5, lowered periapsis altitude to 200 km. Shortly after the start of MESSENGER's second year in orbit about Mercury, i.e., early in the first extended mission, on 16 April and 20 April 2012, OCMs 7 and 8 reduced the spacecraft's orbital period from 11.6 h to 8 h.[8] This period reduction was split between two OCMs to minimize risk and deplete remaining accessible oxidizer.[9] Due to the rotation of the orbital line of apsides through its northernmost Mercury latitude of 84.1° N about 12 days prior to the 18 March 2013 start of the second extended mission, solar gravity perturbed the orbit in such a way that no OCMs were required to maintain the desired periapsis altitude until MESSENGER's fourth and final year in orbit.

During the mission's final year, the MESSENGER team performed four OCMs (OCMs 9−12), that enabled a low-periapsis-altitude campaign consisting of orbits with periapsis altitudes between 15 and 200 km. OCMs 9−11 each targeted times before the next OCM when periapsis altitude settled with little variation over many orbits to about 25 km above the closest terrain feature beneath the spacecraft. OCM-12 targeted an extended period when periapsis altitude settled with little variation over many orbits to about 15 km above Mercury's terrain.[10] During the mission's final 44 days, MESSENGER performed seven ambitious OCMs (OCMs 13−18) as part of a low-periapsis-altitude "hover" campaign to maintain unprecedented minimum altitudes from 5 km to 35 km above Mercury's terrain before the spacecraft's inevitable final descent and impact onto Mercury's surface on 30 April 2015.[11]

DESIGN CONSIDERATIONS

A combination of constraints, requirements, and scientific objectives[12] influenced the MESSENGER trajectory design both at the outset[13] and as the mission progressed.[1, 2] The spacecraft's battery capacity dictated that time in solar eclipse last no longer than 65 minutes. This constraint, combined with an objective to avoid complex mission-operations scheduling, led to the choice of 60.0º N sub-spacecraft periapsis latitude and 12-h orbital period for the initial orbit. 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. An initial orbital inclination of 82.5° was finalized late in 2009 to facilitate the science measurements of libration amplitude and gravitational field structure and to determine the composition of radar-reflective materials at Mercury's poles. Several science objectives, including determining the geometry of Mercury's internal magnetic field, mapping the elemental and mineralogical composition of Mercury's surface, and globally imaging Mercury's surface at a 250-m resolution or better, led to an orbit design that maintained periapsis altitudes between 200 km and 500 km for just over three of the first four years in orbit. Near the beginning of MESSENGER's second year in orbit the orbital period was reduced from 12 h to 8 h in order to facilitate more frequent data collection and global imaging, while still avoiding complex mission-operations scheduling.



Thruster Set	Net ΔV Direction in S/C Frame	Thruster Size and Type	Thruster Plume Impingement
LVA	+Z	667-N bipropellant	none
C1-C4	+Z	22-N monopropellant	sunshade
P1-P2	+Y	4.4-N monopropellant	none
S1-S2	-Y	4.4-N monopropellant	minimal
A1-A4	+X	4.4-N monopropellant	solar array
B1-B4	-X	4.4-N monopropellant	solar array

Figure 1. MESSENGER Spacecraft in Flight Configuration with Spacecraft Thruster Set Details.

Thermal considerations also affected maneuver design. 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 was plentiful, the sunshade pointed toward the Sun. Because of the location of the spacecraft's sunshade (see Figure 1), maneuvers less than 0.85 AU from the Sun were performed with a spacecraft orientation that maintained a spacecraft –Y-axis direction within 12° of Sun pointing in order to protect the spacecraft bus from direct sunlight exposure. To meet this constraint during orbit, large deterministic orbit-correction maneuvers (OCMs) were executed when Mercury's heliocentric orbit true anomaly was near 5° or 184° due to the locations of the spacecraft's thrusters (see Figure 1) relative to the sunshade. Another factor in determining maneuver timing was the requirement to monitor maneuvers from the ground. Therefore, during heliocentric maneuvers, 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. During orbit, no maneuvers were performed when the spacecraft was occulted by Mercury when viewed from Earth. Furthermore, with the exception OCM-15A, no maneuvers were planned during superior solar conjunction when the Sun–Earth–spacecraft angle was less than 3° and the Sun was between the Earth and the spacecraft.

Because of this solar conjunction constraint, DSM-2 was moved more than 1.5 weeks earlier than its optimal time.

Science objectives developed for the spacecraft's final year in orbit, including characterization of surface features, crustal structure, crustal magnetization, and the north polar hydrogen distribution, all at high resolution, required observations at low altitudes. However, the thermal input from solar radiation reflected off Mercury's surface increased when the spacecraft was at low altitudes. The hottest seasons for the spacecraft also corresponded to times when the planet's surface was visible at periapsis. To facilitate the completion of these science objectives, a low-periapsis-altitude campaign was designed that balanced planetary lighting and thermal conditions while still achieving periapsis altitudes between 15 km and 200 km for approximately 11 months prior to maintaining minimum altitudes less than 35 km above Mercury's terrain for the 2.5 months before the spacecraft's Mercury surface impact.

LAUNCH

MESSENGER's original trajectory design included a primary trajectory with a launch period in March of 2004, and backup trajectories for launch periods in May and July–August of 2004.[13, 14, 15] The spacecraft's launch was delayed twice to accommodate necessary spacecraft testing and to increase redundancy, resulting in a successful launch on 3 August 2004 aboard a Delta II 7925H-9.5 launch vehicle at 06:15:56.5 UTC with a launch energy of 16.388 km^2/s^2. Table 1 lists the effect of each launch delay on selected trajectory parameters. Although the August launch resulted in a lower deterministic ΔV for the mission, it also resulted in a time of flight two years longer than for the original primary trajectory. This longer flight time was the result of adding an Earth flyby as well as a third Mercury flyby to the heliocentric trajectory design for the August launch period. Because of a larger-than-average 2.0-standard-deviation under burn during launch (the targeted launch energy was 16.513 km^2/s^2), the flight team began planning TCM-1 soon after the spacecraft departed Earth orbit.

Table 1. MESSENGER Launch Options during 2004.

	March	**May**	**August**	**August (launch day)**
Launch dates (mm/dd)	10-29	5/11-22	7/30-8/13*	**8/3**
Launch period (days)	20	12	15	**-**
Launch energy (km^2/s^2)	≤ 15.700	≤ 17.472	≤ 16.887	**16.388**
Earth flybys	0	0	1	**1**
Venus flybys	2	3	2	**2**
Mercury flybys	2	2	3	**3**
Deterministic ΔV (m/s)	≤ 2026	≤ 2074	≤ 1991	**1966**
Total ΔV (m/s)	2300	2276	2277	**2251****
Orbit insertion date (UTC, mm/dd/yy)	4/6/09	7/2/09	3/18/11	**3/18/11**

* The start of the final launch period was August 2 because of delays in the availability of the launch crew.

** Lower total ΔV reflects a reduced propellant load required to meet the spacecraft launch weight limit.

HELIOCENTRIC TRAJECTORY

The heliocentric trajectory design for the August 2004 launch period seen in Figure 2 included six large, deterministic maneuvers (DSMs 1-5 and MOI) and six planetary flybys (one of Earth, two of Venus, and three of Mercury). This design also contained features that increased mission risk compared with trajectories designed for earlier launch periods, including the largest number of large, deterministic maneuvers; the largest number of planetary flybys; 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 2: 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 also contained an MOI ΔV of 868 m/s, slightly higher than the actual MOI ΔV of 862 m/s.

