# Maneuver Design Strategy Enables Precise Targeting of the First MESSENGER Mercury Flyby

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**On 14 January 2008 MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) completed the first Mercury flyby since Mariner 10 did so in March 1975. This paper will describe how post-launch modifications to MESSENGER's maneuver design process contributed to highly accurate delivery near the encounter B-plane aim point for the second Venus and first Mercury flybys. Maneuver performance for completed trajectory-correction maneuvers and requirements for upcoming maneuvers and planetary flybys will further demonstrate maneuver design and trajectory optimization improvements made since launch. Also included are the effects of all six planetary gravity assists on the spacecraft trajectory.**

## I.   Introduction

**O**n 14 January 2008 MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) became the first spacecraft to fly by the planet Mercury since the third Mariner 10 flyby in March 1975. Designed and operated by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) 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), 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 at 02:15:56.537 EDT[1]. Four years after launch the spacecraft has completed three large deep-space maneuvers (DSMs), one Earth flyby, two Venus flybys, and one Mercury flyby. The ecliptic plane projection of the MESSENGER spacecraft's heliocentric trajectory in Fig. 1 shows the location of two additional Mercury flybys and two more DSMs planned during the remainder of its 6.6-year ballistic trajectory to Mercury. The mission's core science objectives[2] will be addressed using carefully coordinated sequences of instrument observations during a one-year Mercury orbit phase that begins on 18 March 2011.

Demonstration of the assertion that improvements in maneuver design strategy contributed to precise targeting for the spacecraft's first Mercury flyby requires a description of spacecraft configuration, operational constraints, and maneuver target constraints that affect maneuver performance. Major components of the three-axis-stabilized MESSENGER spacecraft (S/C) include two rotatable solar arrays, a ceramic cloth sunshade, the spacecraft bus (on

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which all 17 thrusters are mounted), and a magnetometer boom (Fig. 2). As the spacecraft reaches a distance of less than 0.5 AU (astronomical units) from the Sun, the solar arrays are rotated between 30°and 72° from the full-Sun orientation in order to maintain solar array surface temperature well below 150°C yet still provide adequate power for the spacecraft. Attitude control is accomplished with four reaction wheels. These wheels also store momentum produced by environmental torques. In order to prevent *active* momentum dumps (via thruster use) the torque due to solar radiation pressure (SRP) can be used for *passive* reduction of momentum stored in the reaction wheels. Passive momentum management is achieved by controlling solar radiation pressure induced torque with: (1) pointing offsets that orient each solar array at slightly different orientations relative to the Sun, (2) selection of sunshade orientation within ± 12° Sun keep-in constraints, and (3) attitude changes around the direction to the Sun, thereby forcing the SRP torque to oppose the direction of the current system momentum. Spacecraft attitude history and prediction files are created using information about spacecraft attitude from momentum management, science activities, navigation events for orbit determination, operational tests, and spacecraft uplink and downlink. Application of these attitude history and prediction files to orbit determination and orbit propagation using gravitational attraction and solar radiation pressure perturbations on the spacecraft all contribute to the precise determination of requirements for trajectory correction maneuvers (TCMs).
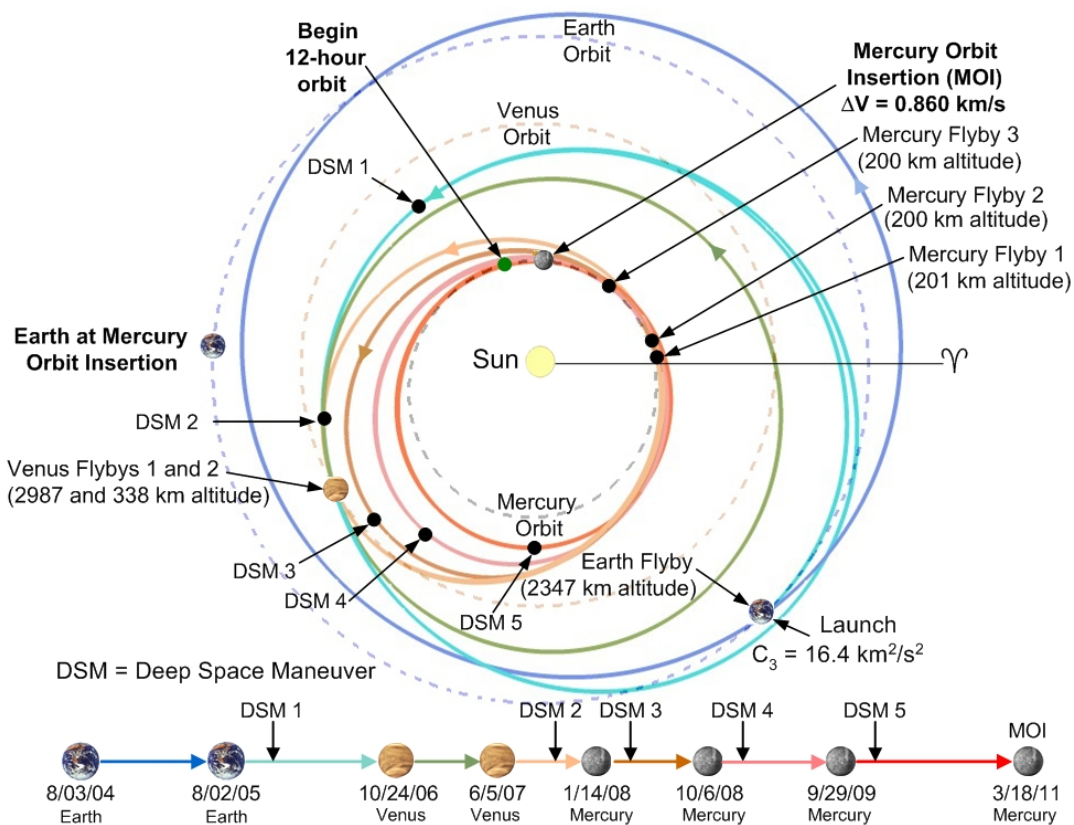


**Figure 1. Ecliptic plane projection of the MESSENGER heliocentric trajectory.**

The spacecraft's dual-mode propulsion system draws hydrazine from two large fuel tanks and one small auxiliary fuel tank and nitrogen tetroxide from one large oxidizer tank. The 660-N large-velocity-adjust (LVA) thruster (specific impulse of 316 s) and 16 smaller monopropellant thrusters (specific impulse of 200 to 235 s) provide capability for TCMs in any direction, even when considering sunshade orientation constraints. Four 22-N monopropellant thrusters are mounted on the same deck as the LVA thruster and twelve 4-N thrusters are situated in groups of four at the corners of both solar array sides of the spacecraft bus and in pairs on the sunward and anti-sun sides of the spacecraft. The 12 smallest thrusters are used for attitude control during burns and for small TCMs. The net direction of velocity change (ΔV) for each thruster set and primary spacecraft structures contributing to thruster plume impingement are listed in Fig. 2. Plume impingement provides significant reduction in propulsive efficiency for TCMs requiring significant duty cycles for the A (-x side) and B (+x side) thrusters. Additional details of the spacecraft's propulsion system are provided by engineers who directed the subsystem design and pre-launch tests[3].

Operational constraints for TCM design and planetary flybys restrict both spacecraft orientation and proximity to the planet. An operational limitation on sunshade orientation when the spacecraft is closer than 0.85 AU from the Sun is called the Sun keep-in (SKI) constraint. For SKI-compliant ΔVs that are not directed toward or away from the Sun, the Sun-spacecraft-ΔV angle must be between 78° and 102°. During heliocentric cruise this constraint limits the timing for DSMs. During the Mercury orbit phase this constraint restricts the timing of orbit insertion and confines the timing of TCMs to twice per 88-day Mercury year. Periapsis altitude limits during planetary flybys included 300-km altitude (200 km with 3σ errors) at Venus and 200-km altitude (150 km with 3σ errors) at Mercury. Additional upper limits were placed on total ΔV cost incurred through Mercury orbit insertion if projected TCM execution errors and potential orbit propagation errors exceeded a

| 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. Thruster orientation for MESSENGER (-y axis points near the Sun).**

limit set for each flyby. All TCMs must occur outside of superior solar conjunction, defined by Sun-Earth-spacecraft angle < 3° where solar-plasma-induced noise interferes with communication with the spacecraft. The requirement for real-time monitoring of the spacecraft during TCM execution is compromised during solar conjunction.
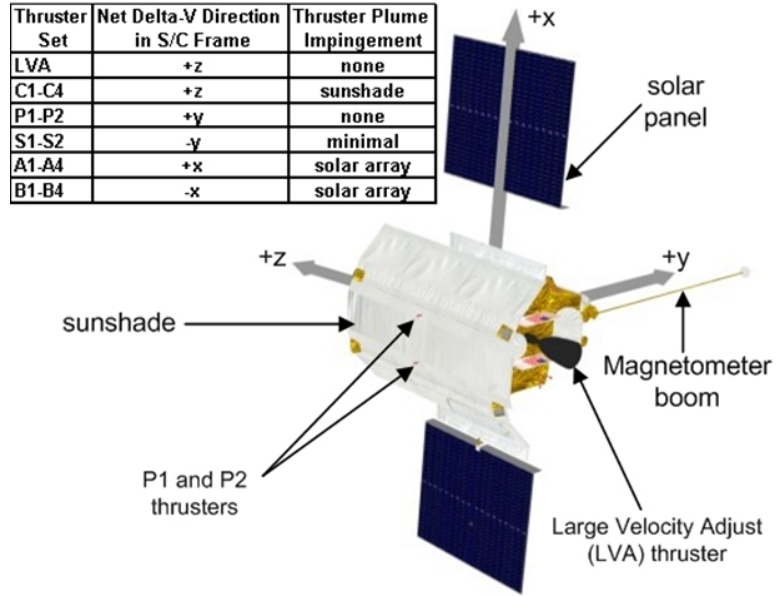
## II.   Maneuver Design Options at Launch

