AAS 07-171

EARTH TO VENUS-1 NAVIGATION RESULTS FOR NASA'S MESSENGER MISSION TO MERCURY

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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 interval from Earth flyby through Venus flyby 1, and focuses on orbit determination results, navigation analyses supporting statistical trajectory correction maneuvers, and maneuver reconstruction results for this interval. Also included are preliminary results from several tests performed for optical navigation imaging and Delta-Differential One-way Ranging (Delta-DOR) tracking data types taken on approach to Venus flyby 1.

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

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After launch on August 3, 2004, the spacecraft began its six-and-one-half year interplanetary cruise that will culminate with rendezvous and orbit insertion at the planet Mercury (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.[1] Once in orbit, MESSENGER will perform detailed 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) to return 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.

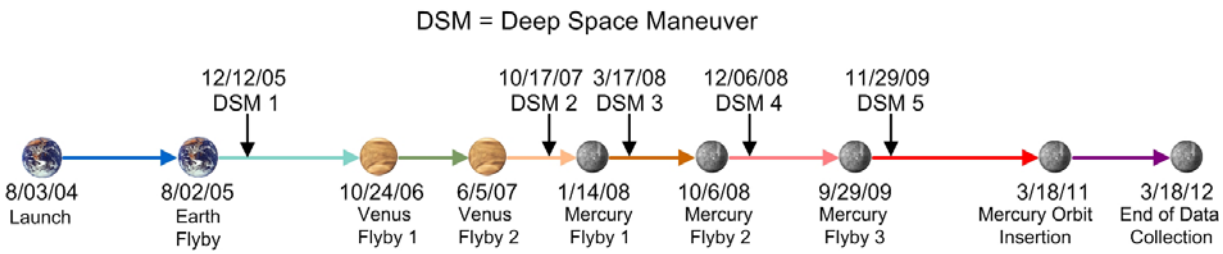

Figure 1. MESSENGER Timeline for Planetary Flybys and Deep Space Maneuvers (DSMs).

The Earth flyby occurred on August 2, 2005 and Venus flyby 1 occurred on October 24, 2006. During this interval, the primary goal of the MESSENGER Navigation Team (NAV) was to determine and control Venus flyby 1 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[2] on the basis of the available telemetry and DSN Doppler and ranging tracking data. Because of its high altitude, Venus flyby 1 was initially considered less demanding than subsequent flybys, so the mission plan was to perform tests on approach to validate and improve orbit determination for the more critical encounters later during cruise. The tests scheduled the MESSENGER Navigation Team's first use of DSN Delta-Differential One-Way Ranging (Delta-DOR) and Optical Navigation (OpNav) using images from the two on-board science cameras. These two tracking data types provide important additional information for determining the trajectory on approach to planetary flybys.

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”.

Regardless of the apparent low risk of the targeted high altitude at Venus flyby 1 (3040 km), there were several challenges for this encounter:

(1) During the approach to Venus, the viewing geometry from Earth was especially poor for determining the flyby B-plane position using Doppler and ranging data, because the Earth-to-spacecraft vector was near zero declination. Thus, there was liable to be an appreciable delivery error in the B-plane. This was initially not regarded as a problem because of the high altitude of the flyby.

(2) Attitude modeling errors affected Orbit Determination (OD) results in the B-plane by several tens of kilometers due to coupling with solar pressure forces in the filter. Modeling numerous spacecraft attitude changes leading up to the flyby became one of the largest and most time-consuming OD tasks.

(3) Spurious changes in spacecraft velocity (ΔV) due to angular momentum dumps were larger than expected, and not predictable. If a large momentum dump ΔV occurred soon after the last planned TCM, it could result in a 50-km shift in the B-plane.

(4) A superior solar conjunction with low Sun-Earth-Probe (SEP) angle (SEP < 3°) began 7 days before the flyby and ended 25 days after it. Radio metric data would be noisy leading into this period, and the data could not be guaranteed at all inside the conjunction, so the project and the Navigation Team had to plan TCM locations and other critical events accordingly.

In July of 2006, 3 months before the flyby, the Navigation Team discovered that the global mission cruise ΔV usage was extraordinarily sensitive to Venus flyby errors, even after re-optimization. This unexpected and unintuitive result, in which an error of 50 km could cost the mission an additional 45 m/s of ΔV, meant that the largest navigation challenge for the flyby had become delivering the spacecraft accurately to Venus in the face of the other challenges listed above.

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 is headed by the Navigation Team Chief, Tony Taylor. The MESSENGER Navigation Team performs orbit determination and trajectory correction maneuver reconstruction, and it additionally performs TCM design and trajectory re-optimization in conjunction with the Mission Design Team. Orbit determination for cruise phase segments is based on DSN radio metric data types: two-way Doppler (F2), three-way Doppler (F3), and ranging from the DSN Sequential Ranging Assembly (SRA). On approach to Venus flyby 1 the first Delta-DOR tracking of MESSENGER was obtained as described below, and it was verified by comparison to Doppler and ranging solutions. 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 to correct the trajectory back to the aim point.

The MESSENGER Navigation Team is also implementing and testing an OpNav capability for use on approach to the Mercury flybys and Mercury orbit insertion. This capability was first tested on approach to Venus flyby 1. Because the MESSENGER camera was not designed to be sufficiently sensitive for optical navigation, multiple image exposure tests were performed to determine a suitable scenario for future OpNavs. The OpNavs taken on approach to Venus flyby 1 were not used to determine the trajectory or TCMs on approach, because the atmosphere of Venus makes it a poor OpNav target. Additional OpNav testing will be performed at Venus flyby 2 before the method is used operationally at Mercury flyby 1. The results of the OpNav tests at Venus flyby 1 are discussed below.

