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The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, led by principal investigator Sean C. Solomon of the Carnegie Institution of Washington, is the seventh mission in NASA's Discovery Program. The spacecraft was launched from Cape Canaveral Air Force Station on August 3, 2004, to begin its six-and-one-half-year interplanetary cruise to arrive in orbit about Mercury beginning in March 2011. The cruise phase includes planetary gravity-assist flybys of Earth (in August 2005), Venus (in October 2006 and June 2007), and Mercury (in January and October 2008 and September 2009). This paper describes the navigation results for the period encompassing Venus flyby 2 and focuses on orbit determination results, navigation analyses supporting statistical trajectory correction maneuvers, and maneuver reconstruction results. Also included are discussions of optical navigation tests performed after the encounter and implications derived from Venus flyby results for the upcoming first Mercury encounter.

INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is being flown as the seventh mission in NASA's Discovery Program. The MESSENGER mission is led by the principal investigator, Sean C. Solomon, of the Carnegie Institution of Washington. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) designed and assembled the spacecraft and serves as the home for project management and spacecraft operations. Navigation for the spacecraft is provided by the Space Navigation and Flight Dynamics Practice of KinetX, Inc., a private corporation. Navigation for launch and interplanetary cruise makes use of

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radio metric tracking data from NASA's Deep Space Network (DSN) augmented by optical navigation from on-board images of planet flybys.

After launch on August 3, 2004, the spacecraft began its six-and-one-half year interplanetary cruise[1] that will culminate with rendezvous and Mercury orbit insertion (MOI) beginning in March 2011. Figure 1 shows the mission timeline of planetary flybys and deterministic deep space maneuvers (DSMs) from launch to MOI. The interplanetary trajectory includes an Earth gravity-assist flyby about one year after launch, followed by two Venus flybys and three Mercury flybys before orbit insertion.[2] Once in orbit, MESSENGER will perform science observations of Mercury for one Earth year. Spacecraft navigation during interplanetary cruise involves estimating the trajectory based on available tracking data and computing trajectory correction maneuvers (TCMs) that deliver the spacecraft as close as possible to nominal target parameters at each planetary flyby. Since total fuel usage is carefully controlled to ensure mission success, the remaining trajectory is re-optimized after each large propulsive maneuver and planetary flyby to accommodate execution errors and trajectory uncertainties. The KinetX Navigation Team works closely with the Mission Design Team at JHU/APL to optimize the flyby targets and to compute the TCMs.

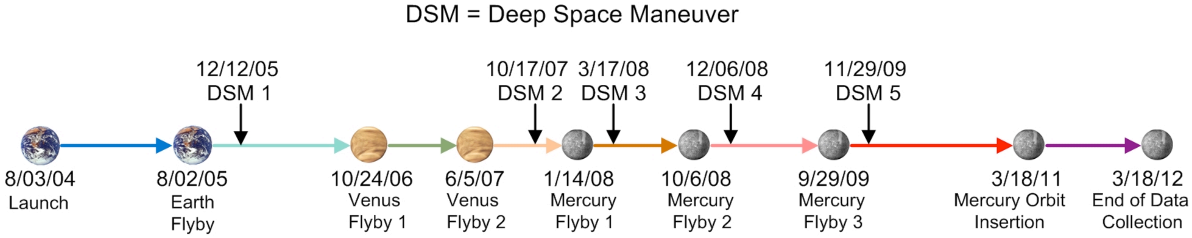


Figure 1. MESSENGER Timeline for Planetary Flybys and Deep Space Maneuvers (DSMs)

The Venus flybys occurred on October 24, 2006, and June 5, 2007. During the cruise between flybys, the primary goal of the MESSENGER navigation team was to determine and control Venus flyby 2 conditions to ensure successful completion of the remainder of the cruise phase to Mercury. During this period, the spacecraft attitude was modeled and solar radiation pressure (SRP) parameters were estimated on the basis of available telemetry and DSN Doppler and ranging tracking data.

With a periapsis altitude of approximately 340 km, Venus flyby 2 was more demanding than the previous flyby, which had a flyby altitude over 3000 km. Moreover, for OpNav (Optical Navigation) testing, there were a number of similarities between the viewing geometry for Venus immediately after the flyby and the approach viewing geometry for the first Mercury encounter in January 2008. The mission plan was to perform OpNav tests only after critical maneuvers and other events on approach were completed. Tests were performed post-flyby to validate and improve OpNav capabilities using images from the two on-board science cameras. The use of OpNav in addition to other tracking data types provides important additional information for determining the trajectory on approach to planetary flybys. This is especially true for the first Mercury encounter, since it is the best way in advance to reveal any Mercury planetary ephemeris errors, which would not be apparent with Earth-based radio metric tracking alone.

The measure used to judge the accuracy of the estimated trajectory and trajectory correction maneuvers on approach to the flyby is the intercept point in the hyperbolic impact-plane (or B-plane) at Venus. The B-plane is the plane normal to the incoming asymptote of the hyperbolic flyby trajectory that passes through the center of the target body (Venus in this case). The “S-axis” is in the direction of the incoming asymptote and hence is normal to the B-plane. For MESSENGER, the “T-axis” is parallel to the line of intersection between the B-plane and the Earth Mean Ecliptic plane of J2000 (and is positive in the direction of decreasing right ascension). The “R-axis” (positive toward the South Ecliptic Pole) completes the mutually orthogonal, right-handed Cartesian coordinate axes “T-R-S”.

In addition to the low flyby altitude, there were several challenges to navigation posed by Venus flyby 2:

(1) The requirement to achieve the proper departure asymptote to satisfy both Mercury flyby conditions and Deep Space Maneuver 2 (DSM-2) spacecraft attitude constraints while staying within the spacecraft fuel budget imposed tight constraints on the targeted aim point at Venus 2. There was also a heightened concern about impact with Venus and its atmosphere (assumed to lie within 200 km of the surface) with targeting to a significantly lower altitude (340 km) than the previous Venus flyby.

(2) First operational use of Delta Differential One-way Ranging (Delta-DOR) on the MESSENGER mission was needed to achieve the accurate flyby targeting, which required building upon successful tests of this capability performed previously for Venus flyby 1.

(3) Spurious velocity changes (ΔVs) due to angular momentum dumps could be larger than expected and are not predictable. Consequently, spacecraft momentum was carefully monitored and dumped as a component of TCMs, to avoid unexpected, autonomous momentum dumps.

(4) OpNav testing needed to occur at non-critical times and in a manner that would simulate the approach sequence for Mercury flyby 1. Consequently, such tests were conducted after Venus flyby 2 in parallel with flyby reconstruction activities.

(5) Two significant spacecraft anomalies had to be overcome. These included (a) apparent outgassing from large velocity adjustment (LVA) engine bell, which caused the orbit determination (OD) solution to shift several tens of kilometers until analyzed and properly modeled, and (b) premature timeout of TCM-15, which produced a 25% shortfall in ΔV, but was subsequently corrected by TCM-16, achieving a final accuracy of 1.6 km and 0.7 s from the targeted aim point.

All of the aforementioned challenges to navigation raised by Venus flyby 2 were successfully addressed, as described further in subsequent sections.