In order to understand the basis for post-launch maneuver design improvements, it is beneficial to summarize maneuver design options that were available in mission design software as of launch. Most of these maneuver design options had been practiced and documented during a series of pre-launch operational readiness tests. 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 June 21, 2006. The relative ΔV magnitude reserved for each propulsive mode increases as the mode number increases from one to three. Table entries with two

**Table 1.   MESSENGER maneuver types available at launch.**

| 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 |

propulsive modes are multiple-component TCMs since two ΔV vector components are required to obtain the net ΔV with Sun-spacecraft-ΔV angle between 12° and 78° or between 102° and 168° while maintaining spacecraft attitude

within SKI limits. The "lateral" ΔV component direction indicates that the ΔV direction is within 12° of orthogonal to the sunward or anti-sun (also called "radial") direction. One mission-critical (unable to achieve Mercury orbit without) maneuver type missing from Table 1 is the "turn while burn" approach used with constant rate changes in ΔV vector right ascension and declination. Development and testing of mission design software for this "turn while burn" method needed for Mercury orbit insertion was planned during the cruise phase. Some details of the mode 2/1 and mode 1/1 component maneuver design were not fully developed before MESSENGER's launch.

Another aspect of maneuver design is the strategy for recovery from maneuver anomalies. Prior to launch the schedule for deterministic (well known before launch) TCMs placed such ΔVs at the point of minimum total mission ΔV with adjustment in timing to make DSM-2 compliant with the solar conjunction exclusion constraint. If a mission-critical DSM was missed or had a large underburn, the contingency cleanup option could require either a violation of the 12° Sun-spacecraft-ΔV SKI constraint (leading to direct solar heating on sensitive spacecraft components for a short time before, during, and after a contingency TCM) or a delay of about one orbit with large increase in total mission ΔV. Statistical TCMs (cleanup maneuvers after launch, DSMs, or planetary flybys) were placed after DSMs and at carefully considered times before and after each planetary encounter. Prior to launch, contingency (or backup) TCMs were not scheduled. However, the pre-launch placement of DSM-2 was about one week before reaching a 2° Sun-Earth-spacecraft angle within solar conjunction.

### III.  Maneuver Design and Trajectory Prediction Improvements after Launch

Maneuver design and trajectory prediction improvements after launch include factors that lower mission risk, preserve ΔV margin, and minimize offsets from planetary encounter target objectives. MESSENGER flight team members responsible for these improvements include navigation, mission design, guidance and control, and propulsion. These improvements include aspects of orbit determination and maneuver performance estimation that contribute to reductions in uncertainty in the location and timing of the spacecraft trajectory propagated to the next planetary encounter. Improvements are organized in three categories based on their effect (significant, minimal, or none) on the success of targeting for the spacecraft's first Mercury flyby. Those maneuver design improvements with no effect of Mercury flyby 1 targeting are included because understanding these adjustments is necessary to explain the timing of completed and planned TCMs that are discussed in subsequent sections.

Description of the TCMs designated for the targeting and post-encounter cleanup of Mercury flyby 1 is helpful toward understanding the effectiveness of several maneuver design improvements. Note in Fig. 3 the placement of DSM-2 (TCM-18) well before the  longest solar conjunction, providing opportunity for a contingency  TCM prior to
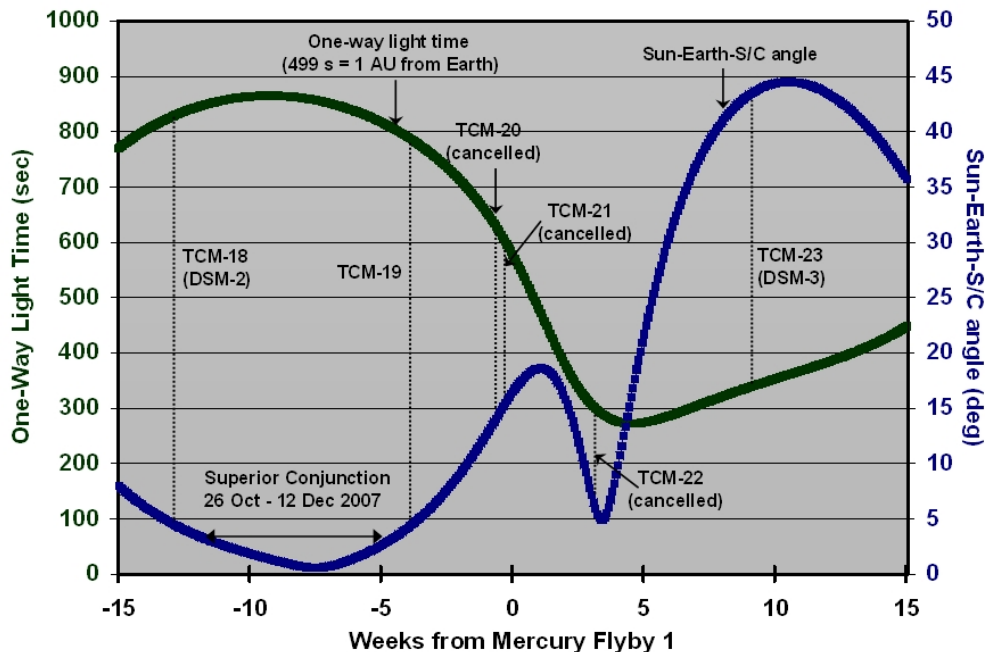


**Figure 3.  Communication parameters and TCM placement near the first Mercury encounter.**

entering conjunction and also giving time for orbit data collection and maneuver performance estimation before conjunction. The placement of DSM-2 well before the minimum-total-ΔV date provided a valuable head start on preliminary planning for TCM-19, which was scheduled only 26 days before the Mercury encounter. Minimal execution error, accurate trajectory propagation, and Mercury encounter target adjustment using adjustments in solar panel orientation all contributed to the cancellation of TCM-20 and TCM-21 (contingency placeholder) before the Mercury flyby and TCM-22 after the flyby.

Accuracy of the predicted flyby trajectory and approach trajectory correction maneuvers is assessed using the B-plane, or hyperbolic impact-plane, intercept at Mercury periapsis. The B-plane is the plane normal to the incoming asymptote of the hyperbolic flyby trajectory that intersects the center of the target body (i.e., Mercury). The reference vector normal to the B-plane, the "S-axis," lies along the incoming asymptote. For MESSENGER planetary encounters, the "T-axis" is parallel to the line of intersection between the B-plane and the Earth Mean Ecliptic plane of January 1.5, 2000 (and is positive in the direction of decreasing right ascension). The "R-axis" (positive toward the south ecliptic pole) completes the orthogonal, right-handed "T-R-S" Cartesian coordinate axes.

### A. Improvements with Significant Effect on Mercury Flyby 1 Targeting

Although the precise targeting of MESSENGER's first flyby of Mercury required significant contributions from many aspects of the flight team, there were three adjustments that provided notable improvements in targeting accuracy. These adjustments include:

1) integrating solar radiation pressure perturbations with changes in solar array orientation to shift the Mercury encounter B-plane intercept,
2) using additional Delta Differential One-way Ranging (Delta-DOR) data to improve trajectory estimation,
3) adjusting spacecraft attitude during TCM implementation to offset performance bias observed in maneuver Monte Carlo simulations.