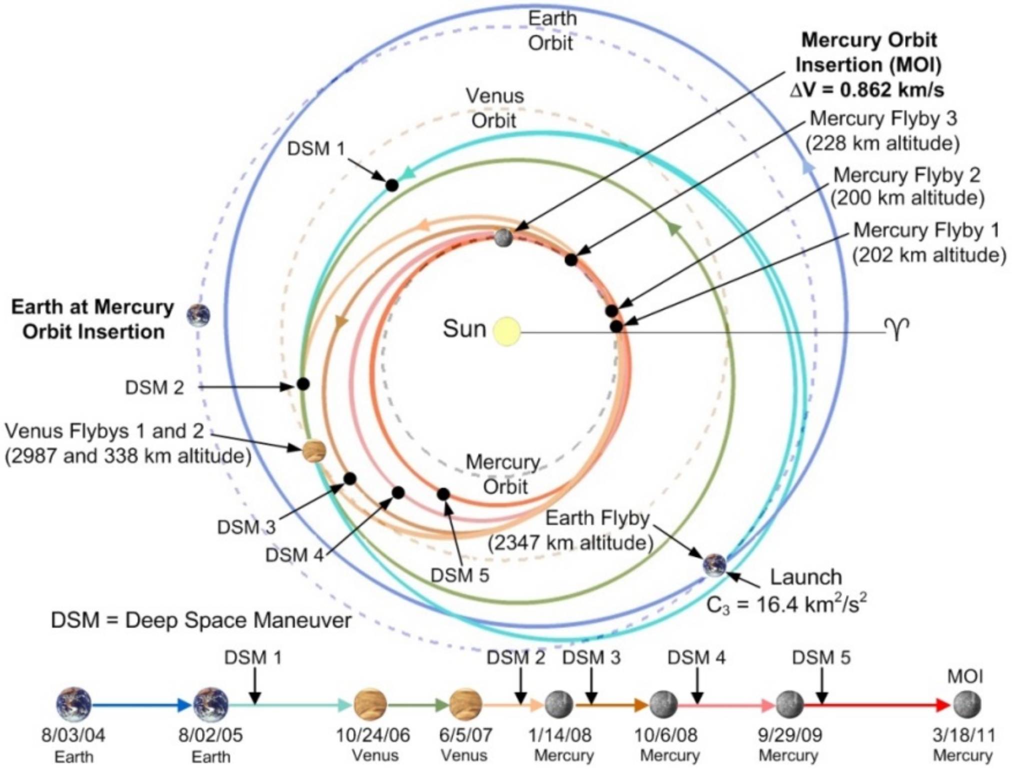


Figure 2. MESSENGER's Heliocentric Trajectory and DSM Locations as Seen from Above the North Ecliptic Pole.

Table 2. Orbit Changes Resulting from MESSENGER's Planetary Flybys and DSMs.

Event	Equivalent ΔV (km/s)	Longitude of perihelion (deg)	Lon. to goal (deg)	Orbit Inclination (deg)	Incl. to goal (deg)	Perihelion distance (AU)	Dist. to goal (AU)	Aphelion Distance (AU)	Dist. to goal (AU)
Launch	-	205	128	6.3	0.7	0.923	0.615	1.077	0.610
Earth flyby	5.9963	132	55	2.5	4.5	0.603	0.295	1.015	0.548
DSM-1 (TCM-9)	0.3156	-	-	-	-	-	-	1.054	0.587
Venus flyby 1	5.5225	104	27	8.2	1.2	0.547	0.239	0.900	0.433
Venus flyby 2	6.9378	47	30	6.8	0.2	0.332	0.024	0.745	0.278
DSM-2 (TCM-18)	0.2274	-	-	-	-	0.325	0.017	-	-
Mercury flyby 1	2.3040	56	21	6.9	0.1	0.313	0.005	0.700	0.233
DSM-3 (TCM-23)	0.0722	-	-	-	-	0.315	0.007	-	-
Mercury flyby 2	2.4526	68	9	7.0	0.0	0.302	0.006	0.630	0.163
DSM-4 (TCM-29)	0.2467	-	-	-	-	0.310	0.002	-	-
Mercury flyby 3	2.8361	81	4	7.0	0.0	0.303	0.005	0.567	0.100
DSM-5 (TCM-35)	0.1778	-	-	-	-	0.308	0.000	-	-
Orbit about Mercury (goal)	**0.8617 (MOI)**	**77**	**-**	**7.0**	**-**	**0.308**	**-**	**0.467**	**-**

Note: values apply to the spacecraft's orbit after completion of the listed event.

In general, the purpose of each of MESSENGER's six flybys was to bring the spacecraft's heliocentric orbit closer to that of Mercury, thereby minimizing the amount of ΔV required to insert the probe into orbit around Mercury. The first two DSMs aided with Earth–Venus and Venus–Mercury phasing, respectively. Furthermore, as seen in Figure 2, DSMs 3-5 shifted the location of each Mercury encounter closer to Mercury's perihelion, the desired location at MOI. Table 2**Error! Reference source not found.** lists the effect of each major planetary flyby and DSM on key orbital parameters. Equivalent ΔV comes from the equation:

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

where V_∞ is approach hyperbolic excess velocity, r_p is periapsis distance, and μ_p is the planet's gravitational parameter (the product of the gravitational constant and the planet's mass). Longitude of perihelion is measured as positive counterclockwise from the Sun–Earth direction at the autumnal equinox to the Sun–spacecraft direction at perihelion.

Table 3. Comparison of ΔV Budget Shortly after Launch with Actual ΔV.

Maneuver Category	**Launch + 4 months ΔV (m/s)**	**Actual ΔV (m/s)**
Deep space maneuvers	1008	1039
Launch vehicle and navigation errors (99%)	121	69
Mercury orbit insertion	868	862
Mercury orbit correction maneuvers and momentum dumps	85	238
Mercury orbit correction maneuvers and momentum dumps using helium pressurant	N/A	5
Contingency	169	N/A
Total	**2251**	**2213**

A comparison of the ΔV budget a few months after launch with the actual ΔV values from the mission as it was flown appears in Table 3. Changes in DSM ΔV resulted from DSM date shifts with contingency DSM planning and from offsets in planetary flyby targets 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. Part of the large decrease in ΔV required to correct navigation errors (<12 m/s) was the result of implementing a solar sailing methodology that combined a carefully planned sequence of sunshade rotations and tilts, along with changes in solar panel tilt to effect a gradual low-thrust trajectory correction.[3, 4] An overall reduction in total ΔV capability resulted from changes in documented propulsion system performance, cruise-phase analysis of usable propellant, and other factors.

Earth Flyby

The first flyby of the heliocentric trajectory occurred on 2 August 2005 at 2347 km altitude above Earth. This flyby enabled the launch vehicle to lift a slightly heavier spacecraft, lowered perihelion from 0.9 to 0.6 AU and moved the perihelion direction 73° closer to that of Mercury. The flyby also provided opportunities for calibrating several science instruments with observations of the Moon, thereby removing science observations from the early post-launch operations schedule. Five maneuvers (TCMs 1, 2, 3, 5, and 6) corrected launch insertion and navigation errors leading up to the encounter. A summary of the dates, times, and performance as well the main thruster set used for each of these maneuvers is given in Table 4. Figure 1 contains thruster set definitions; additional information on the MESSENGER propulsion system may be found elsewhere.[16, 17] At the time of TCM-1, a ΔV of 21.2 m/s was required to correct for launch injection errors; however, late in the TCM-1 design cycle the project chose to limit the maneuver ΔV to 18 m/s in order to mitigate risk associated with the first firing of the spacecraft's thrusters. The remaining ΔV was assimilated into the TCM-2 maneuver. As expected, each subsequent TCM became smaller in magnitude as navigation errors leading up to the encounter decreased. Furthermore, although TCM-4 had been planned, it was deemed unnecessary given navigational accuracy. As seen in Table 4, all five maneuvers had good performance and successfully targeted the Earth flyby with 0.764 km and -0.875 s of error in closest approach distance and time, respectively.

Table 4. Targeted versus Achieved Parameters of the First Five Maneuvers and Earth Flyby.

Maneuver	Date and Start Time	Main Thruster Set Used	EME2000**			ΔV Magnitude (m/s)	Duration* (s)	Mass Used (kg)
			ΔV_x (m/s)	ΔV_y (m/s)	ΔV_z (m/s)			
TCM-1	24 Aug 2004 21:00:07 UTC	C1-C4	-7.8279	-15.0637	-5.6788	17.9009	203.00	8.834
			0.309° directional error			-0.55% error		
TCM-2	24 Sep 2004 18:00:00 UTC	C1-C4	0.0862	-4.1872	-1.8749	4.5885	62.86	2.353
			0.274° directional error			-0.03% error		
TCM-3	18 Nov 2004 19:30:00 UTC	C1-C4	2.2448	-2.1861	-0.8524	3.2473	48.86	1.703
			0.343° directional error			0.33% error		
TCM-5	23 Jun 2005 14:30:00 UTC	S1, S2	-0.5613	-0.9471	0.0721	1.1033	171.22	0.715
			0.374° directional error			-3.65% error		
TCM-6	21 Jul 2005 18:00:01 UTC	P1, P2	-0.0371	-0.1455	0.0092	0.1505	22.46	0.100
			4.577° directional error			2.51% error		

Event	Date		Periapsis Time (UTC)	Periapsis Radius (km)	EME2000***	
					B·T (km)	B·R (km)
Earth flyby	2 Aug 2005	Design Target	19:13:09.201	8713.431	-18012.290	-13179.022
		Reconstruction	19:13:08.326	8714.195	-18025.631	-13162.600
		Deviation	-0.875 s	0.764	-13.341	16.422

*Duration does not include ~30-s spacecraft attitude stabilization "tweak" at the end of each maneuver.