NAVIGATION SYSTEM OVERVIEW

The MESSENGER Navigation Team is organized as part of a multi-mission navigation support group so that the team size can be adjusted as mission events dictate. The Navigation Team has been headed by Tony Taylor, Navigation Team Chief. The MESSENGER Navigation Team performs OD and TCM reconstruction and additionally performs TCM design and trajectory re-optimization in conjunction with the Mission Design Team. OD for cruise phases is based on the following DSN radio metric data types: two-way Doppler (F2), three-way Doppler (F3), two-way ranging (SRA), and Delta-DOR. Tracking of MESSENGER was obtained as described below, and verified by comparison to OD solutions predicted from previous tracking data. These radio-only solutions are used to estimate the trajectory and certain dynamic parameters so that the predicted intercept point and its uncertainty can be used to plan TCMs that correct the trajectory back to the aim point.

The MESSENGER Navigation Team is also implementing and testing an OpNav capability for operational use on approach to the Mercury flybys and Mercury orbit insertion. This capability was first tested on approach to Venus flyby 1. Taking OpNav images on approach to Venus flyby 2 was not possible, however, due to pointing constraints that insure the Sun does not illuminate certain parts of the spacecraft. Since OpNav is planned to be used for navigation on approach to Mercury flyby 1 and since the MESSENGER camera was not designed to be sensitive enough for imaging Mercury and background stars in a single image, a test was devised that took images on departure from Venus flyby 2 in order to prove the multiple image OpNav procedure designed by the Navigation Team. The results of the OpNav tests at Venus flyby 2 are discussed below.

MESSENGER DSN Doppler and Ranging Processing

DSN tracking coverage was adjusted during the cruise phase between the two Venus flybys to support important events such as the approach to Venus flyby 2 while allowing a reduced schedule of one or two tracks per week during routine cruise intervals. The tracking schedule for this period is shown in Table 1. In addition to spacecraft telemetry, during a track the DSN acquires radio metric Doppler and ranging data that are passed to the Navigation Team for processing. Each coherent two-way track from a single DSN antenna produces two-way Doppler tracking, referred to as “F2” data. If a second DSN antenna receives the same downlink such as what happens during a station-to-station handover, then three-way Doppler tracking, or “F3,” is produced. Almost every track for MESSENGER is also configured to acquire two-way ranging from the DSN Sequential Ranging Assembly, and the resulting measurements are referred to as “SRA” data.

Table 1. DSN Tracking Schedule for MESSENGER from Venus Flyby 1 to Venus Flyby 2

DSN Tracking Schedule	Tracking Interval and MESSENGER Events
4 tracks per week	Nov-Dec 2006
4 tracks per week	Jan 2007
3 tracks per week	Feb-Mar 2007
7 tracks per week	TCM-15 (April 25, 2007) for 4 weeks
6 tracks per week	May 2007
Continuous	Venus Flyby 2 (June 5,2007) for 5 days
4 tracks per week	June-July 2007

MESSENGER Delta-DOR Processing

The DSN Delta-DOR tracking data type is formed by differencing two Very Long Baseline Interferometry (VLBI) measurements between a spacecraft tone signal and one or more nearby quasars. Since a VLBI measurement determines the spacecraft offset from the baseline between the two DSN antennas used in the measurement, the VLBI data provide a direct measurement of the spacecraft angular position relative to the baseline. During the Delta-DOR tracking session, the two DSN antennas slew from the spacecraft to nearby quasars and return, taking about 10 minutes of VLBI data from each source. The DSN currently performs a Delta-DOR track by collecting VLBI data from a quasar, then both antennas slew to the nearby spacecraft, followed by a slew to a different quasar. This is denoted by the shorthand label “Q1-S-Q2”. The quasars are chosen so they are within about 10° of the DSN antenna pointing direction to the spacecraft.

The individual VLBI measurements are subject to a variety of error sources including those due to media effects and various station-dependent parameters. Delta-DOR provides cancellation of common error sources by forming the difference between the interleaved VLBI measurements of the spacecraft and nearby quasars. The difference ultimately results in a highly precise measurement of the angular offset between the spacecraft and the known location of the quasars used in the Delta-DOR session. The accuracy of the spacecraft-quasar relative angular position is about 2 nanoradians, which is equivalent to 0.3 km at 1 AU in a direction normal to the spacecraft line-of-sight. Since single-station Doppler and ranging are line-of-sight measurements, the Delta-DOR provides additional navigation information content in an “orthogonal” direction that is ideal for detecting and removing orbit determination errors in that direction. The addition of Delta-DOR data provided a level of robustness and increased accuracy to the radio metric orbit determination at Venus flyby 1 (Ref. 5) and Venus flyby 2. As a result, Delta-DOR data are planned for each of the remaining Mercury flybys and orbit insertion.

In order to obtain a position measurement on the plane-of-sky, two nearly orthogonal baselines are used within the DSN: a roughly north-south baseline made up of antennas from the Goldstone, California, and Canberra, Australia, complexes, and a roughly east-west baseline made up of antennas from the Madrid, Spain, and Goldstone, California complexes. When the Delta-DOR data from north-south and east-west baselines are combined with Doppler and ranging in an orbit determination filter, the spacecraft position is very well determined in space. Table 2 contains a schedule of the nine Delta-DOR tracks taken in May on approach to Venus flyby 2 and the four post-flyby tracks and shows the use and distribution of both north-south and east-west baselines. During the cruise between Venus flyby 1 and flyby 2 there were also an additional twelve Delta-DOR tracks taken in March and April 2007 to support TCM-15 design and to prepare for Venus flyby 2. In Table 2, the baselines are identified by the DSN complex location on either end. Also included in the table are the quasar-spacecraft-quasar sequences and the result.

Table 2. Delta-DOR Tracks Taken on Approach to Venus Flyby 2 (June 5, 2007)

Date	Baseline	Sequences	Result
May 4, 2007	Goldstone – Madrid (E-W)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
May 5, 2007	Goldstone – Canberra (N-S)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
May 6, 2007	Goldstone – Madrid (E-W)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
May 7, 2007	Goldstone – Madrid (E-W)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
May 9, 2007	Goldstone – Canberra (N-S)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
May 9, 2007	Goldstone – Madrid (E-W)	Q1-S-Q2	One Sequence: Degraded
May 12, 2007	Goldstone – Canberra (N-S)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
May 15, 2007	Goldstone – Madrid (E-W)	None	No Sequences: Failed
May 19, 2007	Goldstone – Canberra (N-S)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
Jun 10, 2007	Goldstone – Canberra (N-S)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
Jun 10, 2007	Goldstone – Madrid (E-W)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
Jun 16, 2007	Goldstone – Madrid (E-W)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful
Jun 17, 2007	Goldstone – Canberra (N-S)	Q1-S-Q2, Q1-S-Q2	Both Sequences: Successful

Of the nine Delta-DOR measurements scheduled for May, one was lost due to a problem with the DSN Service Preparation Subsystem (SPS) prediction system, and another on May 9 was partially lost due to a DSN antenna problem. The remaining data from the May 9 measurement had to be deleted from navigation solutions because it was an outlier. The seven good measurements in May exceeded the six measurements originally requested by the Navigation Team, and yielded excellent results.

MESSENGER Optical Navigation Processing

The OpNav process for planetary flybys uses images of the target planet and background stars to determine the inertial pointing direction from the spacecraft to the planet. This gives a measure of the relative position and is a powerful measurement type to determine precisely the flyby conditions on approach and in a reconstruction. For MESSENGER, optical navigation, as a complement to the radio metric tracking, is planned to be used to estimate the flyby conditions for the three Mercury flybys and the approach to Mercury orbit insertion. Ideally, a single OpNav image would contain the planet and background stars. However, the MESSENGER cameras are science cameras made for mapping the bright surface of Mercury and not specifically designed for optical navigation, so individual images of the planet and of stars must be combined by the Navigation Team to form the OpNav measurement.