### 1. Application of Solar Sailing to Effectively Utilize Solar Radiation Pressure Perturbations

As the spacecraft approached Mercury the flight team worked diligently to fully define the spacecraft sunshade and solar array orientation for all times leading up to Mercury closest approach (C/A). This full knowledge of spacecraft attitude, not available in time for submittal of the final TCM-19 design, helped minimize trajectory propagation error contributions from solar radiation pressure acting on the spacecraft. The 1 January 2008 orbit solution indicated a flyby altitude of 208 km (± 16 km 3σ). This put the spacecraft at risk of incurring up to a 12 m/s increase in total ΔV to correct the offset from the optimal Mercury flyby 1 aim point in the B-plane. Shortly before a meeting to discuss plans either to proceed with or cancel design and implementation of TCM-20 (scheduled four days before Mercury periapsis), the guidance and control lead engineer proposed moving a planned solar array configuration change (Sun offset angle from 50° to 70°) four days earlier. The resulting change in solar radiation pressure on the spacecraft imparted an effective ΔV of 0.005 m/s per day, with much of the resulting translational change decreasing periapsis altitude closer to the 200-km goal. Both navigation and mission design teams computed that a shift toward Mercury of 7 to 8 km along the B-plane -T axis and a shift of 5 to 6 km south along the B-plane R axis would occur if the additional solar panel tilt occurred on January 4. By reducing the encounter altitude to between 201 and 202 km, this would effectively replace the majority of shift achieved with TCM-20 on 10 January 2008. Fig. 4 depicts the B-plane aim point and the translational shift in the predicted B-plane point achieved by this "solar sail" type alteration of solar array orientation. The red dashed line corresponds to 200-km altitude.

### 2. More Delta-DOR Tracks before Mercury Flyby 1 to Reduce Mercury Encounter Trajectory Uncertainty

With a 7-week-long solar conjunction occurring from about one week after DSM-2 until five weeks before the Mercury flyby, the navigation team recommended the scheduling of Delta-DOR tracks near DSM-2, solar conjunction entry and exit, and on final approach to Mercury. The Delta-DOR tracking session includes slews by two Deep Space Network (DSN) antennas from the spacecraft to nearby (within 10° pointing direction) quasars and return to the spacecraft. About 10 minutes of VLBI (very long baseline interferometry) data are collected from each source (spacecraft or quasar) using two DSN antennas at widely separated tracking complexes. More detail on the application of Delta-DOR to the MESSENGER mission is available in Refs. 4 (Venus flyby 1), 5 (Venus flyby 2), and 6 (DSM-2 and Mercury flyby 1). Figure 5 shows the timing and frequency of Delta-DOR tracks scheduled near DSM-2, the subsequent solar conjunction, and Mercury flyby 1. These tracks include a balance of north-south (N-S) and east-west (E-W) baseline tracks indicating the VLBI separation of DSN antennas. The navigation team's incorporation of Delta-DOR tracking data into orbit solutions enabled faster and more accurate reconstruction of DSM-2, and more accurate estimation of the Mercury B-plane intercept for more precise planning of TCM-19.
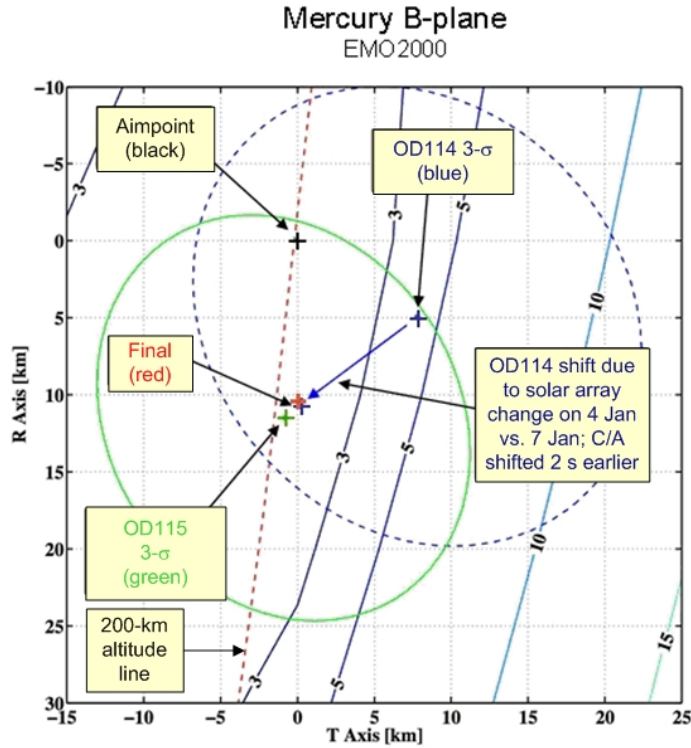
**Figure 4. Mercury flyby error ellipses and B-plane intercept points at selected orbit determination (OD) solutions during Mercury approach.**
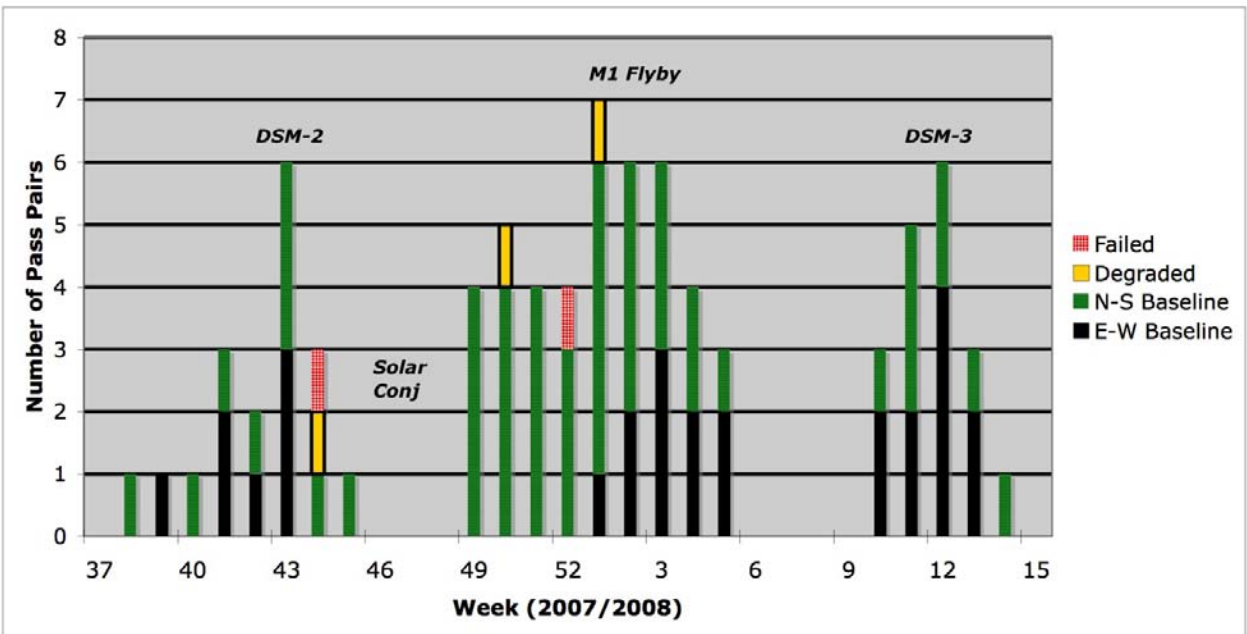


**Figure 5. Delta-DOR tracks associated with Mercury flyby 1.**

*3. Adjustment of Spacecraft Attitude to Correct Demonstrated TCM Execution Performance Bias*

   TCM-19 was the first MESSENGER maneuver to include an attitude bias based on experience at prior maneuvers. The $\Delta V$ for this maneuver was imparted by the B-thrusters, which are on the +x face of the spacecraft