**X, Y, and Z components of the ΔV are given in the Earth Mean Equator of J2000 coordinate frame.

***The B-plane axes include T, which is in the Earth Mean Equator of J2000 X-Y plane; S, which is parallel to the spacecraft's incoming hyperbolic excess velocity; and R, which completes the right-handed axes set.

Venus Flybys

Four months after the Earth flyby, DSM-1 targeted the first flyby of Venus, which occurred on 24 October 2006, increased the spacecraft's orbital inclination to 8.2°, and decreased the orbital period by lowering both the aphelion and perihelion distances. The flyby also positioned the spacecraft in a 1:1 resonant transfer with Venus so that the second Venus flyby took place one solar revolution later at about the same point in Venus' orbit. This second Venus encounter, on 5 June 2007 at a periapsis altitude of 338 km, lowered the perihelion and aphelion distances to 0.3 and 0.7 AU, respectively, thus enabling the first Mercury flyby. Because the first Venus closest approach occurred during superior solar conjunction at a Sun–Earth–spacecraft angle of 1.37°, it was not known if receiving transmissions from the spacecraft would be possible while close to Venus. The first eclipse, the heliocentric cruise phase's longest at 56 minutes, also occurred during this conjunction. Multiple tests involving the spacecraft and ground-based simulations lessened concerns regarding this first eclipse. Further solar conjunction risk mitigations included a moderate flyby periapsis altitude of 2987 km as well as having no encounter science.

After DSM-1, TCMs 10-12 were required to target the first Venus flyby. Table 5 contains design and performance data for these maneuvers as well as the first Venus flyby. The first use of the bipropellant large velocity-adjust (LVA) thruster occurred during DSM-1, which had excellent performance with only a -0.03% error in magnitude and a 0.026° error in direction. TCM-10, the first maneuver to use the B thrusters to generate the desired ΔV, was terminated at the maneuver time-out of 135 s before fully achieving the ΔV target. This underperformance was determined to be a result of thruster plume impingement on the solar arrays that reduced the effective thrust by 15%.[16] Due to the spacecraft's configuration (see Figure 1), this impingement occurred anytime the A or B thrusters were used. For the remaining maneuvers that utilized the A and/or B thrusters, this reduced effective thrust was included in the maneuver design. TCM-11, with a required ΔV direction about 159° from the Sun–spacecraft direction, was the first maneuver to be split into components in order to maintain sunshade protection. As seen in Table 5, TCM-11A utilized the 22-N C1-C4 thrusters, whereas TCM-11B was accomplished with the 4.4-N S1-S2 thrusters. The large 11.1° direction error for TCM-11B was the result of three factors.[16] To ensure the predictable removal of excess momentum, the S thrusters were fired at 100% duty cycle instead of being allowed to off-pulse for enhanced attitude control. Furthermore, the maneuver had to operate within tight steering constraints to maintain sunshade protection. As a result, the accumulating direction errors caused by an unanticipated offset between the center of mass and the center of pressure were too difficult to manage with the attitude control capability available. TCM-12 was designed to clean-up the remaining targeting errors. However, after the TCM-12 final design, incorporation of delta differential one-way ranging 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. Although a 0.74-m/s contingency TCM, designed to occur on 12 October 2006, would have saved almost 40 m/s of statistical ΔV, the short nine-day cycle for implementing, testing, and uploading TCM-12C2 to the spacecraft was deemed too risky to attempt. As a result, the periapsis altitude of the first Venus flyby was 74.39 km lower than the target altitude and the time of closest approach was 5.110 s later than the target time.

Table 5. Targeted versus Achieved Parameters for DSM-1 through the First Venus Flyby.

Maneuver	Date and Start Time	Main Thruster Set Used	EME2000			ΔV Magnitude (m/s)	Duration* (s)	Mass Used (kg)
			ΔV_x (m/s)	ΔV_y (m/s)	ΔV_z (m/s)			
DSM-1 (TCM-9)	12 Dec 2005 11:30:00 UTC	LVA, C1-C4	-250.2484	-190.4689	-26.8662	315.6334	522.56	106.488
			0.026° directional error			-0.03% error		
TCM-10	22 Feb 2006 16:00:00 UTC	B1-B4	-1.2276	0.3013	0.2060	1.2807	135.00	0.901
			2.556° directional error			-8.98% error		
TCM-11A	12 Sep 2006 23:00:00 UTC	C1-C4	-0.6158	-0.4168	-0.3801	0.8351	22.88	0.536
			0.638° directional error			0.60% error		
TCM-11B	12 Sep 2006 23:10:00 UTC	S1-S2	0.8496	-1.1599	-0.1386	1.4444	202.08	1.020
			11.105° directional error			-1.04% error		
TCM-12	5 Oct 2006 22:30:00 UTC	B1-B4	-0.0232	-0.1242	-0.4853	0.5014	64.60	0.348
			1.840° directional error			0.96% error		

Event	Date		Periapsis Time (UTC)	Periapsis Radius (km)	EMO2000**	
					B·T (km)	B·R (km)
Venus flyby 1	24 Oct 2006	Design Target	08:33:54.818	9113.471	-5673.300	-11104.200
		Reconstruction	08:33:59.928	9039.081	-5684.670	-11010.571
		Deviation	5.110 s	-74.390	-11.370	-93.629

*Duration does not include ~30-s spacecraft attitude stabilization "tweak" at the end of each maneuver

**The B-plane axes include T, which is in the Earth Mean Ecliptic of J2000 X-Y plane, S, which is parallel to the spacecraft's incoming hyperbolic excess velocity, and R, which completes the right-handed axes set.

Less than six weeks after the first Venus flyby and about two weeks after the end of the solar conjunction, TCM-13, the mission's only three-component maneuver, accomplished most of the ΔV required to place the spacecraft back on course toward the second Venus flyby. The design and performance of TCMs 13-16 and the second Venus flyby appear in Table 6. Because the P-thruster component required for TCM-13 was longer than the auxiliary fuel tank could support, it was split into two components, TCM-13A and TCM-13C, each using about 50% of the fuel stored in the auxiliary fuel tank. A refill of the auxiliary tank occurred during the middle TCM-13B component, which was performed with the LVA thruster while drawing fuel from the main fuel and oxidizer tanks. Due to the length of the TCM-13A and 13C monopropellant components, 29 and 27 minutes, respectively, valuable information regarding the reliability of one of the four onboard accelerometers was revealed. This new understanding enhanced the accuracy of several future TCMs. The next maneuver, TCM-15, resulted in a 25.4% under burn despite continuing until the maneuver time-out of 140.0 s. This under burn was caused by the omission of an acceleration term in the guidance and control software that resulted in the A thrusters (which opposed the B thrusters being used for the maneuver) having a higher-than-normal duty cycle for attitude control. The guidance and control software was subsequently updated and, as seen in Table 6, maneuver performance improved for TCM-16. As a result, the second Venus flyby occurred with only a 0.805-km error in periapsis altitude and a 0.695-s error in periapsis time.

Table 6. Targeted versus Achieved Parameters for TCM-13 through the Second Venus Flyby.