All OpNav images for MESSENGER are taken with the Mercury Dual Imaging System (MDIS). If an MDIS picture is over-exposed to image dimmer stars, then the planet is over-exposed and this causes stray light and image blooming problems that obscure fine details in the image. There are two cameras contained in the MDIS housing: one narrow-angle camera (NAC) with a 1.5°-square field of view (FOV), and one wide-angle camera (WAC) with a 10.5°-square FOV. Each camera has a 1024 by 1024 pixel charge-coupled device (CCD) in its respective focal plane for taking the picture. The NAC has a 25.5-μrad/pixel FOV, while the WAC has a 179-μrad/pixel FOV. The MDIS housing is mounted via a single-axis pivot to the spacecraft bus, so both NAC and WAC boresights are nominally co-aligned and can be pointed by a combination of re-orientation of the spacecraft and moving the pivot.

OpNav testing for Venus flyby 2 was conducted in parallel with flyby reconstruction activities. Images were taken according to a particular timeline which, when considered in reverse order, simulates the sequence of images to be taken during the Mercury flyby 1 approach. This also mitigated the operational risk by minimizing interference with more critical activities prior to the flyby. A version of this timeline is shown in Figure 2. Each of the OpNav opportunities consists of eight images, four from the NAC and four from the WAC. The eight images are interleaved with slightly different pointing to obtain images of the planet and nearby stars without the planet in the FOV. This sequence was developed as a result of the OpNav tests at Venus flyby 1 and is designed to take advantage of the strengths of each imager to independently determine the pointing direction relative to the known location of catalogued stars[4] and the location of the planet in the image after further image processing by the Navigation Team. It takes about 15 minutes on average for the MESSENGER spacecraft to re-orient and acquire all eight images. Note that all the OpNav images were taken after Venus flyby 2 on June 5 since this was a test and was not meant to support approach navigation for Venus flyby 2.

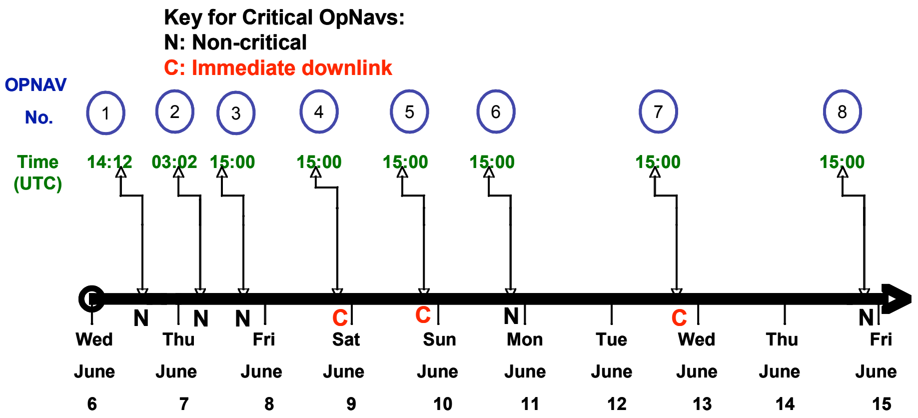


Figure 2. Timeline for MESSENGER Post-Venus Flyby 2 OpNav Tests

An overview of the OpNav process data flow is shown in Figure 3 from the MIRAGE orbit determination software.

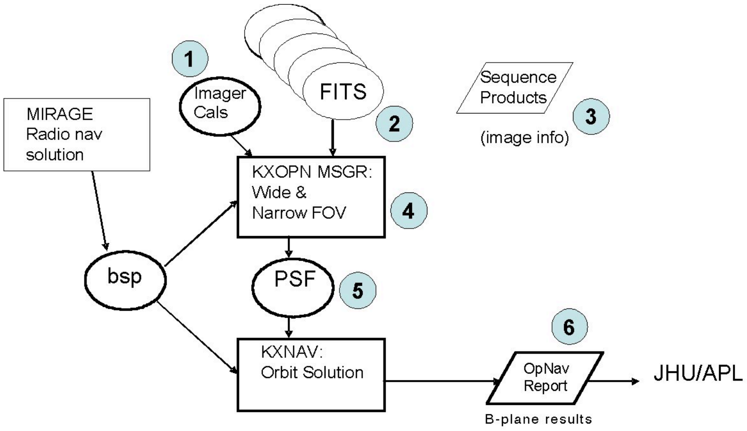


Figure 3. MESSENGER OpNav Data Flow

The numbered items in Figure 3 are the test focus items that were demonstrated and validated during the post flyby OpNav test: (1) Determine imager calibration values for distortion, focal length, etc.; (2) verify Flexible Image Transport System (FITS) file format and interface; (3) verify sequence reader summary and interface; (4) test KXOPN program for image processing; (5) verify Picture Sequence File (PSF) interface; and (6) exercise KXNAV orbit determination program and its bsp (SPICE trajectory file) input to generate and test the OpNav solution report format and interface.

MESSENGER ORBIT DETERMINATION RESULTS

A trajectory reconstruction was performed using the Doppler, ranging, and Delta-DOR data available over the arc from Venus flyby 1 to Venus flyby 2. The data started on November 25, 2006, 16:45, UTC after Venus flyby 1 and ended on July 5, 2007, 19:25 UTC, after Venus flyby 2. The orbit determination filter arc includes three propulsive TCMs that were estimated and reconstructed as discussed below. The quality of the fit is demonstrated by the observation residuals; i.e., the observed measurements minus the computed values based on the estimated parameters, which are presented in the following three plots. The DSN Doppler residuals are shown in Figure 4. As shown, the Doppler residuals are plotted for all 6,645 individual measurements. The different DSN antennas used are indicated by different letters on the plot. The residual mean is nearly zero (-0.007 mm/s) with a standard deviation of 0.28 mm/s over the eight-month data arc, which indicates a very good fit to the Doppler tracking data. The low noise in the Doppler measurements per pass is indicated by the small scatter on a pass-by-pass basis. The slightly larger noise earlier in the arc, in November and December 2006, is due to effects from solar plasma corresponding to a smaller Sun-Earth-probe (SEP) angle as MESSENGER was exiting the solar conjunction that occurred in October 2006. With only a few exceptions, the DSN Doppler measurement noise per pass is seen to be much less than the assumed data weight of 0.5 mm/s that was used in the filter.

The DSN ranging residuals and Delta-DOR residuals are shown in Figure 5 and Figure 6. The ranging residuals show systematic trends of about 100 m over the filter arc, but this is consistent with the relative data weighting of 75 m used for ranging. This weight is a compromise to allow the DSN Doppler data to dominate the fit since it is less prone to measurement biases. The pass-by-pass measurement noise in the ranging is seen to be about 10 m or less, which is typical for the DSN SRA ranging system at the distances seen on this arc. The ranging residuals appear to be much improved during the period in between flybys when the Delta-DOR measurements were made in late March and early April. This is to be expected since, as discussed above, the Delta-DOR adds measurement information in a dimension that is more-or-less orthogonal to the ranging measurements (see Ref. 3). The residual mean for ranging over the eight-month fit is about 4 ± 32 m.