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. The individual wideband VLBI measurements provide a precise measurement of the difference in time of arrival of the waveform received by two DSN antennas. A simplified VLBI diagram[3] is shown in Figure 2. It shows the position vector between the two antennas referred to as the "baseline" vector, **B**. The VLBI observable is the time difference or delay, τ, of the signal arrival between the two stations making up the baseline. Because the inertial orientation of the DSN baseline at the time of the VLBI measurements is known very precisely, a highly accurate angular offset (the angle θ in Figure 2) of the signal (either spacecraft or quasar) relative to the baseline, can be inferred. Hence the VLBI data provide a direct measurement of the spacecraft angular position.

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 provides a level of robustness to a radio metric orbit determination strategy. In fact, Delta-DOR tracking has been included on approach to Mars for every Mars mission since the failed Mars Climate Orbiter that did not use Delta-DOR. For the MESSENGER Venus flyby 1, the addition of Delta-DOR to Doppler and ranging on approach improved the spacecraft delivery uncertainty in the planet B-plane.

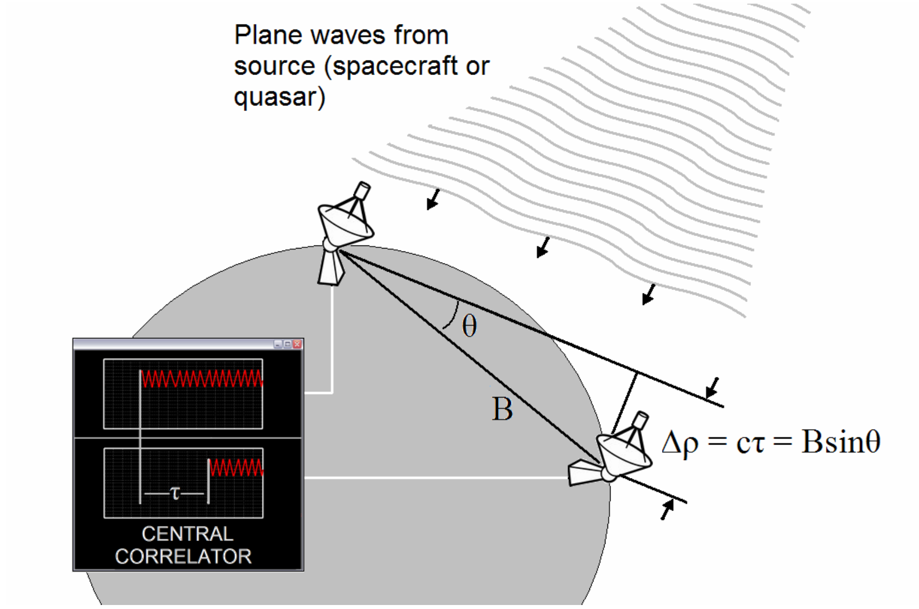

Figure 2. Simplified Diagram of Very Long Baseline Interferometry (VLBI) Tracking Employing Two DSN antennas. Delta-Differential One-Way Ranging (Delta-DOR) Is Made by Differencing Spacecraft and Quasar VLBI Scans.

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 sequence is denoted by the shorthand label “Q1-S-Q2” in the following. The quasars are chosen so they are within about 10° of the DSN antenna pointing direction to the spacecraft. Figure 3 shows a diagram of the viewing geometry from Earth for the Delta-DOR session on July 10, 2006, that included quasar 1, CDT 26, and quasar 2, 0446+11. The quasar-spacecraft-quasar observing sequence forms the interleaved VLBI measurements that will be differenced by the Navigation Team. This process is repeated, resulting in two Delta-DOR measurements for each baseline during the session. The total time for the VLBI session, including the time to slew the antennas between spacecraft and quasars, is about one hour.

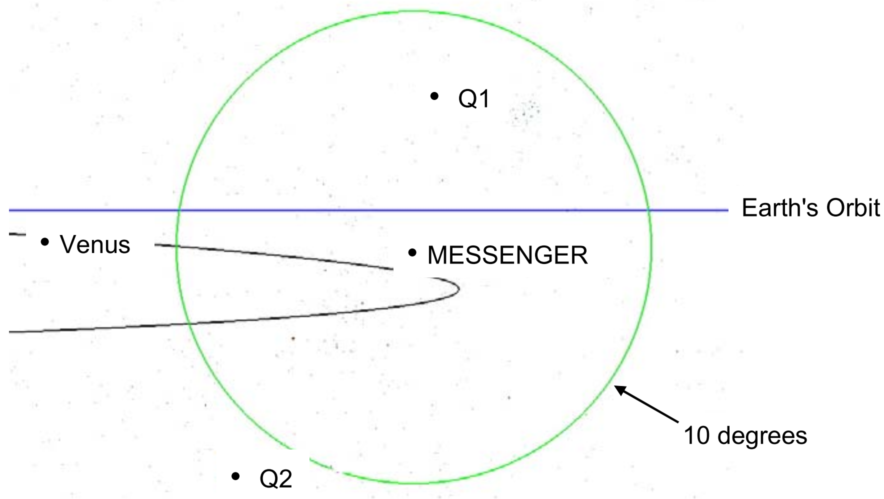

Figure 3. Typical Delta-DOR Session on July 10, 2006, 20:30 – 21:30 as Viewed From Earth. The 10° Circle Centered on the MESSENGER Spacecraft Shows the Separation of the Two Quasars Used and the Relative Position of Venus.

In order to obtain a position measurement on the plane-of-sky, two nearly orthogonal baselines are used: 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 1 contains a schedule of Delta-DOR tracks taken on approach to Venus flyby 1 which shows the use of both north-south and east-west baselines. In the table, the antennas are identified by their DSN number. Thus, the first baseline identified as “25-45 (N-S)” refers to the use of Deep Space Station (DSS) antenna DSS-25 at the Goldstone, California, complex and antenna DSS-45 at the Canberra, Australia complex to form a north-south baseline. Additional antenna identification used in Table 1 includes: DSS-24 and DSS-26 at Goldstone, California; DSS-34 at Canberra, Australia; and DSS-55 and DSS-65 at Madrid, Spain. Also included in the table are the quasar-spacecraft-quasar sequences and the result. Except for a single sequence on July 17 that was hampered by a ground antenna problem, all the Delta-DOR tracking passes were successful.