Maneuver	Date and Start Time	Main Thruster Set Used	EME2000			ΔV Magnitude (m/s)	Duration* (s)	Mass Used (kg)
			ΔV_x (m/s)	ΔV_y (m/s)	ΔV_z (m/s)			
TCM-13A	2 Dec 2006 21:00:00 UTC	P1, P2	-2.7416	-6.0599	-3.6594	7.5914	1712.23	4.798
			1.151° directional error			-6.64% error		
TCM-13B	2 Dec 2006 22:00:00 UTC	LVA, C1-C4	18.2760	-8.6036	1.4328	20.2506	97.92	7.056
			1.723° directional error			2.22% error		
TCM-13C	3 Dec 2006 03:00:00 UTC	P1, P2	-2.8480	-6.1908	-3.9318	7.8674	1592.48	5.061
			2.280° directional error			-3.24% error		
TCM-15	25 Apr 2007 17:30:00 UTC	B1-B4	-0.4207	0.0307	-0.3870	0.5724	140.00	0.590
			0.322° directional error			-25.35% error		
TCM-16	25 May 2007 16:00:00 UTC	B1-B4	-0.0384	0.2051	0.0398	0.2125	35.84	0.148
			2.015° directional error			0.24% error		

Event	Date		Periapsis Time (UTC)	Periapsis Radius (km)	EMO2000	
					B·T (km)	B·R (km)
Venus flyby 2	5 Jun 2007	Design Target	23:08:18.000	6389.314	-9542.560	867.268
		Reconstruction	23:08:18.695	6390.119	-9543.578	865.999
		Deviation	0.695 s	0.805	-1.018	-1.269

*Duration does not include ~30-s spacecraft attitude stabilization "tweak" at the end of each maneuver

Mercury Flybys

The final three flybys in the heliocentric trajectory were of Mercury and brought both the longitude of perihelion and aphelion distance progressively closer to the goals of 77° and 0.5 AU, respectively. The first and second Mercury flybys also increased orbit inclination to the desired 7.0°. Table 7 includes details of the results of the last seven maneuvers for the heliocentric trajectory as well as all three Mercury flybys and Mercury arrival. The first maneuver to target a Mercury flyby, DSM-2 was performed on 17 October 2007, eight days prior to a 47-day solar conjunction. This maneuver was required to aid Venus-Mercury phasing; however, it was also used to achieve two engineering goals. The maneuver was split into two components; DSM-2A used the LVA thruster to impart 226.0 m/s of the ΔV, and the much smaller 1.4-m/s DSM-2B used the B thrusters to shift the propellant location in the tanks to enable passive angular momentum management by way of planned changes in spacecraft attitude. DSM-2B also characterized the thruster plume impingement on the solar array while using a 72° Sun-offset solar array tilt angle similar to that needed for small maneuvers just prior to Mercury flybys and near Mercury perihelion once the spacecraft was in orbit.

The final TCM of the cruise phase, TCM-19, was successfully executed on 19 December 2007, one week after exiting the solar conjunction. Orbit determination following TCM-19 revealed that the first Mercury flyby was sufficiently off-target to result in a 5 m/s ΔV penalty at the next DSM. Rather than implement a very small TCM four days before the flyby, the mission chose to implement a plan to change the solar panel orientation for a sufficiently long period so that most of the aim-point offset was removed as a result of solar radiation pressure on the spacecraft. This strategy to use a carefully planned sequence of sunshade rotation and tilt, along with changes in solar panel tilt to effect a gradual low-thrust trajectory correction was very successful in targeting the first Mercury flyby on 14 January 2008 at 202 km periapsis altitude with only -2.735 s and 1.406 km error in periapsis time and altitude, respectively. Furthermore, it marked the beginning of the solar sailing method of refining planetary encounter targeting that was used successfully for the remainder of the heliocentric trajectory.[3, 4]

Table 7. Targeted versus Achieved Parameters for DSM-2 through Mercury Arrival.

Maneuver	Date and Start Time	Main Thruster Set Used	EME2000			ΔV Magnitude (m/s)	Duration* (s)	Mass Used (kg)
			ΔV_x (m/s)	ΔV_y (m/s)	ΔV_z (m/s)			
DSM-2A (TCM-18A)	17 Oct 2007 22:00:00 UTC	LVA, C1-C4	-82.4506	190.5891	89.1642	225.9924	385.34	68.904
			0.221° directional error			-0.01% error		
DSM-2B (TCM-18B)	17 Oct 2007 22:30:00 UTC	B1-B4	-0.4543	1.2252	0.5571	1.4205	132.70	0.893
			2.642° directional error			-0.04% error		
TCM-19	19 Dec 2007 22:00:00 UTC	B1-B4	0.8635	-0.0392	0.6860	1.1035	110.52	0.698
			0.215° directional error			-0.06% error		
DSM-3 (TCM-23)	19 Mar 2008 19:30:00 UTC	LVA, C1-C4	56.3128	-44.0298	-10.3358	72.2259	149.38	21.229
			0.046° directional error			-0.01% error		
DSM-4 (TCM-29), part 1	4 Dec 2008 20:30:00 UTC	LVA, C1-C4	188.2124	-97.0268	-66.9080	222.0694	314.98	61.048
			0.014° directional error			-0.04% error		
DSM-4 (TCM-29), part 2	8 Dec 2008 20:30:00 UTC	LVA, C1-C4	21.6983	-9.7764	-6.4199	24.6498	71.80	6.941
			0.101° directional error			-0.33% error		
DSM-5 (TCM-35)	24 Nov 2009 21:45:00 UTC	LVA, C1-C4	172.8791	-11.9781	-39.6916	177.7810	244.80	45.551
			0.055° directional error			0.02% error		

Event	Date		Periapsis Time (UTC)	Periapsis Radius (km)	EMO2000	
					B·T (km)	B·R (km)
Mercury flyby 1	14 Jan 2008	Design Target	19:04:42.136	2639.700	3206.195	376.234
		Reconstruction	19:04:39.401	2641.106	3206.355	386.494
		Deviation	-2.735 s	1.406	0.160	10.260
Mercury flyby 2	6 Oct 2008	Design Target	08:40:19.818	2639.700	3348.950	220.100
		Reconstruction	08:40:22.222	2638.941	3348.308	217.535
		Deviation	2.404 s	-0.759	-0.642	-2.565
Mercury flyby 3	29 Sep 2009	Design Target	21:54:.57.918	2667.993	4168.250	-52.100
		Reconstruction	21:54:55.724	2667.197	4168.395	-48.673
		Deviation	-2.194 s	-0.796	0.145	3.427
Mercury Arrival	18 Mar 2011	Design Target	00:50:22.040	2714.8	276.480	-5657.942
		Reconstruction	00:50:22.873	2720.8	275.034	-5665.829
		Deviation	0.833 s	6.0	-1.446	-7.887

*Duration does not include ~30-s spacecraft attitude stabilization "tweak" at the end of each maneuver

The only maneuver between the first and second Mercury flybys, DSM-3 provided a low-risk opportunity to test the active trajectory guidance, or "turn while burning," method that was required for MOI. Occurring on 19 March 2008, the maneuver had a ΔV of 72.2 m/s, the lowest of all five DSMs. After a successful DSM-3 variable-thrust-direction test at the same turn rate as planned for MOI, refinements in the solar sailing maneuver clean-up strategy were developed and implemented, resulting in a second flyby of Mercury on 6 October 2008 at a closest approach altitude of 200 km, 0.759 km lower than the target, and time of 08:40:22.222 UTC, only 2.404 s from the target.

Only one-half-orbit after the second Mercury encounter, DSM-4 was performed. This maneuver was split into two parts; DSM-4, part 1 imparted 222.1 m/s of ΔV on 4 December 2008 and DSM-4, part 2 imparted 24.6 m/s of ΔV on 8 December 2008. The second part served as a test of timed, i.e., open-loop, thrust cut-off while implementing the planned MOI maneuver turn rate. This open-loop maneuver method would have been used if accelerometer data had not been available at the time of MOI. Continuation of solar sailing after the successful completion of DSM-4 eliminated the need for any further maneuvers prior to the flyby. The third Mercury flyby occurred on 29 September 2009 at a closest approach altitude of 228 km. A very accurate flyby, the errors in periapsis time and altitude were only -2.194 s and -0.796 km, respectively. Two months after the third Mercury flyby, DSM-5 was the final opportunity to make major changes in the pre-MOI Mercury arrival trajectory. With an accurate delivery on 29 September 2009 of 177.8 m/s of ΔV followed by solar sailing to eliminate the need for any further maneuvers until MOI, DSM-5 set the stage for MESSENGER's arrival at Mercury.