The two-way Doppler pass-by-pass mean and 1-σ noise for this arc are shown in the upper panels of Figure 7, and the pass-by-pass mean and 1-σ noise for the ranging data are shown in the lower panels of Figure 7. The behavior is similar to the previous Earth-to-Venus flyby 1 leg of the mission. The Doppler means and noise show a decline coming out of the superior solar conjunction that occurred in October 2006. Following the solar conjunction period, the ranging means show a sinusoidal trend with a period of approximately 30 days, but the overall magnitude of this un-modeled effect is less than 30 m peak-to-peak. The 1-σ noise on the ranging passes is less than 10 m peak, and normally is less than 3 m throughout this arc.

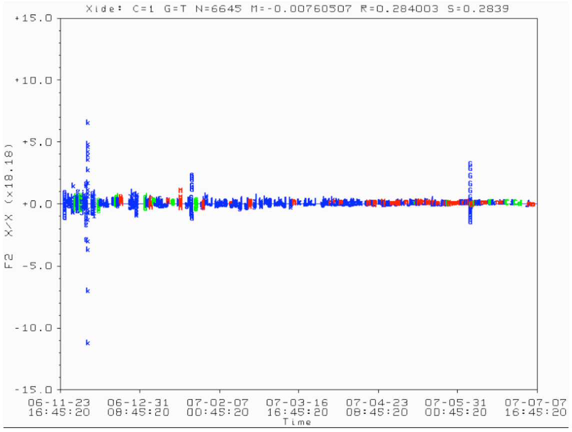


Figure 4. DSN 2-Way, X-band Doppler (F2) Residuals for Reconstructed Trajectory from Venus Flyby 1 to Venus Flyby 2. Plot Scale is ±15 mm/s

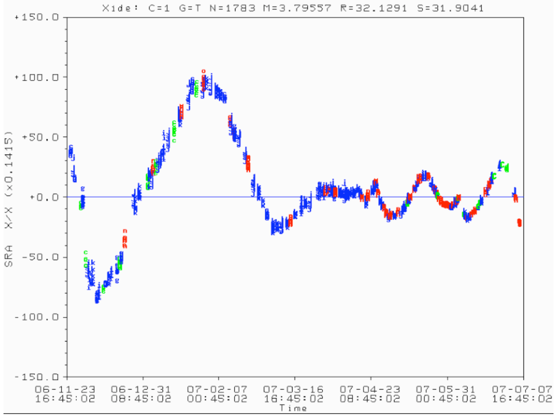


Figure 5. DSN 2-Way, X-band Sequential Ranging (SRA) Residuals for Reconstructed Trajectory from Venus Flyby 1 to Venus Flyby 2. Plot Scale is ±150m

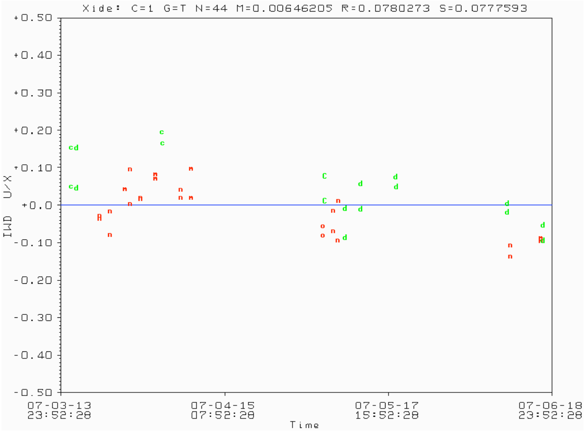


Figure 6. DSN Delta-DOR Tracking Residuals for Reconstructed Trajectory from Venus Flyby 1 to Venus Flyby 2. Plot Scale is ± 0.5 ns or the equivalent of about ± 15 cm

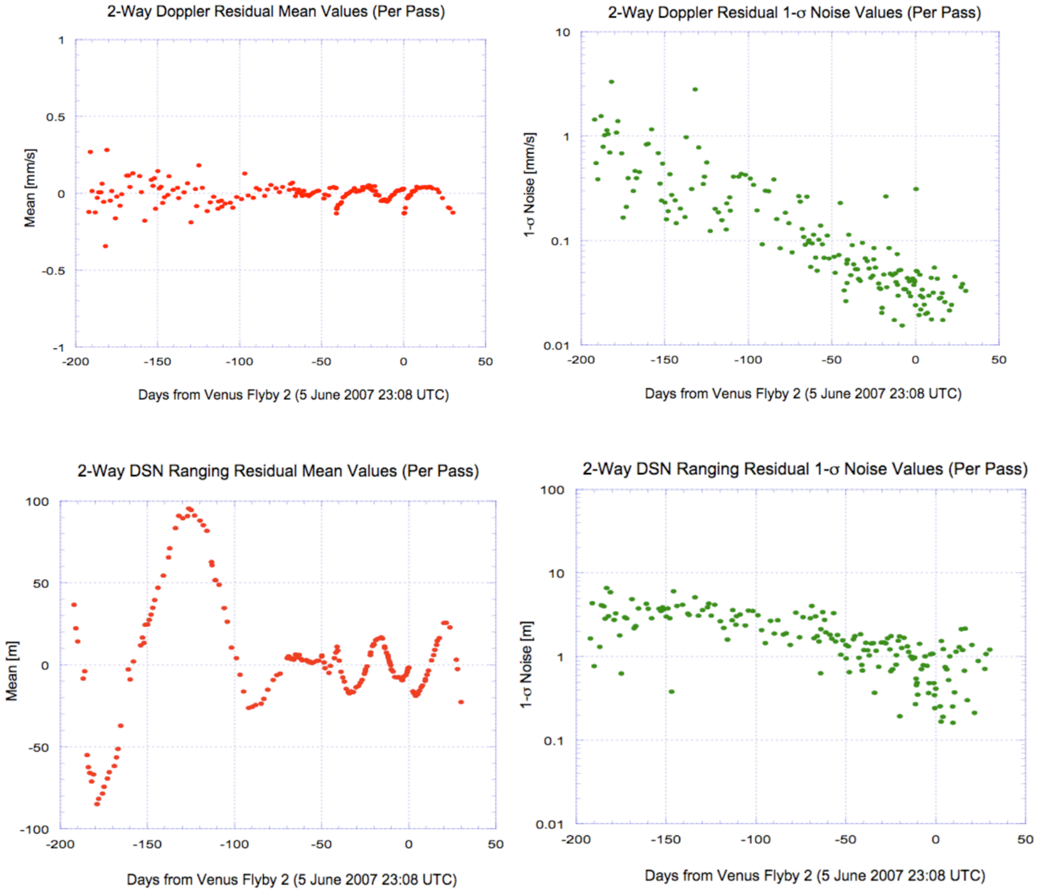


Figure 7. 2-Way Doppler and DSN Ranging Residual Means and 1-σ Noise for the Data Arc from Venus Flyby 1 to Venus Flyby 2

The effect of adding the Delta-DOR to the solution at various data cut-off times on approach to Venus is demonstrated in Figure 8 and Figure 9. The top plot shows the evolution of the estimate for the B-plane component $B \cdot R$ and its 1-σ uncertainty, and the bottom plot shows the same for the $B \cdot T$ component. The $B \cdot R$ direction was the least well determined by the Doppler and ranging solutions as can be seen by comparing the size of the uncertainties on $B \cdot R$ and $B \cdot T$ before the Delta-DOR measurements occurred. The first large jump in the estimated value at about 12d before Venus is due to TCM-16 execution errors. The estimate uncertainty is also increased by the TCM-16 execution errors, and the solution errors do not return to their previous uncertainty level up to the Venus flyby due to the previously mentioned poor viewing geometry for Doppler and ranging during this period. The Delta-DOR has its largest effect on the $B \cdot R$ component errors due to the particular Earth viewing geometry at this encounter. The $B \cdot T$ component is very well determined by Doppler and ranging alone in this case as seen by the size of the uncertainties in Figure 9. When compared with the targeted aim point in the B-plane, the reconstructed trajectory was different from the aim point by 1.0 km in $B \cdot R$, 1.3 km in $B \cdot T$, and 0.7 s in time-of-flight.