Table 1. Delta-DOR Tracks Taken on Approach to Venus Flyby 1. Venus Flyby 1 Occurred on October 24.

Date	Baseline	Sequences	Result
10 Jul	25-45 (N-S)	Q1-S-Q2, Q1-S-Q2	Both sequences:Successful
17 Jul	25-45 (N-S)	Q1-S-Q2, Q1-S-Q2	1st sequence: Ground antenna problem 2nd sequence: Successful
28 Sep	24-34 (N-S)	Q1-S-Q1, Q1-S-Q1	Both sequences:Successfu l
3 Oct	25-65 (E-W)	Q1-S-Q1, Q1-S-Q1	Both sequences:Successful
9 Oct	26-45 (N-S)	Q1-S-Q2, Q1-S-Q2	Both sequences:Successful
10 Oct	24-55 (E-W)	Q1-S-Q2, Q1-S-Q2	Both sequences:Successful

The first verification test performed on the Delta-DOR tracking was to form data residuals relative to the trajectory estimate using only Doppler and ranging. This is shown in the left plots of Figure 4. These pre-fit residuals show two distinct linear trends: one for the E-W baseline and one for the N-S baseline. These slopes indicate there are angular rate errors along the respective baseline directions in the plane-of-sky. When the data are included in the OD filter, the linear trends are removed as seen in the right plot of Figure 4, and the trajectory estimate adjusts to be consistent with the Delta-DOR, so the linear rates are de-trended. The Delta-DOR 1-σ weight used for this fit was 0.06 ns, and the post-fit residual RMS is < 0.05 ns.

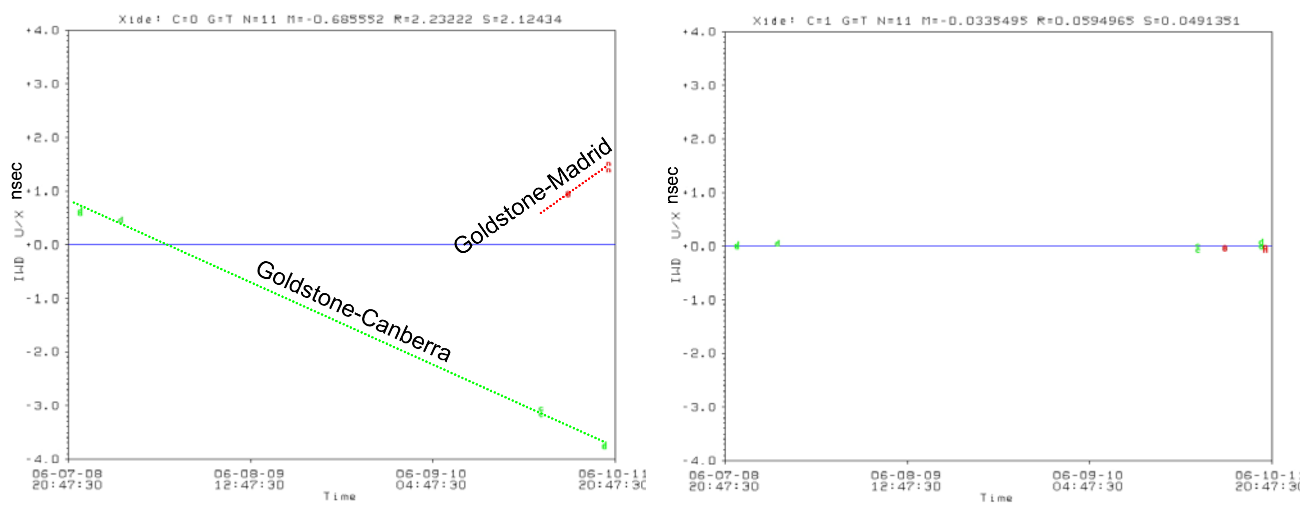

Figure 4. Delta-DOR Pre-fit (Left Plot) and Post-fit (Right Plot) Residuals in Nanoseconds. The Pre-fit Residuals were Relative to a Trajectory Determined with Doppler and Ranging Data Only.

Because the use of Delta-DOR had not yet been validated on MESSENGER, the orbit determination solutions delivered to the project on approach to Venus flyby 1 were based on Doppler and ranging only, and the eleven successful Delta-DOR sequences were incorporated into a parallel orbit determination solution on approach. The parallel solution was monitored but was not used in maneuver design decisions. Originally, the plan was to verify the Delta-DOR process for MESSENGER after Venus flyby 1, but the Navigation Team presented the fully operational Delta-DOR solutions ahead of schedule on October 12, twelve days before the closest approach at Venus. Ultimately during the post-flyby reconstruction, these Delta-DOR solutions proved to be correct, but it was too late to influence the design of the final trajectory correction maneuver, TCM-12, on October 5. The orbit determination results using Delta-DOR are discussed below.

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 precisely 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, not specifically designed for optical navigation, so individual images of the planet and of stars must be combined to form the OpNav measurement.

All OpNav images for MESSENGER are taken with the MESSENGER Dual Imaging System (MDIS) imager. MDIS is designed for imaging a bright surface when in orbit about Mercury, and so it is not sufficiently sensitive to image dim stars. If a picture is over-exposed to image dimmer stars, then the planet is over-exposed, causing 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, and one wide angle camera (WAC) with a 10.5° square field-of-view. Each camera has a 1024 by 1024 pixel charge-coupled device (CCD) in their 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.