MERCURY ORBIT INSERTION

Although the planned date for MOI had remained 18 March 2011 since launch, many design aspects of MOI changed in the 6.6 years from launch to MOI.[5] Not only did improvements in trajectory optimization and maneuver design lower MOI ΔV from 868 m/s at launch to 862 m/s for the MOI final design, the original maneuver design also called for a two-part maneuver whereby ~96% of MOI ΔV was followed by a more precise, adjustable cleanup of the final ~4% of MOI ΔV 3.6 days (6 orbits) later. This two-part MOI met an orbit-period requirement of 12 h ±1 min after MOI, which was relaxed to 12 h ± 10 min early in 2010 following a detailed Mercury orbital-phase science observation analysis. This change in orbit-period tolerance eliminated the need for an adjustable MOI cleanup maneuver. Other design changes included increasing the post-MOI orbit inclination from 80.0° to 82.5° in 2009 to enhance science return as well as incorporating a detailed variable-thrust, variable-specific-impulse engine model for the first 1.5–2.0 min before the bipropellant LVA thruster attained steady-state operation. A final design change on 11 March 2011 improved MOI performance by shifting the MOI start time 5 s earlier, thus reducing the orbital-period error by 35–40 s. The final requirements for the MESSENGER spacecraft's initial orbit consisted of a 200-km (125–225 km) periapsis altitude, a 12-h (±10 min) orbital period, a 60°N (56°–62°N) periapsis latitude, a 350° (169°–354°) right ascension of the ascending node, and an initial orbit inclination of 82.5° (±1°). These requirements, expressed in Mercury-centered inertial coordinates of epoch January 1.5, 2000, were defined from science and engineering requirements along with characteristics of the Mercury arrival geometry.

The MOI maneuver slowed the spacecraft's Mercury-relative velocity by orienting the thrust vector nearly opposite to the instantaneous spacecraft velocity vector. Views of the trajectory during MOI and the resulting initial orbit are shown in Figure 3. Implementation of this MOI strategy was designed to be versatile enough to accommodate an MOI cleanup maneuver even though none was required. The time of day for MOI corresponded to nearly equal spacecraft elevation angles relative to two widely separated Deep Space Network (DSN) ground antennas. Goldstone, California, was the primary location for monitoring MOI, and Canberra, Australia, was the backup location. A Sun–Earth–spacecraft angle of 17.3° at the time of MOI ensured that solar interference did not corrupt communications with the spacecraft during orbit insertion. Because of Earth–spacecraft–ΔV geometry, 72.8% of the MOI maneuver ΔV was visible via Doppler shift during real-time monitoring.

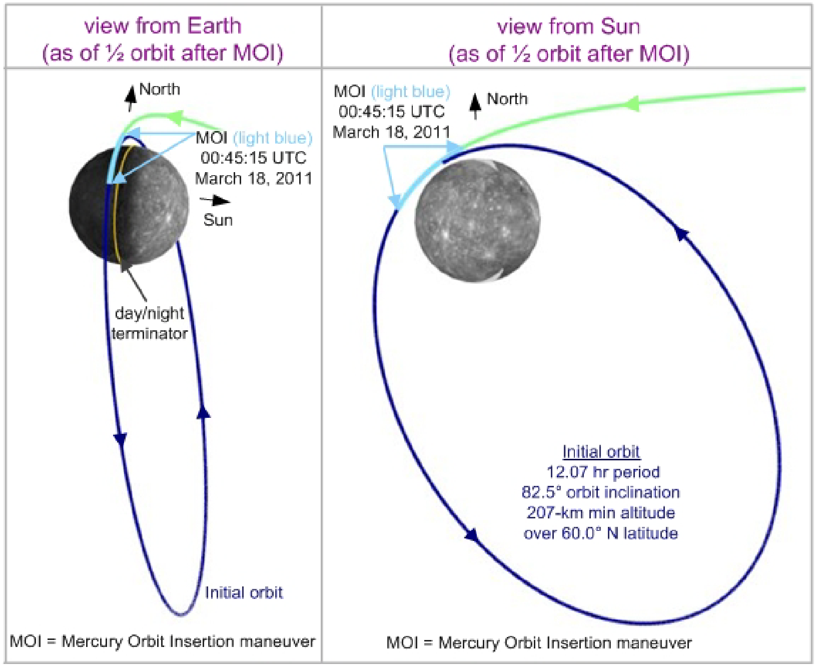


Figure 3. Two Views of MESSENGER's Orbit Insertion and Initial Orbit around Mercury.

Table 8. Targeted versus Achieved Parameters for Mercury Orbit Insertion.

Maneuver	Date and Start Time	Main Thruster Set Used	EME2000			ΔV Magnitude** (m/s)	Duration* (s)	Mass Used (kg)
			ΔV_x (m/s)	ΔV_y (m/s)	ΔV_z (m/s)			
MOI	18 Mar 2011 00:45:16 UTC	LVA, C1-C4	638.153	-198.322	544.041	861.714	885.04	185.618
			0.472° directional error			-0.05% error		

*Duration does not include ~30-s spacecraft attitude stabilization "tweak" at the end of the maneuver

**ΔV is integrated along the flight path

Table 9. Orbital Elements of MESSNEGER's Initial Orbit at Periapsis on 18 March 2011 (Mercury-Centered Inertial Frame).

	Semi-Major Axis (km)	Orbit Eccentricity	Orbit Inclination (°)	Right Ascension Ascending Node (°)	Argument of Periapsis (°)	Time, UTC (hh:mm:ss)
Design Target	10135.120	0.740	82.50	350.17	119.13	12:47:56.0
Reconstruction	10177.098	0.740	82.52	350.16	119.16	12:52:19.8
Deviation	41.978	0.000	0.02	–0.01	0.03	263.8 s

The performance of the MOI maneuver and the orbit resulting from that maneuver differed slightly from those in the final design as seen in Table 8 and Table 9. This difference was due to a solar conjunction from late February through early March that contributed to orbit determination errors thus affecting solar sailing accuracy, as well as to fuel pressures that were lower than those used to model the final maneuver design, resulting in lower thrust during the maneuver. As seen in Table 7, a 6.0-km increase in the arrival periapsis altitude resulted from the B-plane offset. Excluding a 30-s "tweak" segment that ensured spacecraft attitude stability after the spacecraft met its target ΔV, the total thrust duration was 885.0 s. The MOI integrated (along the flight path) ΔV was 861.7 m/s, 0.052% less than the 862.2 m/s target, with 0.472° of pointing error. Table 9 lists the spacecraft's targeted and achieved classical orbital elements in the Mercury-centered inertial frame at the first periapsis (0° true anomaly) after MOI. The resulting orbit about Mercury had a periapsis altitude of 207.39 km (7.39 km above the 200-km target), an orbital period of 43,456.9 s (261.3 s longer than the 43195.6-s target), an inclination of 82.52° (0.02° above the 82.50° target), and a sub-spacecraft periapsis latitude of 59.98° (–0.02° below the 60.00°N target). These orbital parameters were all well within the requirements for the initial orbit about Mercury, so no cleanup or contingency maneuver was required.

IN ORBIT ABOUT MERCURY

After the completion of MOI, the spacecraft entered its initial orbit (orbit 1), which began at apoapsis, approximately one-half orbit after the MOI cutoff, on 18 March 2011 at 06:50:12 UTC. Throughout the 4.1 years orbiting Mercury, MESSENGER's trajectory was perturbed by several forces, of which solar gravity and Mercury's small gravitational oblateness, J_2, were the dominant factors. The non-uniform effect of these trajectory perturbations on the spacecraft's orbital plane is seen in Figure 4. Figure 5 shows the evolution of the periapsis altitude and the sub-spacecraft periapsis latitude throughout the orbital phase. The effect of these perturbations on periapsis altitude was one of the largest influences on the timing of OCMs.