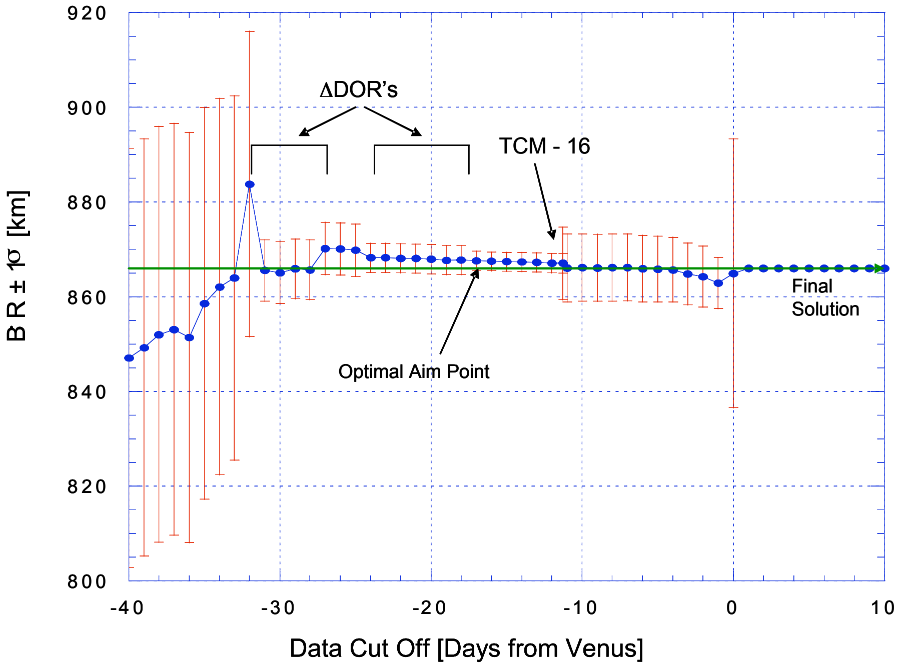


Figure 8. Improvement in B-plane B·R Uncertainties due to Delta-DOR on Approach to Venus Flyby 2

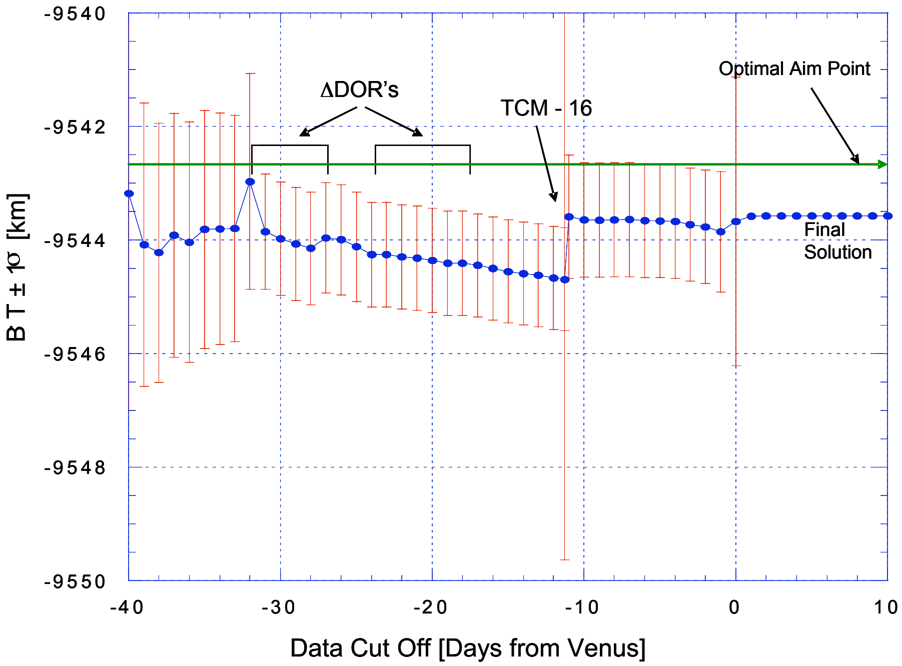


Figure 9. Improvement in B-plane B·T Uncertainties due to Delta-DOR on Approach to Venus Flyby 2

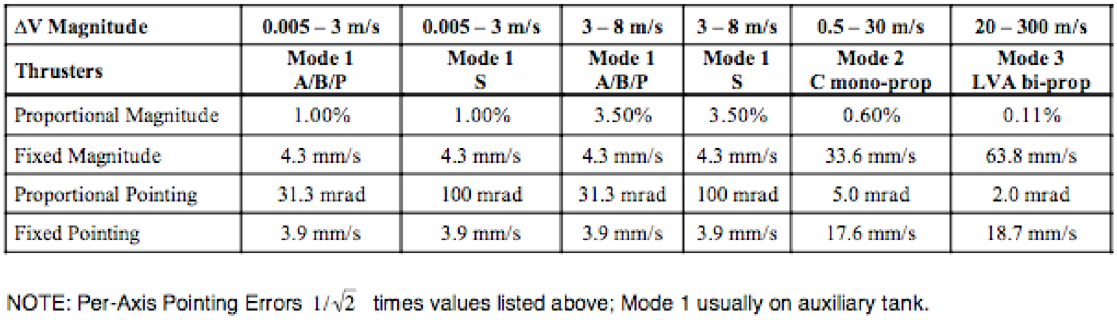
MESSENGER MANEUVER ANALYSIS

There were no nominal DSMs during the leg from Venus flyby 1 to Venus flyby 2, but several trajectory correction maneuvers (TCMs) were required to correct errors in targeting to the Venus-flyby-2 aim point. Targeting errors, in turn, arise from the cumulative effects of both orbit determination errors and maneuver execution errors as the mission unfolds. Constraints on maneuver direction also have an impact on maneuver accuracy and targeting, as described below.