Tests were performed at Venus flyby 1 to determine the best sequence of images to form the OpNav measurements. Venus is not a very good OpNav target because of the center-finding uncertainty caused by the Venus atmosphere, so the OpNavs taken on Venus approach are not used to improve the trajectory estimate. However, the images taken at Venus are used to test the OpNav software and the interfaces between the Navigation Team and the MDIS planning and scheduling team. There were three test phases based on range to Venus: (1) acquisition and exposure tests, (2) calibration and distortion tests, and (3) exposure vs. distance tests. During phase one there were three types of image sequences tested. There was a sequence of three NAC images, with changes in pointing between images to image first stars only, then the planet, then again stars only. This is referred to as an “NNN” triplet. Next there was a sequence of WAC, NAC, and WAC images, all with the same pointing at the planet. This is referred to as a "WNW" triplet. Finally, there was a sequence of NAC, WAC, then NAC images, with the boresight slightly off center of the planet so that the planet only appears in the WAC image. This is referred to as a "NWN" triplet. The goal of taking these sets of triplets was to find the best combination of cameras and exposures to synthesize OpNav measurements of both the planet and background stars.

The images of Venus from the approach tests in both the NAC and WAC are shown in Figure 5. Note that even for the shortest exposure time (7 ms) in the NAC, the image on the left shows there are some image artifacts due to the bright Venus disk. These can be removed, and a center-finding algorithm was successfully used on these image types. The image on the right of Figure 5 shows many more problems from a ~10-s exposure in the WAC. This image could not be used with our center-finding algorithm. Again, some of the artifacts of the WAC long exposure can be removed, a procedure most useful for imaging stars in the four corners of the image, away from the bright center. OpNav results from selected images are shown below.

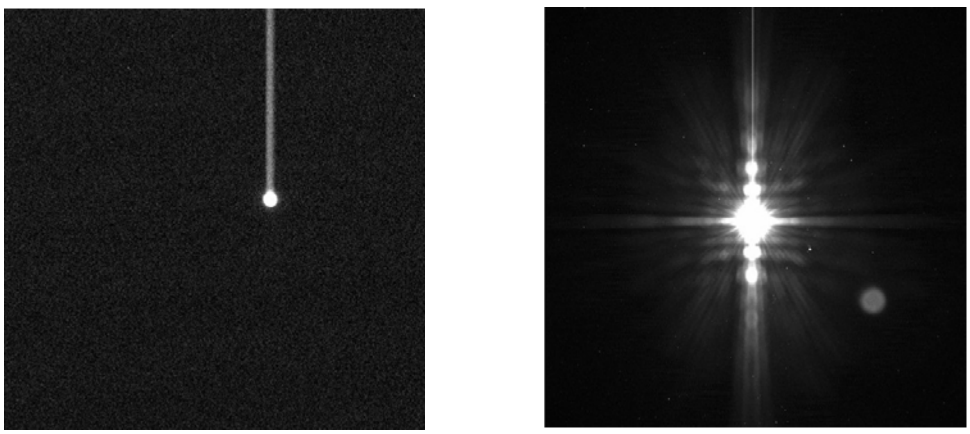

Figure 5. Test OpNav Images of Venus on Approach Taken on October 4, 2006, at 16.8x10^6 km Range. Left Image Is from Narrow Angle Camera, 7-ms Exposure. Right Image Is from Wide Angle Camera, 9988-ms Exposure.

MESSENGER ORBIT DETERMINATION RESULTS

A trajectory reconstruction was performed using the Doppler, ranging, and Delta-DOR data available over the arc from Earth flyby to Venus flyby 1. The data started on August 2, 2005, before Earth flyby, and ended on November 22, 2006, after Venus flyby 1. The two-way Doppler pass-by-pass mean and 1-σ noise for this arc is shown in Figure 6, and the pass-by-pass mean and 1-σ noise for the ranging data are shown in Figure 7. The Doppler means and noise show a rapid rise near the Venus flyby due to the superior solar conjunction. The ranging means show a sinusoidal trend with a period of approximately 30 days, but the overall magnitude of this unmodeled effect is less than 50m 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.

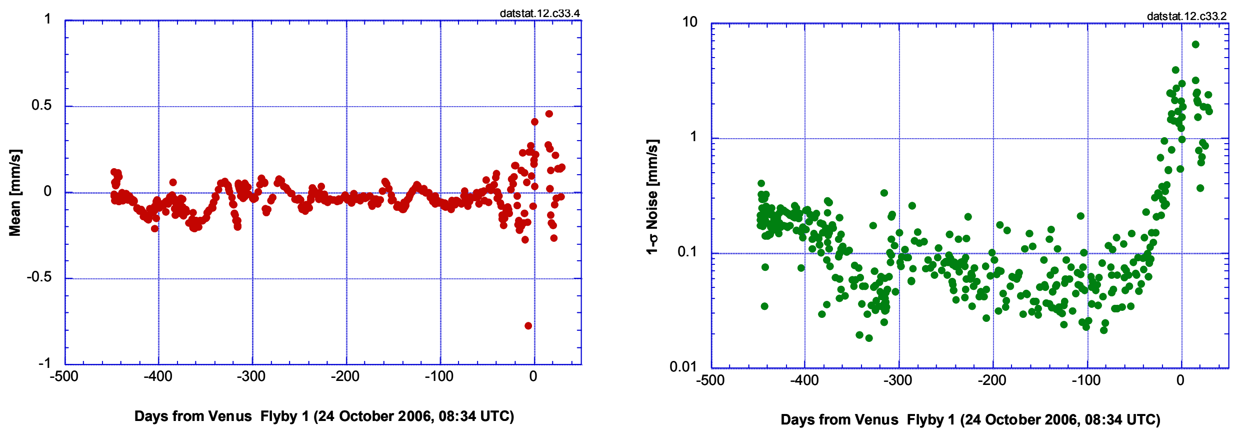

Figure 6. 2-Way Doppler Residual Means (Left Plot) and 1-σ Noise (Right Plot) for the Data Arc from Earth Flyby to Venus Flyby 1.