(producing a -x force in the spacecraft body frame), and are canted in toward the solar array. This cant angle resulted in significant plume impingement for these thrusters, which reduced the thrust in the -x direction by 10-15%. The impingement also produced a small lateral force in the –y direction of about 3-4% of the expected maneuver thrust level. Reduced thrust in the -x direction increases the duration necessary to achieve the desired ΔV. Since each MESSENGER maneuver is terminated on the basis of onboard accelerometer measurement of the ΔV, this does not adversely impact the magnitude performance of the maneuver. The accelerometers sense underperformance due to plume impingement, and resulting adjustments in burn duration are used to compensate for the reduction in thrust. This can be seen in the upper plot in Fig. 6, where the Monte Carlo simulations for TCM-19 show magnitude errors of less then 1% despite the modeled 15% reduction in thrust due to plume impingement. The direction performance in the simulations is clearly biased by about 1.5°, which reflects the modeled impingement force of about 3-4%. Although there is an onboard guidance algorithm to improve direction performance for the maneuvers, it was necessary to disable this algorithm for TCM-19 due to problems experienced at prior maneuvers. While a direction error of 1.5° would have been tolerable at this burn, the team was convinced that the burn attitude could be biased to remove this offset. Since there wasn't a high degree of confidence in the impingement model used to produce Fig. 6, the team relied more heavily on the flight experience of similar burns. The flight data from three similar maneuvers (TCMs 10, 12 and 16) revealed an expected direction error of 2° resulting from the –y impingement force. The burn was biased to account for this expected burn direction error via a 2° tweak to the burn attitude. The execution of TCM-19 revealed that the direction bias improved performance as expected, resulting in a direction error of 0.2° for the maneuver, and significantly improving the Mercury flyby 1 targeting.
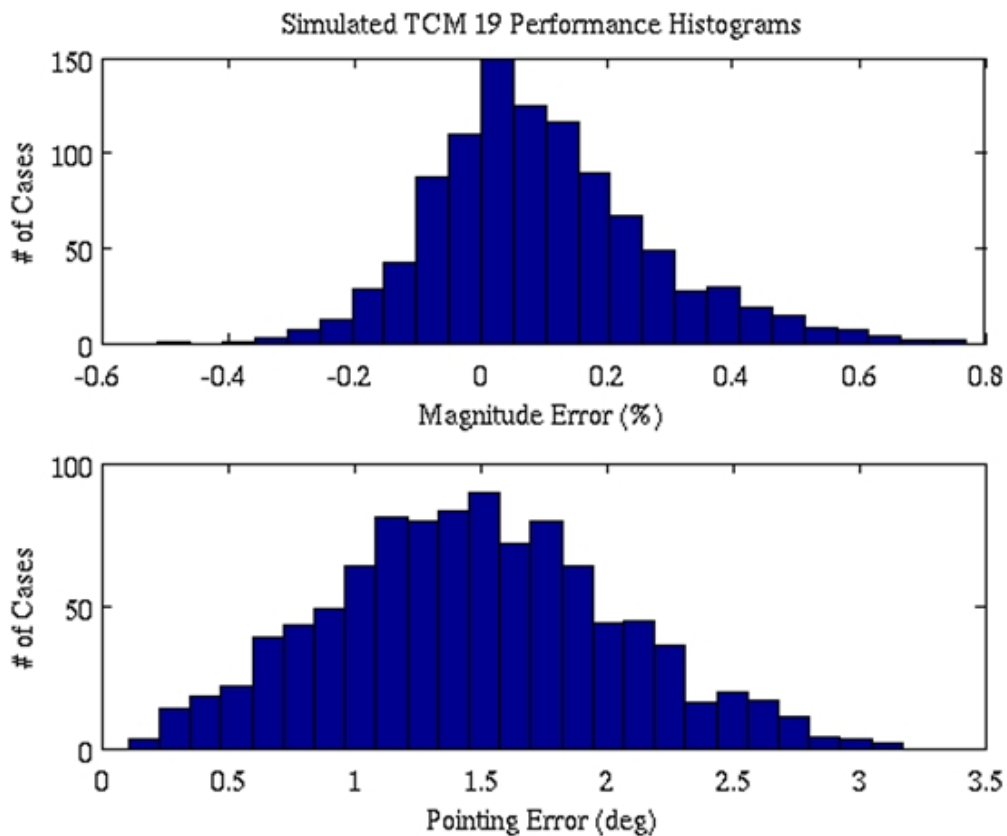


**Figure 6. Monte Carlo simulation results for TCM-19.**

## B. Improvements with Minimal Effect on Mercury Flyby 1 Targeting

Three more post-launch adjustments in TCM planning and design led to small improvements in targeting accuracy. These adjustments include:
1)    accounting for the offset between the true LVA thrust vector direction and the spacecraft +z axis at DSM-2,
2)    restricting planetary approach TCMs to implementation using a single thruster set,
3)    improving TCM performance estimation by detailed accounting of all thrust activity based on in-flight data.

*1. Application of Measured Offset between the LVA Thrust Vector and the Spacecraft's +z Axis*

Analysis of thruster and accelerometer data from the first two LVA thrust events, DSM-1 (TCM-9) on 12 December 2005 and TCM-13B (second component of the Venus flyby 1 cleanup) on 2 December 2006 revealed a misalignment of the LVA thrust vector direction and the spacecraft's +z axis. The Cartesian unit vector (x, y, z) in the spacecraft body frame for the computed LVA thrust vector alignment is (0.003, -0.012, 0.99992), which corresponds to a 0.7° offset. Accounting for this alignment offset with DSM-2 planning contributed to lower execution error for this final deterministic TCM less than three months before Mercury flyby 1. The minimal execution error for DSM-2 led to cancellation of a contingency cleanup TCM just before the spacecraft entered the mission's longest solar conjunction in late October of 2007.

*2. Implementation of Planetary Approach TCMs Using a Single Thruster Set*

Before approach to the first Venus flyby the plan was to use two orthogonal thruster sets (see Table 1) in the Introduction) to achieve ΔVs with Sun-spacecraft-ΔV angle between 12° and 78° or between 102° and 168°. A mode 2/1 component maneuver (TCM-11) was implemented during approach to Venus flyby 1 with a large (> 11°) pointing error. For the final TCM before Venus flyby 1 (TCM-12) and for approach to Venus flyby 2 and Mercury flyby 1 all statistical TCMs had pointing errors at or below 2°. Even though the cause for the large pointing error for TCM-11 was understood, the more accurate and less complex (to design and implement) single-component TCMs were made possible by shifting the periapsis time of the upcoming flyby either later or earlier until the Sun-spacecraft-ΔV angle came within 1° of 90°. Note that two solutions exist – one with earlier and one with later than the nominal (no-TCM) planetary arrival time. Once the lowest-ΔV solution was identified for a preliminary TCM design, the planetary encounter time was frozen to assist final science and operations planning. Orbit determination updates between the preliminary and final TCM designs offered small enough change to allow a SKI-compliant (Sun-spacecraft-ΔV angle within 12° of 90°) design using the frozen planetary encounter time. The well-tested B-thruster set was used for precise implementation of small mode-1 TCMs just before each flyby.

*3. Improved Modeling of TCM Performance for Design*

At the beginning of the maneuver design process inputs from propulsion and guidance and control are delivered to the mission design lead engineer. After incorporation of updated TCM performance parameters such as specific impulse, thrust level, and duty cycle for each thruster set during all segments of the TCM, the mission design team delivers a simplified equivalent (in performance) engine model to the navigation team. Improvements based on post-flight experience using TCM telemetry and on maneuver design software upgrades have minimized differences in propellant usage and thrust duration between TCM final design and TCM final reconstruction. The net result is small improvements in the accuracy of post-TCM trajectory propagation to the planetary encounter.

**C. Improvements with No Effect on Mercury Flyby 1 Targeting**

Although three additional maneuver design adjustments did not affect Mercury flyby 1 targeting accuracy, these adjustments offer varying amounts of risk reduction for upcoming TCMs. These design and schedule adjustments include, in order from highest to lowest change in potential mission risk:
1) developing and completing a test of the "turn while burn" mode required for Mercury orbit insertion,
2) adding fully designed, tested, and scheduled contingency TCM options for mission-critical TCMs,
3) formulating a minimum-cost method for implementing vector-component TCMs.

*1. Upgrade of Maneuver Design Software, Processes, and Test Plans Leading to an Orbit Insertion Test*

The ability to follow a changing ΔV direction during Mercury orbit insertion is a critical requirement for mission success. The MESSENGER spacecraft has insufficient propellant margin to enable orbit insertion using a highly inefficient inertially fixed ΔV direction. The means of implementation chosen well before launch by the MESSENGER project is optimization of initial ΔV vector right ascension and declination, along with optimal rates for right ascension and declination. For the current nominal MOI design the thrust vector changes by about 34° in declination and 6° in right ascension. Application of the same turn rate during DSM-3, the smallest of all five DSMs, produced a ΔV direction change of 3.9° in declination and 0.7° in right ascension. This small deviation from an inertially fixed TCM implementation increased total mission ΔV less than 0.02 m/s. Using DSM-3 to test the ground-based and onboard software for Mercury orbit insertion presented the lowest potential for execution error of any mode-3 LVA maneuver. If the "turn while burn" test revealed the need for a corrective software patch, the test could be performed again for DSM-5 nearly 21 months later – more than enough time to formulate, implement, test, and upload software changes to the spacecraft. An additional advantage to performing the MOI turn test with DSM-

3 is the excellent observability of the Doppler shift – about 99% of the ΔV was observable due to a 172° angle between the ΔV and Earth directions. The resulting performance (see section IV) was the most accurate of the four mode 3 TCMs conducted by MESSENGER. Plans are being developed to use part of DSM-4 to test maneuver performance if accelerometer function is lost before MOI. During this contingency test the spacecraft follows an attitude profile and terminates thrust on the basis of estimated ΔV magnitude.