Maneuver Accuracy and Capabilities

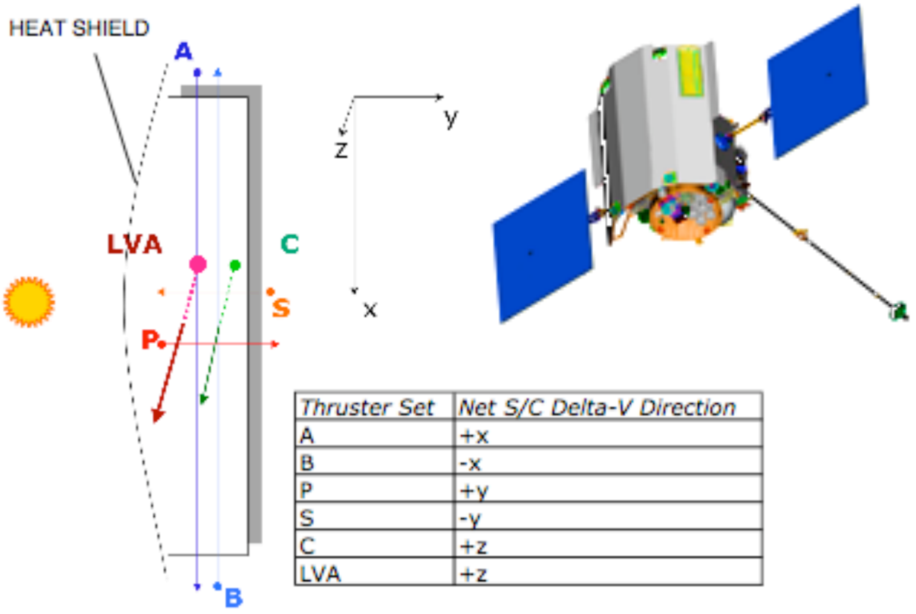
The accuracy of maneuvers is characterized by the parameters shown in Table 2, which specifies execution errors in both magnitude and direction for various thruster modes and ΔV ranges, as certified by the MESSENGER Guidance and Control (G&C) engineer, Dan O'Shaughnessy. Thruster sets are identified in Figure 10 and are shown relative to spacecraft axes and nominal spacecraft-to-Sun orientation. The larger maneuvers, such as DSMs, are performed in thruster mode 3 with the LVA thrusters, which use a bipropellant mixture of fuel and oxidizer to achieve ΔV in excess of 20 m/s. The remaining thruster sets use a monopropellant, with the next highest range of ΔV achieved using the C thruster set supplied from the primary fuel tank. Use of this particular set of thrusters is identified as thruster mode 2, capable of achieving ΔV up to 30 m/s (available but not used for this phase of the MESSENGER mission). Remaining thruster sets are identified as mode 1 and use monopropellant supplied from an auxiliary fuel tank, which is refilled as part of the sequence performed for larger velocity corrections. Mode 1 thrusters are typically used only for smaller velocity corrections during approach maneuvers prior to each planetary flyby.

Table 2. Maneuver Execution Errors Associated with MESSENGER Thrusters



ΔV Magnitude	**0.005 – 3 m/s**	**0.005 – 3 m/s**	**3 – 8 m/s**	**3 – 8 m/s**	**0.5 – 30 m/s**	**20 – 300 m/s**
Thrusters	**Mode 1 A/B/P**	**Mode 1 S**	**Mode 1 A/B/P**	**Mode 1 S**	**Mode 2 C mono-prop**	**Mode 3 LVA bi-prop**
Proportional Magnitude	1.00%	1.00%	3.50%	3.50%	0.60%	0.11%
Fixed Magnitude	4.3 mm/s	4.3 mm/s	4.3 mm/s	4.3 mm/s	33.6 mm/s	63.8 mm/s
Proportional Pointing	31.3 mrad	100 mrad	31.3 mrad	100 mrad	5.0 mrad	2.0 mrad
Fixed Pointing	3.9 mm/s	3.9 mm/s	3.9 mm/s	3.9 mm/s	17.6 mm/s	18.7 mm/s

NOTE: Per-Axis Pointing Errors $1/\sqrt{2}$ times values listed above; Mode 1 usually on auxiliary tank.



Thruster Set	Net S/C Delta-V Direction
A	+x
B	-x
P	+y
S	-y
C	+z
LVA	+z

Figure 10. MESSENGER Thruster Orientation

Targeting Considerations

Targeting errors at Venus flyby 2 have consequences in terms of impacting the planet or surrounding atmosphere, as well as increasing mission ΔV cost to return to a optimal trajectory. This achieves subsequent flyby conditions in order to arrive at Mercury in March 2011 and meet orbit insertion requirements. Mission ΔV cost contours at Venus flyby 2 are illustrated in Figure 11, reflecting global mission cruise ΔV usage sensitivity (in m/s) to flyby errors. The axes correspond to the change in $B \cdot T$ and $B \cdot R$ (using Earth Mean Orbit of January 1.5, 2000 reference plane) from the minimum-total-ΔV (through Mercury orbit insertion) trajectory. The contours allow for trajectory re-optimization beyond Venus flyby 2 to minimize ΔV costs as much as possible. Note that the contours on the side closest to Venus are denser, indicating a steeper gradient in the region closer to the planet. Note, too, that the penalty for larger misses is more severe in the $B \cdot T$ direction than along $B \cdot R$.

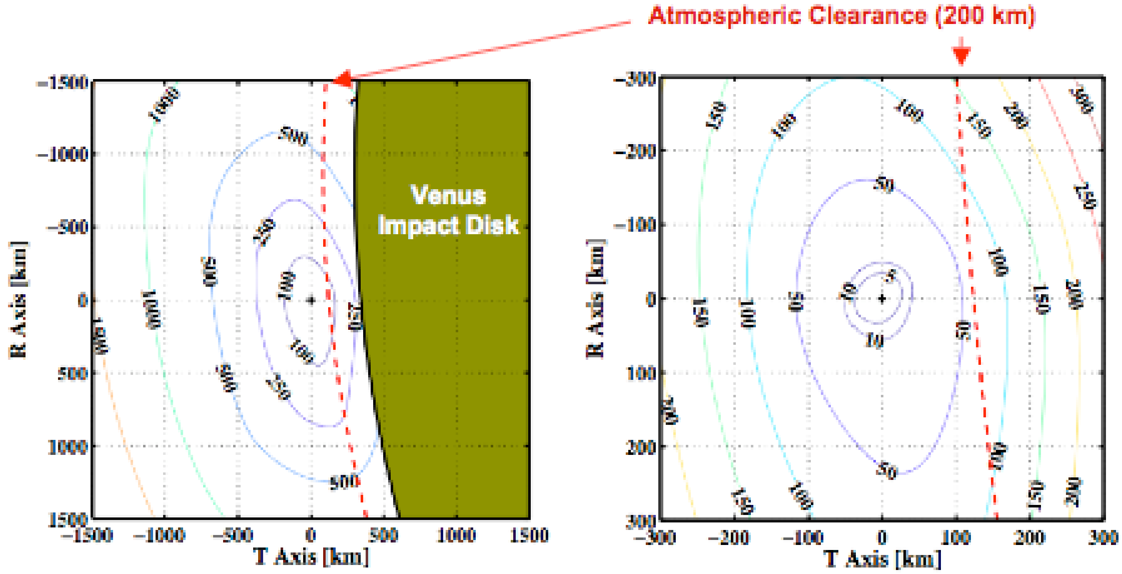


Figure 11. MESSENGER Venus Flyby 2 B-Plane and Mission Cost Contours (m/s). Expanded View on Right Shows Details

Trajectory Correction Maneuvers

There were four nominal TCM opportunities scheduled over the period between the two Venus encounters. The first of these, TCM-13 on December 2, 2006, or 39 days after Venus flyby 1, was used to clean up flyby targeting errors left over from the Venus flyby 1 encounter prior to the solar conjunction period. TCM-14, scheduled for January 24, 2007, after solar conjunction, was planned as a cleanup maneuver for TCM-13, but was not needed. Two more TCMs, TCM-15 on April 25, 2007 (41 days prior to Venus flyby 2), and TCM-16 on May 25, 2007 (11 days prior to Venus flyby 2), provided targeting correction on approach to Venus flyby 2.