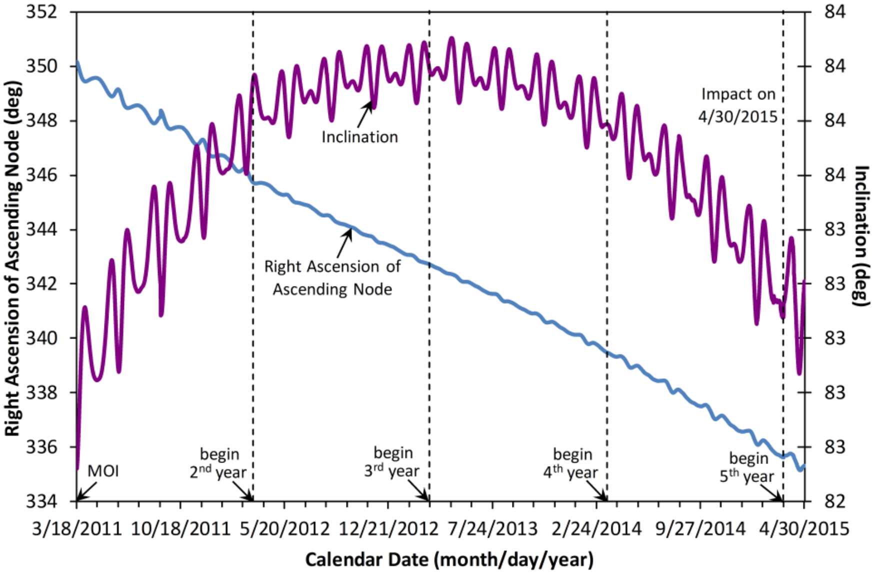


Figure 4. Orbit Plane Rotation during MESSENGER's Orbital Mission Phase.

During the first year of orbital operations, known as the primary mission, the goal of the trajectory design was to maintain a periapsis altitude between 200 and 500 km without altering the 12-h period substantially. To accomplish these goals while limiting disruptions to science observations, OCM's 1, 3, 5, and 6 each imparted a ΔV opposite the spacecraft velocity direction at apoapsis that lowered periapsis altitude back to 200 km about every 88 days when Mercury's heliocentric true anomaly was near 12°. OCMs 1, 3, and 5 accomplished this orbital change using the LVA thruster, and OCM 6 used the C-thrusters. The timing of these maneuvers ensured that Sun–spacecraft–ΔV geometry was such that the sunshade could protect the spacecraft bus from direct sunlight exposure when using either the LVA or C-thrusters.

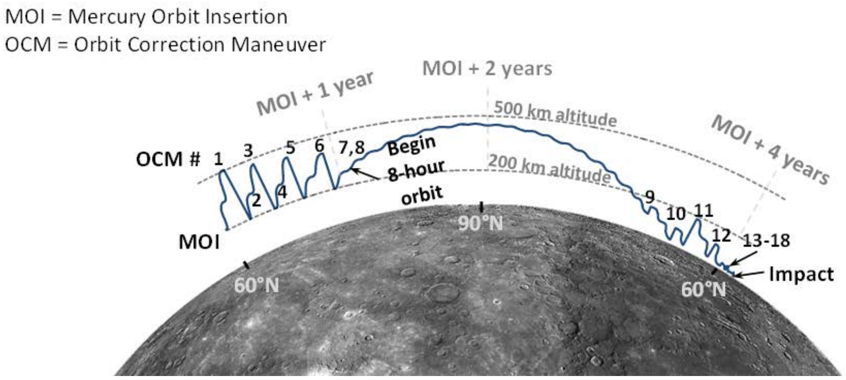


Figure 5. Periapsis Altitude during MESSENGER's Orbital Mission Phase. Periapsis Latitude Began at 60.0° N, Moved Northward to Peak at 84.1° N, and Then Moved Southward to 56.9° N at Mission End.

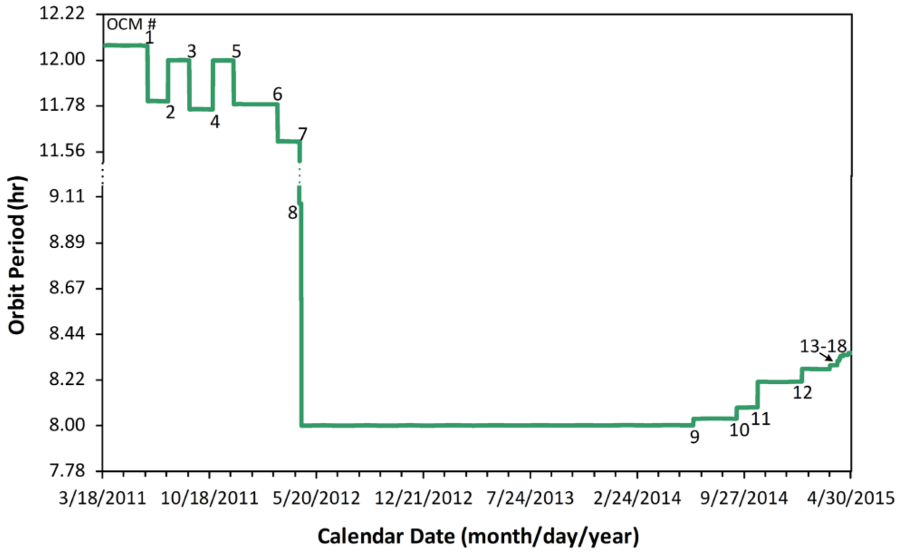


Figure 6. Orbital Period during MESSENGER's Orbital Mission Phase.

Although solar trajectory perturbations had a substantial effect on periapsis altitude, the effect on orbital period was minimal. As seen in Figure 6, all changes in orbital period of more than a few seconds were a direct consequence of OCMs performed. Therefore, to maintain an orbital period near 12 h OCMs 2 and 4 were each performed about 44 days after OCMs 1 and 3, respectively, when Mercury's heliocentric true anomaly was near 192° and the Sun–spacecraft–ΔV angle was once again favorable for use of the C-thrusters. These OCMs used the C-thrusters to impart ΔV in or near the spacecraft velocity direction at periapsis such that apoapsis was raised and the orbital period was increased to 12 h. Table 10 contains the timing and performance of OCMs 1-6. All of these OCMs were designed to begin at the nearest minute to the epoch required to center the ΔV about apoapsis (OCMs 1, 3, and 5) or periapsis (OCMs 2 and 4); however, the actual start time varied slightly from the design, depending on the time-tag bias in place on the spacecraft at the time of the maneuver. All of these OCMs had excellent performance, less than 1° error in pointing and less than 1% error in magnitude, resulting in periapsis altitudes maintained between 200.2 and 505.7 km and an orbital period varying between 12.07 and 11.61 h for the first year of the mission's orbital phase.

Table 10. Targeted versus Achieved Parameters for OCMs 1-8.

Maneuver	Date and Start Time	Main Thruster Set Used	EME2000			ΔV Magnitude (m/s)	Duration* (s)	Mass Used (kg)
			ΔV_x (m/s)	ΔV_y (m/s)	ΔV_z (m/s)			
OCM-1	15 Jun 2011	LVA,	-26.0077	3.8503	-9.1570	27.8402	173.62	6.229
	19:39:50 UTC	C1-C4	0.093° directional error			-0.10% error		
OCM-2	26 Jul 2011	C1-C4	-3.8367	-0.4098	1.1835	4.0359	187.54	1.918
	21:04:03 UTC		0.927° directional error			-0.97% error		
OCM-3	7 Sep 2011	LVA,	-23.5465	5.8020	-5.8063	24.9362	165.50	5.643
	15:08:24 UTC	C1-C4	0.109° directional error			-0.10% error		
OCM-4	24 Oct 2011	C1-C4	-3.5585	1.7643	-1.1688	4.1402	159.30	1.797
	22:11:46 UTC		0.754° directional error			-0.75% error		
OCM-5	5 Dec 2011	LVA,	-21.4813	2.8531	-4.7415	22.1827	291.22	6.057
	16:08:27 UTC	C1-C4	0.112° directional error			-0.13% error		
OCM-6	3 Mar 2012	C1-C4	-18.8618	2.3369	-2.8047	19.2118	171.38	5.162
	01:43:56 UTC		0.052° directional error			-0.11% error		
OCM-7	16 Apr 2012	LVA,	52.5925	-6.2758	5.5626	53.2570	187.76	11.148
	19:13:07 UTC	C1-C4	0.077° directional error			-0.01% error		
OCM-8	20 Apr 2012	C1-C4	31.1392	-3.3076	2.5788	31.4204	240.18	7.942
	23:05:36 UTC		0.060° directional error			-0.07% error		

*Duration does not include ~30-s spacecraft attitude stabilization "tweak" at the end of each maneuver

At the start of the second year of orbital operations, i.e., the first extended mission, the MESSENGER team chose to lower the orbital period to 8 h. This lower orbital period provided one additional orbit per day in which to gather data as well as the ability to image Mercury's southern hemisphere from one-third closer than the primary mission's 12-h orbit while still maintaining a schedule conducive to operations. This reduction in orbital period was accomplished with a maneuver design utilizing two OCMs (OCMs 7 and 8) that had the additional benefit of depleting the remaining usable propellant from the oxidizer tank and one of the two main fuel tanks. Because of substantial uncertainty in the amount of usable oxidizer remaining, OCM-7, the mission's final bipropellant maneuver, was designed so that the thrust duration could vary from 3.0 to 6.6 min depending on the percentage of the 53.3 m/s ΔV that could be accomplished with the LVA thruster. The 3.1-min maneuver executed with excellent performance, as shown in Table 10, and consumed close to the maximum amount of remaining usable oxidizer. OCM-8, scheduled only four days and four hours after the previous maneuver, was redesigned on the basis of OCM-7 performance, with no change in initial thrust time and a 0.13% lower ΔV target than the previous design. Performance information for OCM-8 is shown in Table 10. This dual-maneuver design attained the desired 8-h orbital period with only a 1.8-s offset.