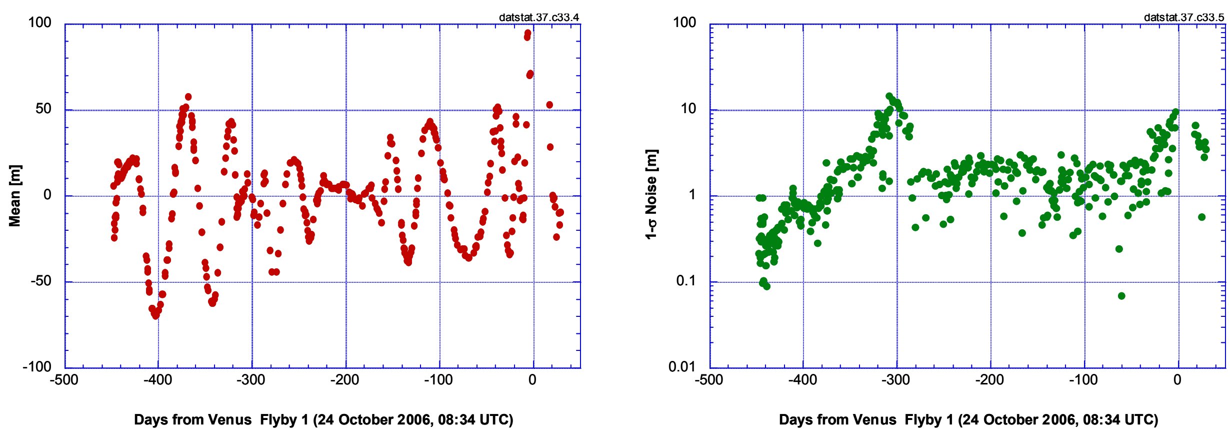

Figure 7. 2-Way DSN Ranging Residual Means (Left Plot) and 1-σ Noise (Right Plot) for the Data Arc from Earth Flyby to Venus Flyby 1.

The improvements in uncertainties in the Venus flyby 1 B-plane due to adding Delta-DOR to the Doppler and ranging solution is shown in Figure 8. This figure shows the optimum aim point at the origin and the pre-encounter 1-σ uncertainty ellipses for solutions with and without Delta-DOR. The optimum aim point after TCM-11 was located at $B \cdot T$ = -5,690 km and $B \cdot R$ = -11,072 km from the center of Venus. Also shown in the figure are the mission total ΔV cost contours for missing the optimal aim point. The Delta-DOR solution moved mostly in the "R-axis" direction, which was the direction of the major axis of the Doppler and ranging error ellipse. The Delta-DOR solution 1-σ error ellipse is much smaller in the "R-axis" direction than that for the solution using only Doppler and ranging. This improvement in flyby knowledge came too late to influence the last targeting maneuver, as mentioned earlier. The reconstructed solution after the flyby is accurate to the sub-kilometer level and hence appears as a point in the figure. Note that the reconstructed solution lies within the 1-σ error ellipse for the solution performed at 12 days before the Venus encounter that included Delta-DOR.

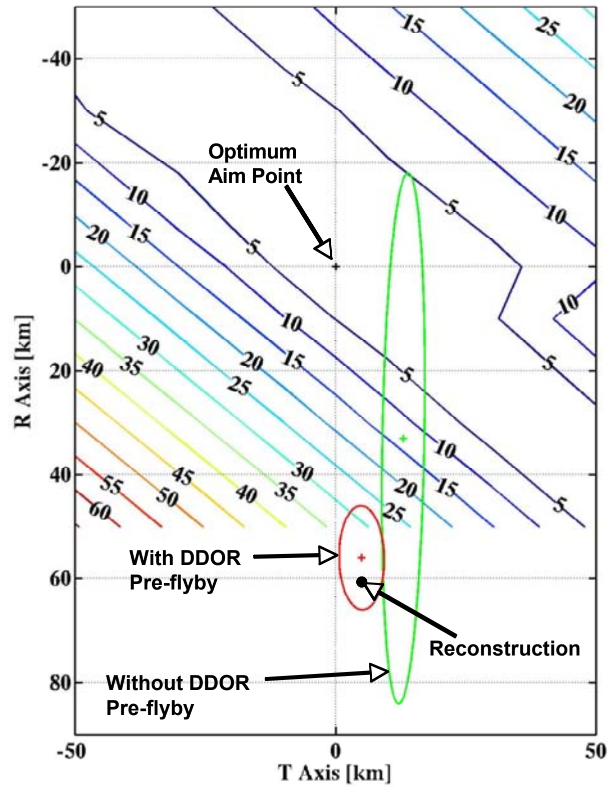

Figure 8. Trajectory Error Ellipses in the Venus Flyby 1 B-plane for Solutions Performed at Venus -12 d. Contours Are Mission Total ΔV Cost in m/s.

The effect of adding the Delta-DOR to the solution at various data cut-off times on approach to Venus is seen by comparing the two plots in Figure 9. The top plot shows the evolution of the estimate for the B-plane component $B \cdot R$ and its 1-σ uncertainty for Doppler and ranging only. The $B \cdot R$ direction was the least well determined by the Doppler and ranging solutions as shown in Figure 8. The first large jump in the estimated value at about 42d before Venus is due to TCM-11 execution errors. The estimate uncertainty is also increased by the TCM-11 execution errors, and the solution errors do not return to their previous uncertainty level until very near the Venus flyby due to the previously mentioned poor viewing geometry for Doppler and range during this period. The lower plot in Figure 9 shows the same arc but including the Delta-DOR. The solution moves to near the final reconstructed value after the first Delta-DOR point is included about 25 days prior to closest approach. Also notice the solution errors are reduced for data cut-off times after TCM-11 when the Delta-DOR data are included in the arc. The improvement in solution error due to the early Delta-DOR points in July 2006 (see schedule in Table 1), is seen in the reduced level of uncertainty before TCM-11.