As indicated in Table 3, the TCMS were progressively more accurate and only three of the four were used. As a result of cancellation of TCM-12 and the ensuing large targeting error[5], a ΔV of nearly 26 m/s was required at TCM-13. This was much larger than initially anticipated and necessitated a composite burn similar to DSMs already planned, consisting of a mode 1 settling burn to achieve optimal placement of the LVA oxidizer and fuel, followed by a mode 3 main burn on the LVA thrusters with auxiliary tank refill and a final mode 1 trim maneuver. Although the individual components of TCM-13 exhibited relatively large execution errors, the overall maneuver performance was good enough to place the spacecraft within a few hundred kilometers of the flyby target, so that TCM-14 was deemed unnecessary and could be cancelled.

Next, the team was ready to perform TCM-15 and TCM-16. For such maneuvers, the most accurate thrusters are the A and B thruster sets, which are oriented laterally or orthogonal to the direction of the Sun, typically, as indicated in Figure 10. Therefore, the preferred maneuver strategy entailed use of these thrusters oriented laterally to keep the spacecraft's sunshade pointed within a specified angle relative to the Sun and thereby protect the spacecraft from overheating. This angle, also known as the Sun keep-in (SKI) limit, is nominally 9° but can be extended to as much as 12° at larger Sun-spacecraft ranges, especially near aphelion. In order to achieve a lateral direction for TCM-15 and TCM-16, the closest approach time at Venus flyby 2 was allowed to drift by as much as 90 s.

A priori targeting errors prior to TCM-15 are shown in Figure 12. Note that the optimal aim point for minimal mission ΔV usage was not used as the final targeted aim point. Instead, the final target was biased off nominal aim point to ensure that the direction of DSM-2 (over 220 m/s on October 17, 2007, after Venus flyby 2) will remain within SKI limits. Otherwise, DSM-2 would have to be decomposed as shown in Figure 13, entailing an excessive ΔV penalty.

Table 3. Design and Reconstruction of TCMs Between Venus Encounters

TCM #	Execution Date (Relative Days)	Mvr Seg	Thr Mode	Final Maneuver Design			Final Nav Reconstruction			Reconstructed Execution Error	
				Mag [m/s]	RA [deg]	Dec [deg]	Mag [m/s]	RA [deg]	Dec [deg]	Mag [m/s]	Ptg [deg]
13	2-Dec-06 (V1+39d)	A	1	8.131	246.6	-28.0	7.591	245.7	-28.8	-0.540 (-6.6%)	1.15 (1.0%)
		B	3	19.810	335.3	2.4	20.251	334.8	4.1	0.440 (2.2%)	1.72 (0.3%)
		C	1	8.131	246.6	-28.0	7.867	245.3	-30.0	-0.264 (-3.2%)	2.28 (1.0%)
		All	1	25.630	-60.2	-15.4	25.175	-58.7	-14.2	-0.455 (-1.8%)	1.93 (1.0%)
15	25-Apr-07 (V2-41d)	All	1	0.767	175.9	-42.2	0.572	175.8	-42.5	-0.194 (-25%)	0.32 (1.1%)
16	25-May-07 (V2-11d)	All	1	0.212	102.7	10.7	0.213	100.6	10.8	0.0005 (0.3%)	2.02 (2.3%)

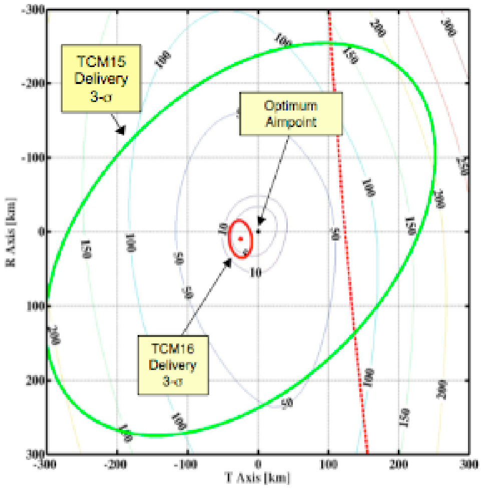


Figure 12. MESSENGER Delivery Errors at Venus Flyby 2 Estimated Prior to TCM-15

Redesign of Final TCM

An anomaly was experienced during TCM-15, in which the thrusters used for attitude control inadvertently reduced the net ΔV by opposing the thrusters selected for the burn itself. As a result of this anomalous response by the G&C system, the burn was only 75%

complete when the maximum cutoff time, defined to prevent an overburn, had been reached. Consequently, TCM-16 was re-planned to make up the shortfall.

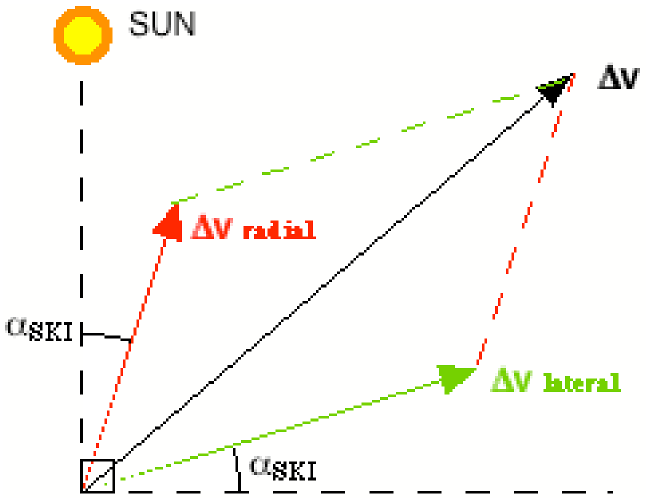


Figure 13. Maneuver Decomposition Required for Sun Keep-In Restrictions

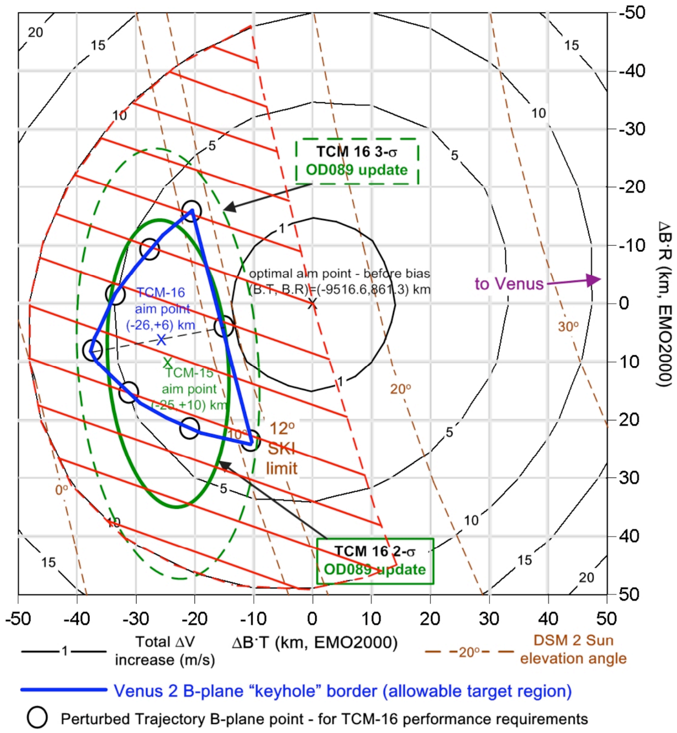


Figure 14. Venus Flyby 2 Targeting Success Criteria Established Prior to TCM16 (Final Correction)