*2. Addition of Complete Designs for Contingency Opportunities for Mission-Critical TCMs*

Due to phasing of five DSMs and six planetary flybys, along with decreasing heliocentric orbit period and increasing risk for performing TCMs outside of restricted spacecraft orientations, the MESSENGER project has chosen to design and schedule additional TCMs for selected mission-critical TCMs. To qualify for scheduling a backup or contingency TCM, failure to complete a "mission-critical" TCM within two weeks of the baseline TCM date would have to result in the potential loss of full mission success as measured by depletion of ΔV margin or unacceptable risk of failure of science objectives for the upcoming planetary encounter. Each of the first three completed DSMs were shifted slightly earlier than the minimum-total-ΔV date in order to create an option for a SKI-compliant "no-burn" contingency TCM opportunity 5-7 days later. A description of all past contingency TCMs, none of which were utilized, appears in Table 2. Sun-Earth-probe angle is denoted as "SEP" in Table 2.

**Table 2.  Past MESSENGER contingency TCMs (all cancelled) and the respective baseline TCMs.**

| Maneuver | Epoch | Timing (days) | Purpose |
|---|---|---|---|
| TCM-9 (DSM-1) | 12 Dec 2005 | E+134d | Target Venus flyby 1 on 24 Oct 2006 |
| TCM-9C | 19 Dec 2005 | DSM-1+7d | SKI-compliant backup to DSM-1 |
| TCM-12 | 05 Oct 2006 | V1-19d | Final target Venus flyby 1 on 24 Oct 2006 |
| TCM-12C | 12 Oct 2006 | V1-12d | TCM-12 backup before solar conjunction |
| TCM-16 | 25 May 2007 | V2-12d | Final target Venus flyby 2 on 5 Jun 2007 |
| TCM-16C | 01 Jun 2007 | V2-4d | TCM-16 backup to target Venus flyby 2 on 5 Jun 2007 |
| TCM-18 (DSM-2) | 17 Oct 2007 | M1-89d | Target Mercury flyby 1 on 14 Jan 2008 |
| TCM-18C1 | 23 Oct 2007 | DSM-2+7d | SKI-compliant backup to DSM-2 before solar conjunction |
| TCM-18C2 | 30 Oct 2007 | DSM-2+13d | Non-SKI-compliant final clean up for DSM-2 at 2.5° SEP |
| TCM-19 | 19 Dec 2007 | M1-26d | DSM-2 clean up; target Mercury flyby 1 on 14 Jan 2008 |
| TCM-19C1 | 26 Dec 2007 | M1-19d | TCM-19 backup if TCM-19 too soon after solar conjunction |
| TCM-19C2 | 31 Dec 2007 | M1-14d | Final contingency to clean up TCM-19 |
| TCM-23 (DSM-3) | 19 Mar 2008 | M1+65d | Target Mercury flyby 2 on 6 Oct 2008; test MOI-1 turn rate |
| TCM-23C1 | 24 Mar 2008 | DSM-3+5d | SKI-compliant backup to DSM-3 |
| TCM-23C2 | 27 Mar 2008 | DSM-3+8d | Non-SKI-compliant final contingency to clean up for DSM-3 |

*3. Formulation of a Minimum-Cost Method for Implementing Multiple-Component TCMs*

During 2006 the navigation team proposed a maneuver decomposition technique that utilizes the spacecraft's ability to roll about a line that is orthogonal to the spacecraft-to-Sun direction. This technique uses two angles (shown as equal angles $\alpha_{SKI}$ in Fig. 7), both compliant with the SKI constraint, to decompose the total ΔV vector into lower total-ΔV non-orthogonal vector components. This efficient TCM design option, while not yet implemented for a MESSENGER TCM, has been incorporated into maneuver design software by the navigation and mission design. No software modifications were required by guidance and control[7] or other components of the flight team. As shown in Fig. 7 the radial component would be implemented by the anti-Sun-mounted S1 and S2 thrusters, and the lateral component would be imparted using either the four A-side or four B-side thrusters.
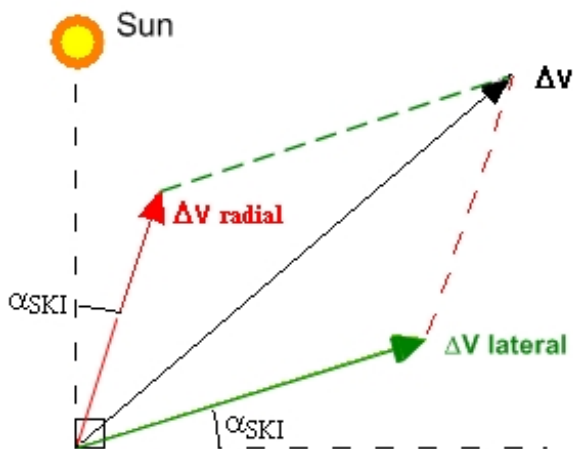


**Figure 7.  SKI-compliant TCM decomposition.**

# IV. Maneuver Performance and Flyby Target Assessment

Although the MESSENGER heliocentric cruise phase has been clearly successful since launch, the implementation of several trajectory-correction maneuvers has led to valuable opportunities to learn more about the effective utilization of the spacecraft's many pointing options and the capable onboard propulsion system. The record of TCM performance and the proximity of the B-plane intercept to the B-plane aim point for each planetary flyby provide a means of assessing the mission's success in delivering the spacecraft on a trajectory whereby important science objectives are possible. While the following material is not intended to provide subsystem details about post-TCM determination of lessons learned, it does illustrate significant improvement in overall mission performance.

## A. Maneuver Performance for Completed Heliocentric Course-Correction Maneuvers

A concise summary of TCM timing and performance (Table 3) illustrates the spacing of phasing (DSM), planetary approach, and post-encounter clean-up course corrections. Precise targeting of the Earth flyby, Venus flyby 2, and Mercury flyby 1 resulted in cancellation of the statistically likely post-encounter TCM before the next DSM.

**Table 3. Trajectory correction maneuver performance for the first half 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) | | | Pointing offset (°) |
|---|---|---|---|---|---|---|---|---|
| | | | | | Design | Result | % Error | |
| 1 | 24 Aug 04-21:00:07 | - | C(2) | 1.040448 | 18.000 | 17.901 | -0.551 | 0.309 |
| 2 | 24 Sep 04-18:00:00 | - | C(2) | 1.066747 | 4.590 | 4.589 | -0.030 | 0.274 |
| 3 | 18 Nov 04-19:30:00 | - | C(2) | 1.071266 | 3.236 | 3.247 | 0.333 | 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 | 0.374 |
| 6 | 21 Jul 05-18:00:01 | - | P(1) | 0.998575 | 0.147 | 0.150 | 2.513 | 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 | 0.026 |
| 10 | 22 Feb 06-16:00:00 | - | B(1) | 0.887902 | 1.407 | 1.281 | -8.977 | 2.556 |
| 11 | 12 Sep 06-23:00:00 | A | C(2) | 0.605094 | 0.830 | 0.835 | 0.599 | 0.638 |
| | 12 Sep 06-23:10:00 | B | S(1) | 0.605087 | 1.460 | 1.444 | -1.040 | 11.105 |
| 12 | 05 Oct 06-22:30:00 | - | B(1) | 0.637723 | 0.497 | 0.501 | 0.963 | 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 | 1.151 |
| | 02 Dec 06-22:00:00 | B | LVA(3) | 0.870919 | 19.810 | 20.251 | 2.223 | 1.723 |
| | 03 Dec 06-03:00:00 | C | P(1) | 0.871385 | 8.131 | 7.867 | -3.243 | 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 | 0.322 |
| 16 | 25 May 07-16:00:00 | - | B(1) | 0.664989 | 0.212 | 0.213 | 0.236 | 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 | 0.221 |
| | 17 Oct 07-22:30:00 | B | B(1) | 0.679328 | 1.421 | 1.421 | -0.042 | 2.642 |
| 19 | 19 Dec 07-22:00:00 | - | B(1) | 0.589260 | 1.104 | 1.104 | -0.056 | 0.215 |
| 20 | 10 Jan 08-22:00:00 | cancelled | | | | | | |
| 21 | 13 Jan 08-08:30:00 | cancelled | | | | | | |
| Mercury Flyby 1 (14 Jan 2008  19:04:39 UTC at 201 km altitude) | | | | | | | | |
| 22 | 05 Feb 08-20:30:00 | cancelled | | | | | | |
| 23 (3) | 19 Mar 08-19:30:00 | A | A&B(1) | 0.689589 | 0.159 | 0.159 | -0.050 | 0.096 |
| | 19 Mar 08-19:30:40 | B | LVA(3) | | 69.617 | 69.611 | -0.008 | 0.048 |
| | 19 Mar 08-19:32:20 | C | C(2) | | 2.470 | 2.471 | 0.020 | 0.047 |