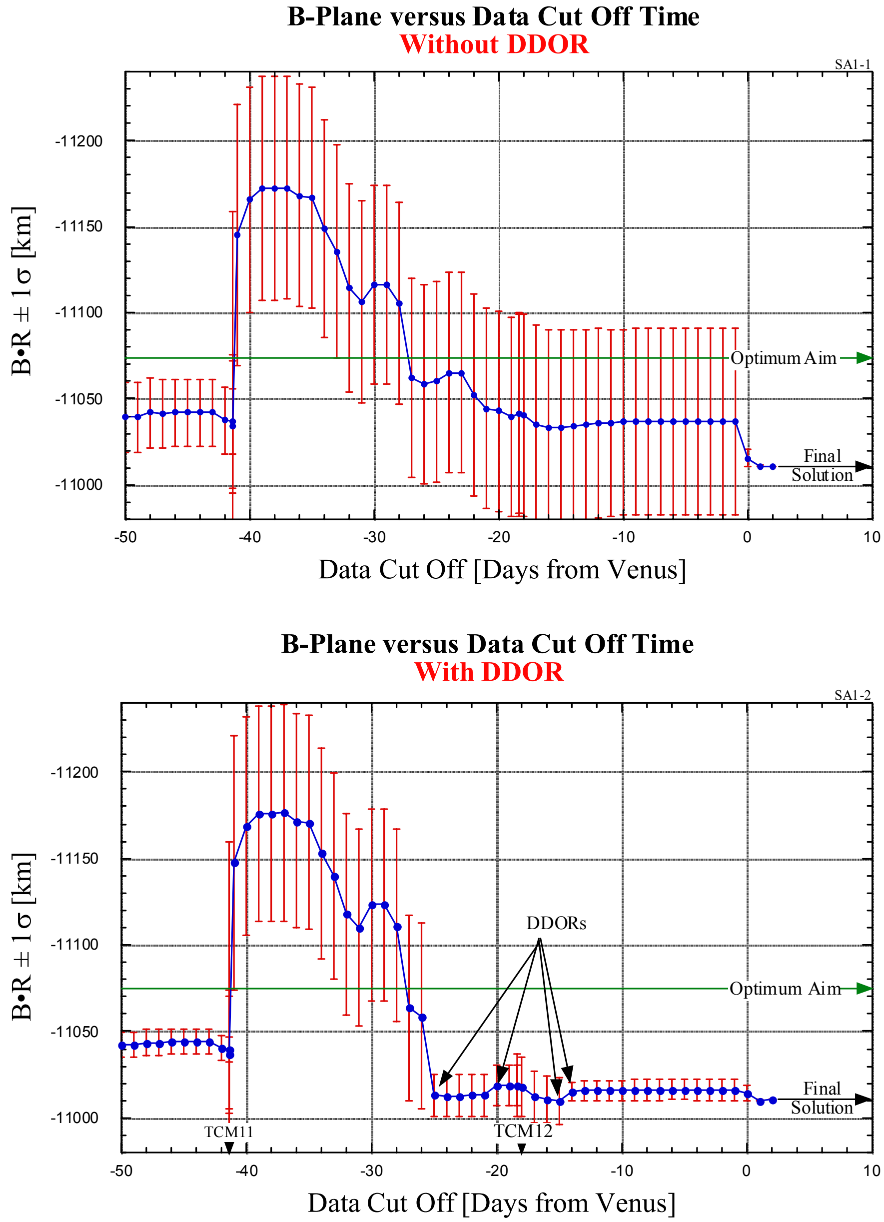

Figure 9. Estimate of *B·R* Component of Intercept Point and 1-σ Error Bars as Data Are Processed on Approach to Venus. The Top Plot Is without Delta-DOR and the Bottom Plot Is with Delta-DOR.

MESSENGER MANEUVER ANALYSIS RESULTS

Figure 10 shows the change in the Venus B-plane conditions due to the ΔV imparted by the second commanded momentum dump (CMD-2) and TCM-11. Both the location of the B-plane intercept point and the time of closest approach (C/A) are shown before and after TCM-11. Also included are the Venus radius and a 200-km reference altitude line mapped to the B-plane. This plot emphasizes that although the momentum dumps ideally should not impart any net ΔV, the actual effect can be sizable.

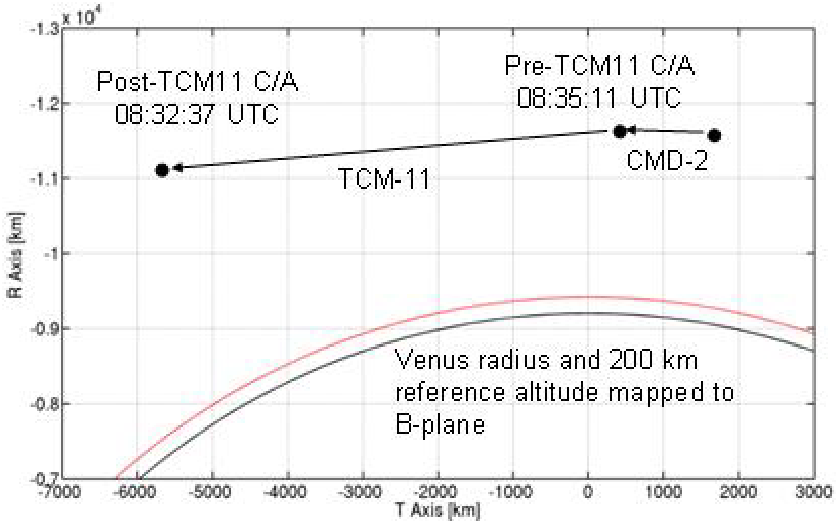

Figure 10. Trajectory Intercept Points in the Venus Flyby 1 B-plane Following TCM-10 on February 22, 2006. Change In Closest Approach (C/A) Time and Intercept Point Due to ΔV Imparted by Commanded Momentum Dump 2 (CMD-2) and TCM-11 Design.

Following the Earth gravity-assist flyby in August 2005, the next scheduled maneuver was TCM-08. TCM-08 was intended as a correction to the Earth flyby but was determined to be unnecessary due to the accuracy of the achieved close approach point relative to the optimal target. The next scheduled TCM was Deep Space Maneuver 1 (DSM-1) on December 12, 2005, which was by far the largest burn to date and the first test of the Large Velocity Adjust (LVA) thruster. DSM-1 execution errors were small, well within the expected uncertainties as can be seen in Table 2 below, resulting in a trajectory on course for Venus flyby 1. Subsequent trajectory re-optimization, along with estimation and modeling errors, resulted in TCM-10, which was scheduled for February 22, 2006, being designed to move the Venus flyby 1 target B-plane some 89,000 km and over an hour earlier in arrival time. TCM-10 execution errors were large and resulted in an approximate 9 percent magnitude error and a right ascension error of about -2.6°, as can be seen in Table 2.