The basis for the TCM-16 redesign is depicted in Figure 14. The near-circular, solid-line contours depict the increase in total ΔV corresponding to variations in the final reconstructed encounter B-plane intersection. The diagonal DSM-2 Sun elevation angle dashed lines illustrate the relationship between B-plane intersection and spacecraft sunshade orientation required at DSM-2. The location of both DSM-2 and a contingency opportunity one week after DSM-2 avoids solar conjunction, i.e., Sun-Earth-spacecraft angle within 3°, and keeps Sun-spacecraft-ΔV angle within 12° of 90° (12° SKI constraint) for each maneuver. Although adjustment of onboard guidance limits could extend the maximum DSM-2 Sun elevation angle to at least 18° without overheating sensitive spacecraft components, the G&C team recommended keeping the DSM-2 Sun elevation angle < 10°. The 2-σ and 3-σ error ellipses correspond to the first orbit update (OD089) after the April 25, 2007, execution of TCM-15. The thick line is the locus of error ellipse center points corresponding to: (1) the rightmost limit of the 3-σ green error ellipse touching the diagonal dashed line (corresponding to 16.5° Sun elevation for DSM-2) passing through the pre-bias optimal aim point at the center of the chart, and (2) the upper and lower edges of the 2-σ error ellipse touching the 10-m/s total ΔV cost contour. The nominal mapped B-plane location based on the post-TCM-16 OD solution needed to fall inside this region to guarantee the proper geometry for DSM-2. The center point of this region, marked by an "X," became the TCM-16 aim point ($B \cdot R$ = +6, $B \cdot T$ = -25). Thus, the B-plane region bordered by the thick line or "keyhole" defined the success criterion for TCM-16.

LESSONS LEARNED AND FUTURE PLANS

The planetary flybys and flight operations thus far on MESSENGER have provided valuable calibration and insight for performing the remainder of the mission. This has been especially true at Venus flyby 2, since the combined Mission Design, Navigation and Mission Operations Teams planned and executed a near flawless planetary gravity assist flyby. The lessons learned will be incorporated into the remaining Mercury encounters.

Lessons Learned

There were many factors that together improved the Venus flyby 2 delivery accuracy over the results obtained for Venus flyby 1. First, there were several benign geometry factors that made flyby 2 different from flyby 1. These included the larger SEP viewing angle, which ensured that the DSN radio metric data were relatively free of solar-plasma-induced noise. Also, there was the more favorable declination of the Venus flyby 2 as viewed from Earth, since the near-zero declination during Venus flyby 1 reduced the effectiveness of the DSN Doppler tracking data for that encounter. Finally, the alignment of the Earth diurnal viewing direction in the B-plane (along the T-axis) allowed more accurate measurements and hence better trajectory determination in the critical direction of altitude. The lesson learned from this was to fully analyze the geometry effects for the remaining encounters. Unfortunately, this same combination will not repeat for the remaining flybys.

Also contributing to improved delivery accuracy was the first operational use of Delta-DOR tracking on approach to Venus flyby 2. The accuracy and consistency of this tracking type was demonstrated by using it during the three months leading up to Venus flyby 2. In addition to improving trajectory estimates, the Delta-DOR tracking also improved the quality of solutions for other estimated parameters, most notably the spacecraft solar pressure model parameters. Delta-DOR is planned at all remaining Mercury encounters. Related improvements in the spacecraft attitude modeling after Venus flyby 1 also produced more accurate, consistent SRP estimates. Attitude model improvements included smaller sample intervals of the spacecraft attitude telemetry, more and better availability of short term predictions for planned attitude events, and fewer attitude changes (as compared with Venus flyby 1). This improved modeling accuracy allows the Navigation Team to better predict encounter conditions and plan TCMs.

TCM-16 magnitude accuracy proved important for achieving delivery accuracy in the critical T direction of the B-plane. Luckily, OD errors balanced out TCM-16 angle error in R direction. On the other hand, there were a number of impediments to delivery accuracy. These included a ΔV anomaly that appeared on April 15 and was linked to possible outgassing from the LVA engine bell, thought to be the consequence of exposure of residual propellant from TCM-13 to sunlight. This anomaly caused the OD solution to jump by several tens of kilometers until the effect was analyzed and modeled. Outgassing may have been due to a minor leak in the outer valve of the LVA propulsion system and will be investigated further after DSM-2 and prior to Mercury flyby 1. However, the other notable anomaly, involving a shortfall in the TCM-15 burn, presented the biggest issue for the cruise phase leading to Venus flyby 2. The Spacecraft Team was able to characterize quickly what had gone awry and made adjustments to the controller to avoid recurrence of this problem in the future, as evidenced by the performance of TCM-16. Nevertheless, a tradeoff between magnitude and pointing accuracy must always be carefully considered in terms of the impact on flyby targeting when designing final Mercury approach maneuvers.

Changes for Mercury Flyby 1

On the basis of the factors that led to improvement in flyby accuracy at the second encounter with Venus, analysis of Mercury flyby 1 revealed the following differences. First, the geometries available at this encounter are not as favorable as those experienced at Venus flyby 2. Namely, the encounter occurs about a month after a superior solar conjunction so tracking data are missing or degraded during the approach. Also, the Earth's diurnal viewing direction is nearly orthogonal to the B-plane T-axis, so the enhanced accuracy in the altitude direction that occurred at Venus flyby 2 will not occur. The encounter occurs at low declination, so there is no overlap between the Madrid and Goldstone tracking stations, and this means there will be no Delta-DOR east-west baselines available for approach. Overlap tracking will still be available between Goldstone and Canberra, so north-south baselines of Delta-DOR are in the schedule.

The Earth-to-spacecraft range will be more than 1.5 AU during much of the final approach to Mercury flyby 1, resulting in lower signal-to-noise and decreased precision in the ranging data. Adjustments to the relative weighting of the Doppler and ranging in the orbit determination filter will minimize the impact this has on trajectory estimates. The flyby will also be the closest heliocentric range to date for the spacecraft, and that will put more emphasis on the solar pressure modeling. Solar pressure modeling will also be impacted by the many attitude changes needed for passive angular momentum control and Earth pointing associated with the low SEP angle. Finally, solar panel offsets of up to about 70° off the Sun will put new stress on correct modeling of the attitude and solar pressure model.

DSM-2 occurs just before the conjunction leading into the first Mercury encounter. The cleanup for this maneuver, which is expected to be a couple of meters per second in magnitude, will occur after reliable tracking is re-acquired post-conjunction, so the approach timeline will be more compressed than that at Venus flyby 2. The cleanup maneuver will include contingency opportunities in case the original maneuver is delayed due to spacecraft issues, since it will most likely induce a large B-plane change in the aim point.

SUMMARY

The second Venus encounter involved a highly accurate delivery, one of the best in deep-space navigation history. The last B-plane solution placed the spacecraft 1.6 km from the targeted aim point and 0.7 s from targeted time of closest approach, based on post-flyby data out to to June 17. The uncertainties associated with these estimates were under 100 m and 0.5 s, respectively, at a 3-σ level.

The final approach (last 40 days) was characterized by exceptionally stable and well-behaved OD solutions. Post-flyby Delta-DOR contributed to the capability to reconstruct the flyby performance. Four of five passes scheduled were successful and of good quality (one was cancelled).

TCM performance based on final reconstructions was quite acceptable in terms of achieving the aforementioned targeting performance. Although TCM-15 experienced an anomalous underburn of 25%, TCM-16 was able to make up the shortfall with a tolerable pointing error of about 2°.

Finally, Optical Navigation test results met or exceeded expectations. Data were successfully received for all eight opportunities with data-flow tests accomplished on two occasions and a solution test completed and results delivered on the seventh opportunity.

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