Additional explanation of the purpose for TCMs not listed in Table 2 demonstrates the TCM variety and flight team experience acquired during the first half of the 7.6-year Mercury orbiter mission. The first two TCMs cleaned up post-launch injection errors. After a small deterministic TCM-3 the mode-1 TCMs 5 and 6 were the first to utilize the anti-Sun S and sunshade-protruding P thrusters as they targeted the Earth flyby. The next four TCMs (9-12) targeted Venus flyby 1, which required a significant multiple-component TCM-13 to clean up the target offset. For TCM-13 the mode-1 component was split in two since the auxiliary fuel tank (used exclusively for mode-1 TCMs) does not hold enough hydrazine to complete the full mode-1 ΔV component with continuous thrusting. TCMs 15 and 16 tar-geted Venus flyby 2. TCM-18 (DSM-2) concluded with a mode-1 firing of the B-side thrusters with solar arrays tilted 65° away from Sun-facing to characterize plume impingement for future Mercury approach TCMs closer than 0.5 AU from the Sun. Another reason for the "B" component of TCM-18 was to use the smallest thrusters to center the fuel in the two large fuel tanks, thereby simplifying passive momentum management for the spacecraft. The A, B, and C segments shown in Table 3 for TCM-23 are part of one contiguous mode-3 maneuver (like DSM-1); the extra detail is here because segments B and C followed a turn rate close to that planned for Mercury orbit insertion.

### B. Planetary Target Offsets and Flyby Trajectory Changes

Another measure of the accuracy of final planetary approach TCMs and orbit estimation is a comparison of the final B-plane target with the reconstructed B-plane intercept. For small differences between the target and achieved periapsis at each flyby, differences in spacecraft altitude also demonstrate a measure of success in minimizing total ΔV (through MOI) cost associated with flyby target results. These results and the "periapsis offset" distance between target periapsis and achieved periapsis (Cartesian vector difference, not B-plane shift) are summarized in Table 4.

**Table 4.   Assessment of planetary encounter targeting for MESSENGER's first four flybys.**

| Planetary flyby | EMO2000 B-plane aim point | | | EMO2000 B-plane intercept | | | Periapsis offsets (km) | |
|---|---|---|---|---|---|---|---|---|
| | B.T (km) | B.R (km) | epoch* | B.T (km) | B.R (km) | epoch* | altitude | position |
| | | | | | | | | |
| **Earth** | -20,877.9 | -7889.1 | 19:13:09.6 | -20,886.8 | -7868.9 | 19:13:08.4 | 1.0 high | 5.9 |
| **Venus 1** | -5690.3 | -11,072.2 | 08:33:54.8 | -5676.8 | -11,038.8 | 08:33:59.9 | 52.8 low | 59.8 |
| **Venus 2** | -9541.6 | 871.3 | 23:08:20.5 | -9543.6 | 866.0 | 23:08:18.7 | 1.4 high | 3.7 |
| **Mercury 1** | 3206.2 | 376.2 | 19:04:42.1 | 3206.4 | 386.5 | 19:04:39.4 | 1.3 high | 8.3 |

 **\* Epochs appear in hours:minutes:seconds in Universal Time Coordinated**

The first Venus flyby occurred during solar conjunction at Sun-Earth-spacecraft angle < 1.4°. Reference 4 provides an account of factors leading to the larger offset between aim point and intercept for this flyby. More favorable approach geometry and assimilation of Delta-DOR orbit data were important factors that helped reduce target offsets for the subsequent second Venus and first Mercury flybys.

Each planetary flyby completed by or planned for MESSENGER achieves significant amounts of change in the heliocentric trajectory's size and orientation. Without even one of these gravity-assist flybys the spacecraft would have been unable to carry enough propellant to attain orbit around Mercury. An account of each planetary flyby's change in spacecraft orbit orientation (longitude of perihelion and orbit inclination) and orbit size (aphelion and perihelion distances) appears in Table 5 of Ref. 8. The equivalent ΔV imparted to the spacecraft trajectory during each planetary gravity assist, is the following:

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

where $V_\infty$ is approach hyperbolic excess velocity, $r_p$ is periapsis distance from the planet's center, and $\mu_p$ is the planet's effective gravitational parameter. This ΔV is 5.9963 km/s for Earth, 5.5225 km/s for Venus flyby 1, 6.9378 km/s for Venus flyby 2, 2.3040 km/s, 2.4521 km/s, and 2.8535 km/s for Mercury flybys 1, 2, and 3, respectively.

Each of MESSENGER's gravity-assist flybys has a periapsis in front of (i.e., on the side associated with the planet's heliocentric velocity vector) the planet, and each flyby decreases the spacecraft orbit's kinetic energy. The first three flybys (Earth in Fig. 8, Venus in Fig. 9) have the spacecraft approach from inside (sunward) the planet's orbit and with the trajectory bending clockwise around the planet as viewed from the north ecliptic pole. The three flybys of Mercury (Fig. 10) have the spacecraft approach from outside (toward the Sun) the planet's orbit and with the trajectory bending counterclockwise around the planet as viewed from the north ecliptic pole. Figures 8 to 10 are

updated since appearing in the most recent MESSENGER mission design and navigation publication[9]. Eclipse entry and exit times indicate time in the penumbra (partial eclipse).
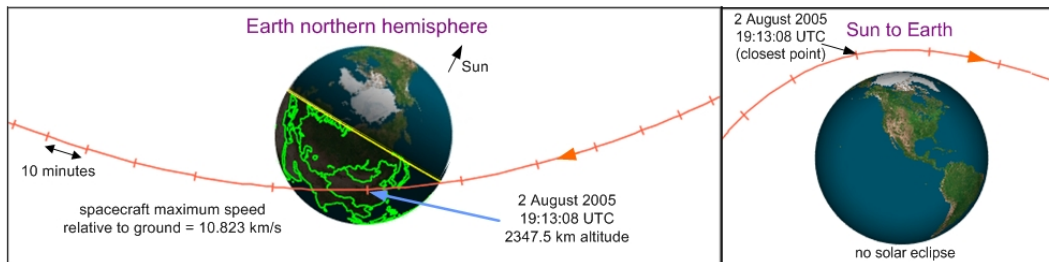


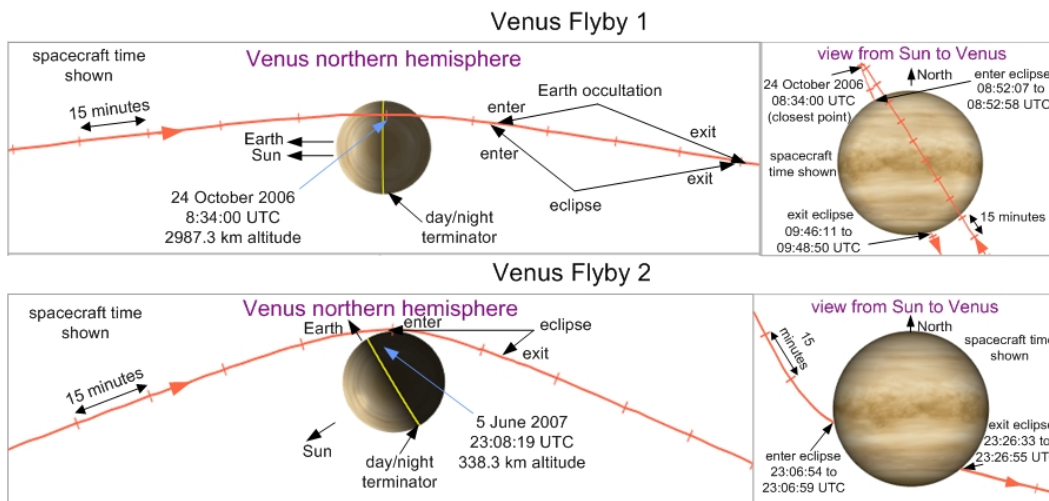**Figure 8. Views of the Earth flyby trajectory from above northern Asia and from the Sun.**