Maneuver spacing after TCM-10 on approach to Venus is pictured in Figure 9. TCM-10 was followed by CMD-2, only the second commanded momentum dump since launch, which moved the target B-plane 1240 km and 21 s earlier in arrival. TCM-11 was executed on September 12, 2006 and corrected another 6100 km in the B-plane and moved the arrival 154 s earlier. TCM-11 incurred larger than expected angular errors of almost 9° in declination and approximately -3.7° in right ascension. The combination of maneuver execution errors and drift in the orbit determination solutions, due primarily to attitude and solar radiation pressure modeling errors, led to the necessity of TCM-12 on October 5, 2006, less than 3 weeks before the flyby. TCM-12 improved a 700-km error in the B-plane but still left a 60 km discrepancy between the resulting trajectory and the optimal aim point, as can be seen in Figure 8, although the earliest post-burn estimates implied a slightly closer approach to the target. Subsequent trajectory estimates, including those incorporating Delta-DOR data, confirmed the arrival point as shown in Figure 8, but these came too late to support designing and implementing an additional maneuver to move the B-plane intercept point closer to the optimal target.

The maneuver reconstruction table presented in Table 2 itemizes the results of TCM execution in comparison to the maneuver design for all of the TCMs performed during the leg of the trajectory between the Earth flyby and Venus flyby 1. In general, the LVA (660-N) thruster has provided the smallest relative maneuver execution errors, while small trajectory correction maneuvers using the attitude control thrusters as their primary source have proved to me more problematic at times. The execution errors in TCM-11 and TCM-12 were mainly angular; in contrast, the error for TCM-10 was primarily in magnitude. TCM-10 and TCM-12 utilized 4.4-N thruster pairs. TCM-11 was a two component maneuver, utilizing 22-N thrusters for the lateral segment and the 4.4-N thrusters along the Sun line for execution of the final component. While it is fortunate that the performance of the LVA is well within mission requirements, as it is needed for the large DSMs with mission-critical implications, the problems encountered during several smaller TCMs have exacerbated the task of estimating maneuver results with short turnaround times. It is desirable to provide the mission planners and schedulers with estimation results as soon as possible after maneuver execution. However, when unexpectedly large execution errors are encountered, the initial estimation results can be misleading because they are being determined primarily by the *a priori* inputs to the OD filter. The closer the maneuver execution is to the design, the more rapidly the estimation results converge to the final solution.

Table 2. TCM Reconstruction Results for Earth to Venus Flyby 1

TCM-09 at 12 December 2005 11:30:00.0 UTC Spacecraft Event Time				
Parameter	Estimated	Design	Reconstruction Uncertainty (1-σ)	Difference from Design
ΔV (m/s)	315.6334	315.7200	0.0004	-0.0866 (-0.03%)
Declination (deg)	-4.8828	-4.8652	0.0005	-0.0177
Right Ascension (deg)	217.2755	217.2570	0.0001	0.0185
TCM-10 at 22 February 2006 16:00:00.0 UTC Spacecraft Event Time				
Parameter	Estimated	Design	Reconstruction Uncertainty (1-σ)	Difference from Design
ΔV (m/s)	1.2807	1.4071	0.0005	-0.1264 (-8.98%)
Declination (deg)	9.2538	9.2223	0.3218	0.0316
Right Ascension (deg)	166.2108	168.8002	0.1273	-2.5894
TCM-11 at 12 September 2006 23:00:00.0 UTC Spacecraft Event Time				
Parameter	Estimated	Design	Reconstruction Uncertainty (1-σ)	Difference from Design
ΔV (m/s)	1.6762	1.6786	0.0004	-0.0024 (-0.14%)
Declination (deg)	-18.0280	-26.9573	0.1653	8.9293
Right Ascension (deg)	278.4358	282.1080	0.0086	-3.6723
TCM-12 at 05 October 2006 22:30:00.0 UTC Spacecraft Event Time				

Parameter	Estimated	Design	Reconstruction Uncertainty (1-σ)	Difference from Design
ΔV (m/s)	0.5014	0.4967	0.0041	0.0048 (0.96%)
Declination (deg)	-75.4059	-75.1148	0.3904	-0.2911
Right Ascension (deg)	259.4165	252.2721	0.2745	7.1445

Post-maneuver trajectory estimates use the design values for the TCM as the *a priori* inputs until such time as results from spacecraft telemetry data become available. Filter uncertainties are set based upon the experience gained from previous burns and referenced to a Gates table that provides expected errors for different maneuver modes. The three maneuver modes are defined based on the size of thruster, or thrusters used for executing the burn, as follows: (1) 4.4 N, (2) 22 N, (3) 660 N (LVA). Over-constraining filter estimates with initial uncertainties that are too optimistic can produce large discrepancies in the post-maneuver results. Experience has shown that it is best to use large maneuver uncertainties, at least initially, to let the data drive the solutions. Figure 11 shows the estimated uncertainties for TCM-12 as a function of time, revealing why it was necessary to delay the final TCM-12 reconstruction until after the flyby.