Because of the lower apoapsis altitude associated with an 8-h orbital period as well as the continued northward migration of the sub-spacecraft periapsis latitude, solar gravity perturbations had a progressively smaller effect on periapsis altitude as the second year of orbital operations progressed. As seen in Figure 5, the orbit's line of apsides rotated over the pole as the sub-spacecraft periapsis latitude reached its northernmost point of 84.1°N about 13 days before the start of the third year of orbital operations (known as the second extended mission). After this orbit "rollover" event, solar gravity perturbations lowered the periapsis altitude between successive orbits at an increasing rate as the sub-spacecraft periapsis latitude progressed southward. Because of the period of lessened solar influence, no OCMs were required until the fourth year of orbital operations and the beginning of the low-periapsis-altitude campaign.

The combined periapsis-raising effect of OCMs 9–12 delayed Mercury surface impact from late August 2014 to late March 2015, and the OCM timing provided several periods during which orbits had low periapsis altitudes. This low-periapsis-altitude campaign resulted in approximately

190 days of spacecraft operation while in an orbit with periapsis altitude at or below 100 km and provided approximately 200 orbits with periapsis altitudes at or below 30 km. To accomplish these low altitudes, OCMs 9-11 each imparted a ΔV in the spacecraft velocity direction at apoapsis that raised periapsis altitude so that the spacecraft altitude reached a minimum of about 25 km above Mercury's terrain prior to the next OCM. OCM-12 imparted a ΔV in the spacecraft velocity direction at apoapsis in order to raise periapsis so that the minimum altitude reached a local minimum of 14.8 km above the terrain during the period when periapsis altitude had little variation prior to OCM-13. All four OCMs had good performance, as seen in Table 11, which also includes maneuver timing. As with all previous OCMs, OCMs 9−12 were performed when Mercury's heliocentric orbit true anomaly was conducive to maintaining sun shade protection while providing for efficient use of the C-thrusters for all four maneuvers. In addition to increasing periapsis altitude, OCM-10 also successfully depleted nearly all remaining usable fuel from the second main fuel tank (the first main fuel tank was depleted during OCM-7). As a consequence, only the auxiliary tank contained significant amounts of usable hydrazine after the maneuver. Because the project anticipated the depletion of the remaining hydrazine fuel prior to the desired end of the mission, the use of gaseous helium pressurant as a propellant was tested during OCM-12. To accomplish this test, the 9.6-m/s ΔV maneuver began and ended while using hydrazine from the auxiliary tank; however, both main fuel tanks were opened during a portion of the maneuver, thus expelling what little usable hydrazine remained in the main tanks followed by gaseous helium expulsion. This test provided information on thruster performance when using only helium.

Table 11. Targeted versus Achieved Parameters for OCMs 9-18.

Maneuver	Date and Start Time	Main Thruster Set Used	EME2000			ΔV Magnitude (m/s)	Duration* (s)	Mass Used (kg)
			ΔV_x (m/s)	ΔV_y (m/s)	ΔV_z (m/s)			
OCM-9	17 Jun 2014 14:52:43 UTC	C1, C4	4.3939	-0.0371	-2.4066	5.0100	190.02	1.873
			0.410° directional error			-1.52% error		
OCM-10	12 Sep 2014 15:54:31 UTC	C1-C4	7.1941	0.0833	-4.6260	8.5535	134.08	2.161
			0.082° directional error			-0.02% error		
OCM-11	24 Oct 2014 18:58:12 UTC	C1-C4	15.9048	0.3463	-11.0000	19.3412	149.88	4.600
			0.105° directional error			0.09% error		
OCM-12	21 Jan 2015 18:27:24 UTC	C1-C4	7.5631	0.2254	-5.9621	9.6332	109.14	2.296
			0.059° directional error			-0.34% error		
OCM-13	18 Mar 2015 14:59:39 UTC	C1-C4	2.2572	1.2891	-1.6273	3.0668	32.96	0.725
			0.518° directional error			0.24% error		
OCM-14	2 Apr 2015 20:29:44 UTC	P1, P2	2.8673	-0.3498	-1.1171	3.0970	401.24	0.926
			0.421° directional error			4.57% error		
OCM-15	6 Apr 2015 16:14:07 UTC	P1, P2	1.7195	0.0598	-0.4258	1.7724	600.00	0.501
			0.245° directional error			-49.36% error		
OCM-15A	8 Apr 2015 16:55:18 UTC	C1-C4	0.3601	-0.1022	-1.7940	1.8326	303.00	0.493
			0.672° directional error			-4.54% error		
OCM-16	14 Apr 2015 15:16:00 UTC	C1-C4	0.5638	-0.0288	-0.7728	0.9570	201.92	0.294
			1.429° directional error			-2.86% error		
OCM-17	24 Apr 2015 17:22:47 UTC	C1-C4	1.3548	0.4309	-0.4522	1.4918	469.22	0.434
			0.600° directional error			-2.62% error		
OCM-18	28 Apr 2015 21:19:57 UTC	C1-C4	-0.1877	-0.0216	-0.3811	0.4254	181.02	0.114
			0.833° directional error			-3.15% error		

*Duration does not include ~30-s spacecraft attitude stabilization "tweak" at the end of each maneuver

Several factors, including spacecraft heating and Mercury surface lighting, were carefully considered when designing the low-periapsis-altitude campaign. Periods of surface visibility at periapsis, which occurred when the solar incidence angle was less than 84°, also occurred around a thermal "hot season," i.e., a period of greater planetary thermal input to the spacecraft. Although periods of low-altitude operation during a hot season raised the spacecraft temperature nearer to allowable limits, Mercury surface visibility was also an important factor for imaging. Furthermore, though the surface may not be visible during the lowest altitude of the orbit (i.e., periapsis) at solar incidence angles greater than 84°, the surface is visible from higher altitudes when the spacecraft is in other portions of the orbit. As seen in Figure 7, the first time near a 25-km periapsis altitude and the first time near a 15-km periapsis altitude occurred soon after a hot season containing periapsis altitudes near 50 km. In contrast, the second and third times near a 25-km periapsis altitude did not occur shortly after a hot season.

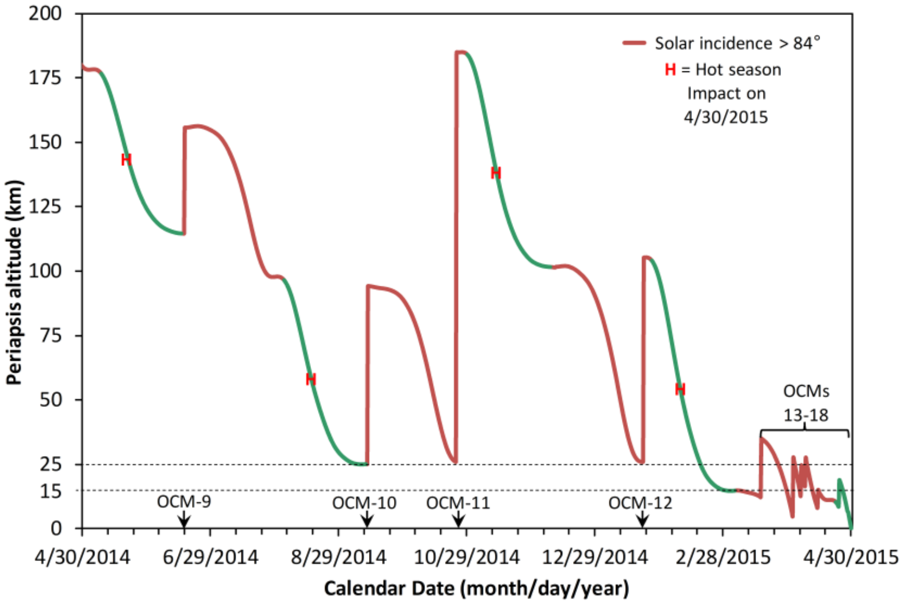


Figure 7. Altitude and Surface Visibility at Periapsis during Low-Periapsis-Altitude Campaigns.