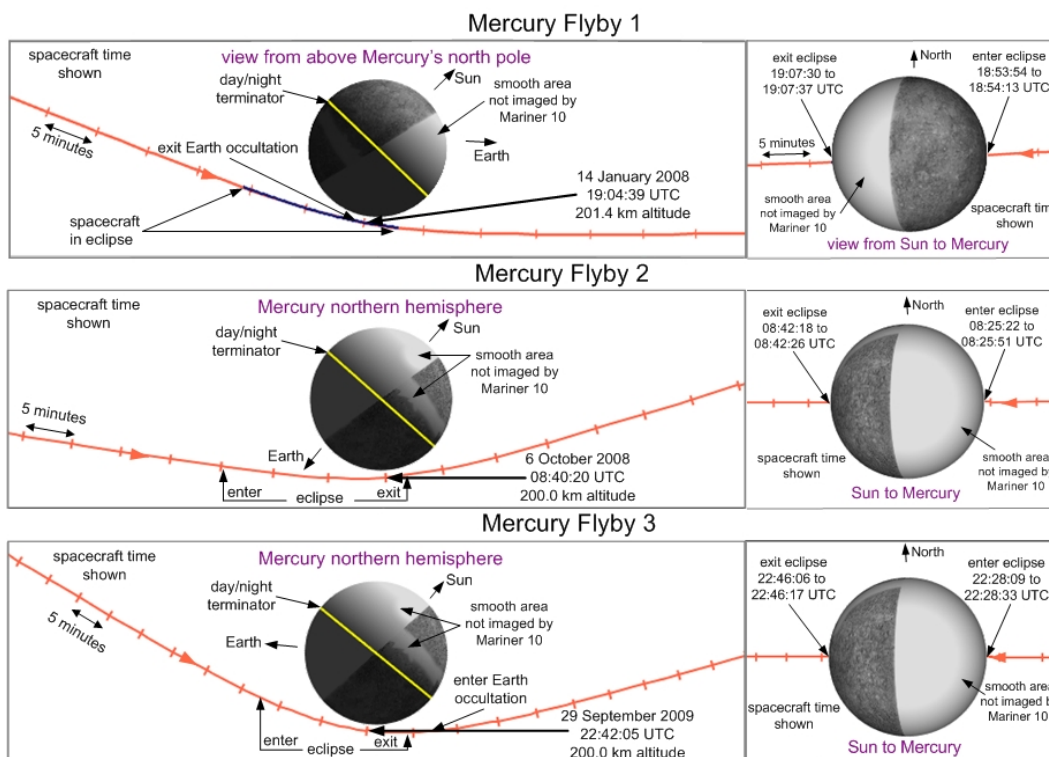**Figure 9. Views of both Venus flyby trajectories from above Venus' north pole and the Sun.**



**Figure 10. Views of all Mercury flyby trajectories from above Mercury's north pole and the Sun.**

Since the primary objectives of the MESSENGER mission involve seeking answers to fundamental science questions, it is useful to see an illustrative example of science data returned by the MESSENGER spacecraft during its first flyby of Mercury. The rightmost image in Fig. 11 compares well with the corresponding simulated view ("NAC" is the spacecraft's narrow-angle camera) of Mercury planned weeks before the flyby. The center view of Fig. 11 shows the progress towards completing the Mercury approach NAC image mosaic. For the first flyby of Mercury by a spacecraft in nearly 33 years, this comparison of the planned view of Mercury's surface with the actual view from the spacecraft demonstrates the success of the flight team, including factors discussed in this paper.
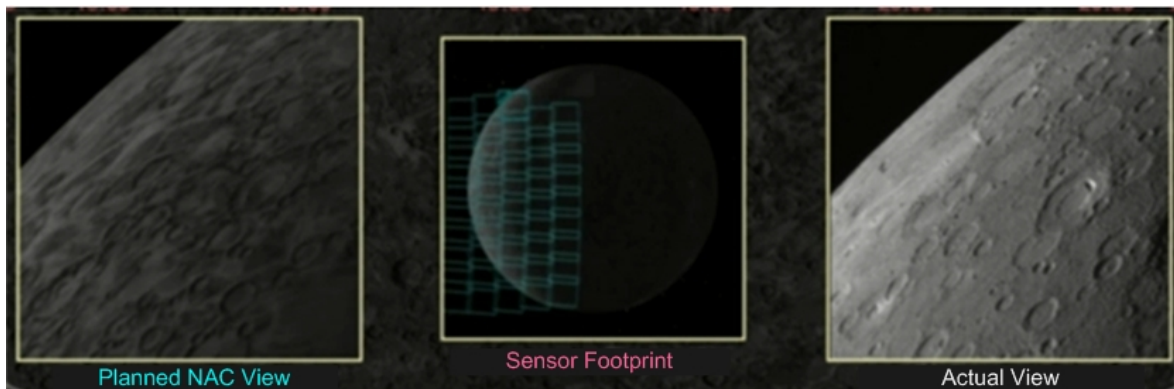


**Figure 11.    Comparison of planned and actual images of Mercury returned by MESSENGER.**

## V.   Conclusion

A little over halfway through its nominal 7.6-year mission to Mercury, the MESSENGER spacecraft has already successfully navigated through many of the higher-risk mission events. Some of these higher-risk mission events include a Venus flyby well into a lengthy solar conjunction, a deep-space maneuver just before entering a 7-week solar conjunction, and the first Mercury flyby at only 200-km altitude just five weeks after departure from this long solar conjunction.

Improvements in techniques for course-correction maneuver design and trajectory estimation have saved propellant and led to the cancellation of numerous planned TCMs. The most significant of these improvements are:

1)   applying a solar sailing technique to effectively utilize solar radiation pressure perturbations to counter small TCM execution errors and improve planetary encounter target accuracy,

2)   scheduling additional Delta-DOR tracks before Mercury flyby 1 to reduce Mercury encounter trajectory uncertainty,

3)   adjusting spacecraft attitude to correct demonstrated TCM execution performance bias.

While TCM execution prior to the second Venus flyby led to a number of lessons learned and revised software on the ground and on the spacecraft, low execution errors and accurate trajectory estimation for the first Mercury flyby, and the approach to the second Mercury flyby, have been far better than pre-launch expectations.

## Appendix – Recent Updates to Planned TCMs and Orbit Phase

Changes in maneuver design strategy and improvements in trajectory optimization made after launch have introduced notable changes in future course corrections to the MESSENGER spacecraft's trajectory. Improvements in trajectory optimization since early post-launch operations late in 2004 yielded a decrease by 1% (8.5 m/s) in Mercury orbit insertion $\Delta V$ magnitude (see Table 5). TCMs during Mercury orbit phase are called OCMs (orbit correction maneuvers). Upcoming DSMs have increased 2.4% (DSM-4) and 0.5% (DSM-5) as a consequence of changes in completed planetary flybys and DSMs and in mission risk reduction measures such as choosing off-optimal maneuver execution dates to allow backup maneuver opportunities. Still other planned TCMs (all six orbit-correction maneuvers planned after MOI) have undergone redesigns with less than 0.01% change in total $\Delta V$.

In order to provide a basis for understanding reduction in Mercury orbit insertion $\Delta V$, an explanation of the Mercury orbit insertion strategy and initial primary science orbit is needed. The large velocity adjust bi-propellant LVA thruster is utilized to insert (MOI-1) the spacecraft into a Mercury orbit inclined 80° relative to Mercury's equator and having an orbit period between 12.8 hours and 16 hours. A much smaller bi-propellant mode-3 TCM

(MOI-2) performed 2-4 days later will place the spacecraft into a 200-km-altitude periapsis by 12-hour-period science orbit.

**Table 5. Timing and ΔV updates for planned MESSENGER deterministic TCMs.**

| Trajectory Correction Maneuver | Maneuver date year month day | Maneuver time (UTC) (hh:mm:ss) | ΔV (m/s) | Earth-S/C range (AU) | Sun-S/C range (AU) | Sun-S/C-ΔV max. angle (deg) | Sun-Earth-S/C angle (deg) |
|---|---|---|---|---|---|---|---|
| Requirement → | | | | | | (78°to 102°) | (>3°) |
| DSM-4 | 04 Dec 2008 | 20:30:00 | 247.341 | 1.590 | 0.623 | 87.4 | 6.7 |
| DSM-5 | 29 Nov 2009 | 19:00:00 | 177.527 | 1.529 | 0.565 | 89.8 | 7.4 |
| MOI-1 | 18 Mar 2011 | 00:30:00 | 822.254 | 1.037 | 0.308 | 98.7 | 17.3 |
| MOI-2 | 21 Mar 2011 | 17:15:00 | 37.382 | 0.936 | 0.316 | 80.8 | 18.5 |
| OCM-1 | 15 Jun 2011 | 17:09:37 | 4.172 | 1.318 | 0.311 | 96.3 | 3.6 |
| OCM-2 | 16 Jun 2011 | 23:46:58 | 26.461 | 1.313 | 0.314 | 99.0 | 5.1 |
| OCM-3 | 09 Sep 2011 | 17:49:15 | 3.905 | 1.103 | 0.308 | 86.9 | 16.0 |
| OCM-4 | 11 Sep 2011 | 00:24:04 | 24.131 | 1.135 | 0.310 | 94.4 | 15.2 |
| OCM-5 | 05 Dec 2011 | 18:24:31 | 3.579 | 0.683 | 0.308 | 83.3 | 3.7 |
| OCM-6 | 07 Dec 2011 | 00:56:28 | 22.238 | 0.692 | 0.308 | 91.1 | 6.6 |

Both MOI-1 and MOI-2 are placed close to crossover points where spacecraft elevation angle above the local horizon is about the same at two widely separated (e.g., Canberra and Goldstone) DSN antenna stations. To achieve this lower-risk communication condition six 14-hour, 44-minute orbits separate MOI-1 and MOI-2. The 3.7-day period between MOI-1 and MOI-2 is the longest separation meeting this communication condition that also leaves sufficient margin relative to the 12° SKI constraint indicated by the maximum Sun-spacecraft-ΔV angle in Table 5. Additional delay in MOI-2 could maintain margin relative to this SKI constraint only with wasteful out-of-orbit-plane implementation of the MOI-2 ΔV. Relative to previous MOI designs, additional improvement came from starting MOI-1 earlier, allowing periapsis during MOI-1 and after MOI-1 to decrease. Because the Mercury approach velocity asymptote provides an initial orbit solution with sub-spacecraft periapsis latitude near 53°, some rotation of the line of apsides (to meet a requirement for 60° sub-spacecraft periapsis latitude after MOI-2) is
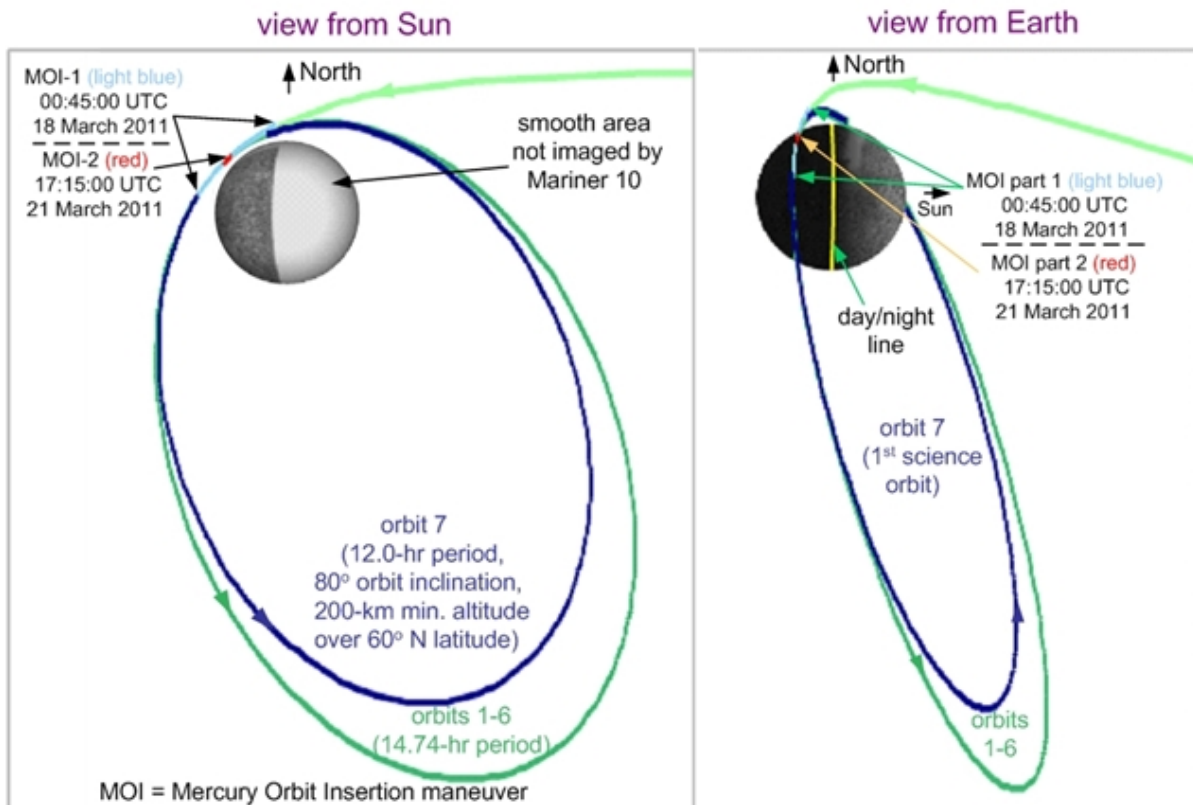


**Figure 12. Mercury orbit insertion trajectory and maneuvers (viewed after MOI-2 at time of orbit 7).**

required during orbit insertion. The prior approach of completing 100% of the apsidal rotation with MOI-1 and centering MOI-2 about periapsis to lower orbit period to 12 hours has been improved slightly by allocating a small portion of the apsidal rotation to MOI-2, which then is performed closer to 20° true anomaly (after periapsis passage). A slight decrease in Mercury approach excess velocity also contributes 2-3 m/s of the net 8.5 m/s ΔV savings in MOI since late 2004. Figure 12 shows the placement of the primary (MOI-1) and clean-up (MOI-2) maneuvers and the eclipse-free (Sun view) and fully observable (Earth view) nature of Mercury orbit insertion. The size of the orbit between MOI-1 and MOI-2 and the number of orbits between maneuvers will provide the flight team sufficient time to evaluate MOI-1 and change the start time and burn duration of MOI-2 to provide a more precise (than using one TCM for the full orbit insertion) insertion into the science orbit.

Each pair of OCMs is designed to return the spacecraft to the initial primary science orbit's size and shape. Solar gravity, solar radiation pressure, and spatial variations in Mercury's gravity will change the orbit by shifting periapsis north, increasing orbit inclination, and rotating the low-altitude descending node away from the Sun direction (when Mercury is at perihelion). The first OCM of each pair delivers a ΔV in the spacecraft velocity direction at periapsis, placing the spacecraft on a transfer orbit with apoapsis altitude equal to that of the 200-km periapsis altitude by 12-hour orbit. Two-and-a-half orbits (30.6 hours) later, at apoapsis, the second OCM of each pair will lower periapsis altitude to 200 km by imparting a larger mode-3 ΔV opposite the spacecraft velocity direction. This second OCM will also return the spacecraft's orbit period to 12 hours.

## Acknowledgments

## References

[1] McNutt, R. L., Jr., Solomon, S. C., Gold, R. E., Leary, J. C., and the MESSENGER Team, "The MESSENGER Mission to Mercury: Development History and Early Mission Status," *Advances in Space Research*, Vol. 38, No. 4, 2006, pp. 564-571.

[2] Solomon, S. C., McNutt, R. L., Jr., Gold, R. E., and Domingue, D. L., "MESSENGER Mission Overview," *Space Science Reviews*, Vol. 131, Nos. 1-4, 2007, pp. 3-39.

[3] Wiley, S., Dommer, K., and Mosher, L., "Design and Development of the MESSENGER Propulsion System," AIAA/SAE/ASME Joint Propulsion Conference, Paper AIAA-2003-5078, 20 pp., Huntsville, AL, July 2003.

[4] Taylor, A. H., Carranza, E., Miller, J.K., Stanbridge, D. S., Page, B. R., Smith, J., Wolff, P., Williams, B. G., Efron, L., Farquhar, R. W., McAdams, J. V., and Dunham, D. W., "Earth to Venus-1 Navigation Results for NASA's MESSENGER Mission to Mercury," *Advances in the Astronautical Sciences*, Vol. 127, Part I, 2007, pp. 1081-1100.

[5] Williams, K. E., Taylor, A. H., Page, B. R., Miller, J. K., Smith, J., Wolff, P., Stanbridge, D., Williams, B. G., and McAdams, J. V., "Navigation for the Second Venus Flyby of the MESSENGER Mission to Mercury," *Advances in the Astronautical Sciences*, Vol. 130, Part II, 2008, pp. 1113-1132.

[6] Williams, K. E., Taylor, A. H., Stanbridge, D. R., Wolff, P., Page, B. R., Williams, B. G., and McAdams, J. V., "Navigation for the MESSENGER Mission's First Mercury Encounter," Paper AIAA-2008-6761, 20 pp., AIAA/AAS Astrodynamics Specialist Conference, Honolulu, HI, August 18-21, 2008.

[7] O'Shaughnessy, D. J. and Vaughan, R. M., "MESSENGER Spacecraft Pointing Options," *Advances in the Astronautical Sciences*, Vol. 109, Part II, 2003, pp. 747-766.

[8] McAdams, J. V., Dunham, D. W., Farquhar, R. W., Taylor, A. H., and Williams, B. G., "Trajectory Design and Maneuver Strategy for the MESSENGER Mission to Mercury," *Journal of Spacecraft and Rockets*, Vol. 43, No. 5, 2006, pp. 1054-1064.

[9] McAdams, J. V., Farquhar, R. W., Taylor, A. H., and Williams, B. G., "MESSENGER Mission Design and Navigation," *Space Science Reviews*, Vol. 131, Nos. 1-4, 2007, pp. 219-246.