During the final 44 days of the mission, a low-periapsis "hover" campaign was implemented that further delayed impact and maintained minimum altitudes above Mercury between 5.4 and 34.2 km prior to the final decent to impact. This campaign consisted of seven maneuvers (OCMs 13–18) to increase periapsis altitude, the closest of which were separated by only two days. Because the maneuvers occurred in such close proximity to each other and the planet's surface, maneuver designs had to be adaptable to the performance of the pervious maneuver as well as changes in predicted altitude.[11] Moreover, a five-day solar conjunction between OCMs 15 and 16, as well as the propulsive abilities of gaseous helium, also had to be considered when determining the timing and magnitude of each maneuver.

Because of the timing of these final OCMs and their respective Sun–spacecraft–orbital plane geometries, the ΔV direction, which would have ideally been in the velocity direction, was required to be out of the plane of the spacecraft's orbit in order to maintain sunshade protection. Depending on the amount of out-of-plane ΔV necessitated by Sun elevation constraints for each maneuver, the OCM was shifted up to 7.6° in orbit true anomaly from apoapsis to increase efficiency. Although five maneuvers were able to use the C thrusters, two maneuvers, OCMs 14 and 15, required the use of the P thrusters to accomplish the desired periapsis altitude increase while keeping within the required 12° Sun elevation angle.

With the exception of OCM-15, the maneuvers during this "hover" campaign performed as anticipated. The performance and timing for OCMs 13–18 are summarized in Table 11, and the effect of each OCM on periapsis altitude is seen in Figure 7. OCMs 13 and 14, the last two maneuvers to be performed using only hydrazine, resulted in good performance, with errors similar to those of previous maneuvers. As anticipated, all usable hydrazine was exhausted during OCM-15, and the remaining OCMs were performed using gaseous helium pressurant; however, the amount of usable hydrazine available for OCM-15 was slightly lower than predicted. Although autonomy successfully switched over to the use of gaseous helium after the hydrazine was exhausted, the P thrusters did not provide enough thrust while using helium to achieve the desired 3.5-m/s ΔV. Despite continuing until the maneuver time-out of 600 s after the start of thrusting, OCM-15 still resulted in a -49.4% error in ΔV magnitude. The OCM-15A clean-up maneuver just two days after OCM-15 is an example of maneuver design adaptability. Because the spacecraft could have impacted Mercury before to the end of the solar conjunction that began about one day after OCM-15, OCM-15A took place just over one day into the solar conjunction when the Earth–Sun–spacecraft angle was only 1.9° and the ability to monitor the maneuver was degraded. This clean-up maneuver, the first to be performed using only gaseous helium, successfully placed the spacecraft back on track to perform OCM-16 about two days after the solar conjunction ended. OCMs 16 and 17 each successfully raised the spacecraft's minimum altitude with only small errors in magnitude and direction. As the spacecraft's impact onto Mercury's surface approached and navigation errors were reduced, it became apparent that the spacecraft's impact would occur one orbit earlier than planned. Because a 70-m Deep Space Network antenna track on the orbit before planned impact would download a substantial amount of data remaining on the spacecraft's recorder, an earlier impact was undesirable. Therefore, OCM-18 raised the minimum altitude by only 1.05 km, enough that spacecraft impacted on the desired orbit on 30 April 2015 at 19:26:01.166 UTC, and at 54.44° N latitude and 210.12° E longitude.

CONCLUSION

After its launch on 3 August 2004 from Cape Canaveral, Florida, the MESSENGER spacecraft proceeded to execute six planetary flybys, five DSMs, and 12 TCMs before insertion into orbit about Mercury on 18 March 2011. With the exception of one Venus flyby during solar conjunction, each planetary flyby came within 1.5 km and 3 s of the planned periapsis altitude and time, respectively. This accurate flyby targeting was achieved using highly accurate maneuvers as well as the implementation of a new solar sailing technique for correcting maneuver errors. The only TCMs with larger errors in ΔV magnitude or direction were those with relatively small ΔV magnitudes. Furthermore, utilizing solar panel tilt and sunshade orientation to affect low-thrust trajectory perturbations imparted by solar radiation pressure eliminated the need for any TCMs after TCM-19. An accurate Mercury arrival only 6.0 km above the targeted periapsis altitude and less than 1 s from the targeted periapsis time set the stage for the Mercury orbit insertion.

MESSENGER became the first spacecraft to orbit Mercury when it successfully completed its orbit insertion maneuver on 18 March 2011 at 01:00:00 UTC. The reconstructed maneuver had a ΔV magnitude and direction that nearly matched the final designed values. The resulting orbit had (relative to the Mercury centered inertial frame) a 207.39-km periapsis altitude, 12.07-h orbital period, 59.98°N sub-spacecraft periapsis latitude, 350.16° right ascension of the ascending node, and 82.52° orbit inclination, all of which were well within required values. The 4.1 years the spacecraft spent orbiting Mercury can be separated into four successive trajectory designs.

Throughout the first year of operation in orbit at Mercury the spacecraft successfully maintained periapsis altitudes between 200 and 506 km and an orbital period between 12.07 and 11.61 h. This outcome was accomplished by successfully performing a maneuver every 44 days. OCMs 1, 3, 5, and 6 countered the effects of a variety of perturbing forces, including those of solar gravity and Mercury's slight oblateness, by lowering periapsis altitude back to 200 km. However, the reduction in periapsis altitude also reduced the orbital period by approximately 15 min from the desired 12 h. Therefore, OCMs 2 and 4 were each used to increase orbital period back to 12 h.

With full mission success recognized after the first year in orbit, the orbital period was reduced to 8.0 h in mid-April 2012, one month after the start of the spacecraft's second year in orbit. Accomplished utilizing OCMs 7 and 8 just four days apart, the achieved orbital period deviated by only 1.8 s from the target. 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 previously possible. No further maneuvers were required to maintain desired periapsis altitudes until the fourth year in orbit.

During the last nine months of the fourth year in orbit (mid-June 2014 to mid-March 2015), OCMs 9–12 enabled a low-periapsis-altitude campaign. The first three of these OCMs each successfully targeted a 25-km minimum altitude when periapsis altitude had little variation just prior to the next OCM. OCM-12 resulted in a 14.8-km minimum altitude during the period prior to OCM-13 when periapsis altitude had little variation. This low-periapsis-altitude campaign resulted in approximately 190 days of spacecraft operation while in an orbit with a periapsis altitude at or below 100 km and about 200 orbits with periapsis altitudes at or below 30 km. The success of this campaign was followed by a low-periapsis "hover" campaign.

During the final 44 days of the mission, the low-periapsis "hover" campaign successfully maintained minimum altitudes above Mercury between 5.4 and 34.2 km prior to the final decent to impact. The campaign consisted of seven maneuvers (OCMs 13–15, 15A, and 16–18), each of which increased periapsis altitude. Because the maneuvers occurred in such close proximity to the planet's surface and to each other (some maneuvers occurred only two days apart), maneuver designs had to rapidly adapt to the previous maneuver's performance as well as changes in predicted altitude. Furthermore, all remaining usable hydrazine was exhausted during OCM-15, and the remaining maneuvers were successfully performed by repurposing gaseous helium pressurant as a propellant. The combination of these two low-altitude campaigns provided unprecedented observational opportunities and helped to further refine Mercury's gravity field prior to the spacecraft's inevitable impact onto Mercury on 30 April 2015.

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