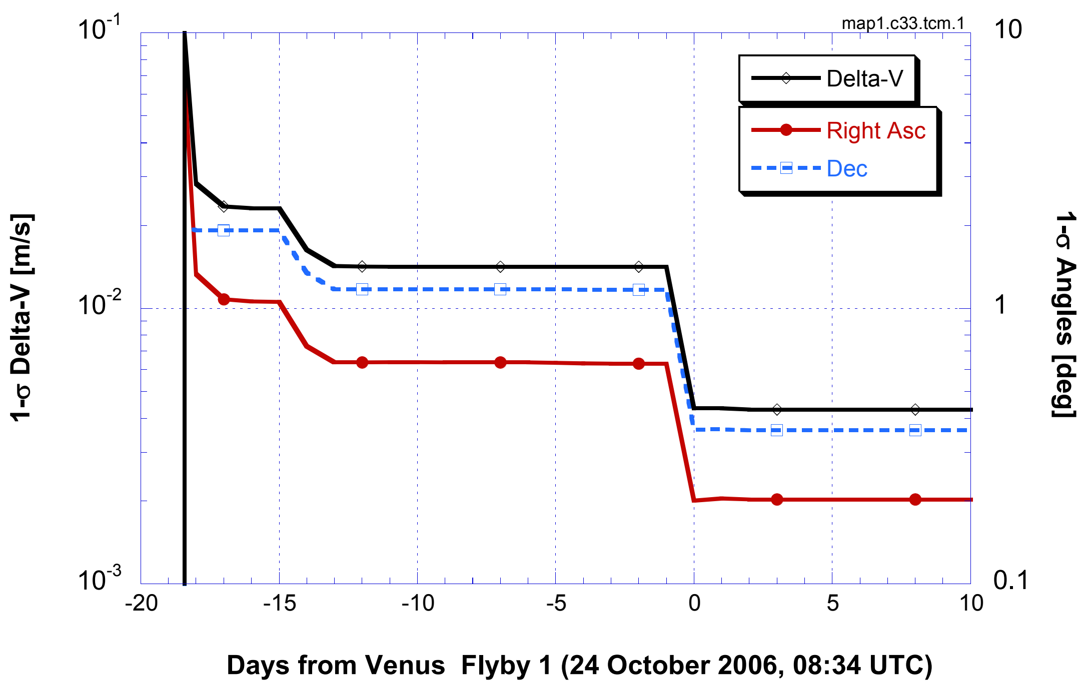

Figure 11. Time History of TCM-12 Magnitude and Direction Estimate Uncertainty (1-σ) through Venus Flyby 1

Venus Flyby 1 OpNav Test Results

OpNav image processing is a two-step process. First the star locations in line and pixel coordinates are extracted from the image(s). Then the line and pixel of the planet center are determined from the same image or from one of the closely spaced triplets of images from the test sequences. The star information is used to determine the camera pointing direction. The information is then reduced to line and pixel offsets between the predicted and observed planet location in the field of view. For MDIS, this simplified description is complicated by the fact that image triplets are used to determine independently the stars and planet line and pixel locations. Since the star information is spread across images taken a few seconds apart that bracket the planet image, least squares algorithms are used to solve for the pointing. In addition to the complications of extracting information from multiple images, the image distortion for NAC and WAC must also be independently calibrated.

Figure 12 shows a WAC image taken at 16,839,450 km from Venus on October 4, 2006 12:19:27.182 UTC spacecraft event time, about 20 days prior to Venus flyby 1. The image has been processed to locate candidate stars, shown by the smaller red circles, and the corresponding catalog star locations, shown by the white circles with various diameters. The diameter of the white circles is linearly related to the catalog star apparent magnitude. The star catalog used for identifying stars is the Tycho-2 catalog.[4] The image in Figure 12 has not been corrected for boresight offset or distortion. Notice that there are six or seven catalog stars (white circles) that have a corresponding candidate star slightly offset to the 11:00 o'clock position, or upper left. This offset varies from three to ten pixels depending on the location on the CCD. These offsets are reduced to less than a pixel after the imager is calibrated for distortion and attitude offset. The Venus image in the center of the picture shows image artifacts that distort and blur the Venus disk, and thus the Venus center-finding, denoted by the small green dot on Venus, is biased. This is not the case for shorter exposures with the WAC, or for images of Venus taken with the NAC. The OpNav test results from analyzing images such as this were used to plan the next series of OpNavs to be taken at Venus flyby 2. These plans are discussed in the next section.

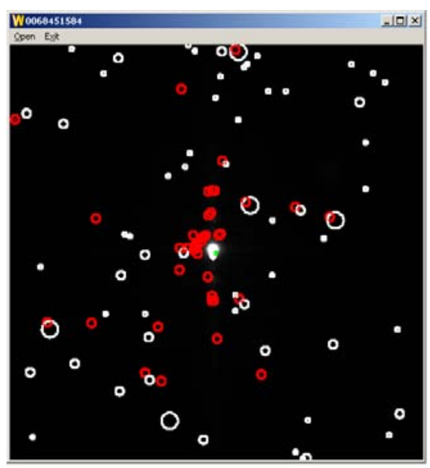

Image Is Not Corrected for Boresite Offset or Distortion. Venus at Center, Smaller Red Circles Are Detected Stars and White Circles Are Catalog Stars with Diameter Linearly Related to Apparent Magnitude.

Figure 12. Processed WAC Image Taken on October 4, 2006 at 16.8x10^6 km from Venus Closest Approach.

NAVIGATION PLANS

There remain one Venus flyby and three Mercury flybys over the next three years before MESSENGER is inserted into orbit about Mercury in March 2011. The June 2007 Venus flyby 2 will be used to test OpNav and science sequences further for upcoming Mercury flybys. The remaining flyby events are shown in Figure 1. The experience gained from the Earth flyby and Venus flyby 1 has been used to create flyby templates for placement of targeting maneuvers, Delta-DOR measurements and OpNavs for the subsequent encounters. The template for Mercury flyby 1 has to be modified somewhat from the others because of a solar conjunction that limits communication and tracking of the spacecraft. The templates showing the planned placement of Delta-DOR and TCMs for several weeks around future flybys are shown in Figure 13. The Delta-DOR plans have a minimum of three baselines per week before encounter to support the TCM design, and four baselines for a week after encounter to enhance trajectory reconstruction. The baselines will alternate between north-south and east-west over the Delta-DOR tracking intervals. These plans may be altered slightly depending on the results of on-going navigation analysis and constraints from project operations and DSN scheduling.

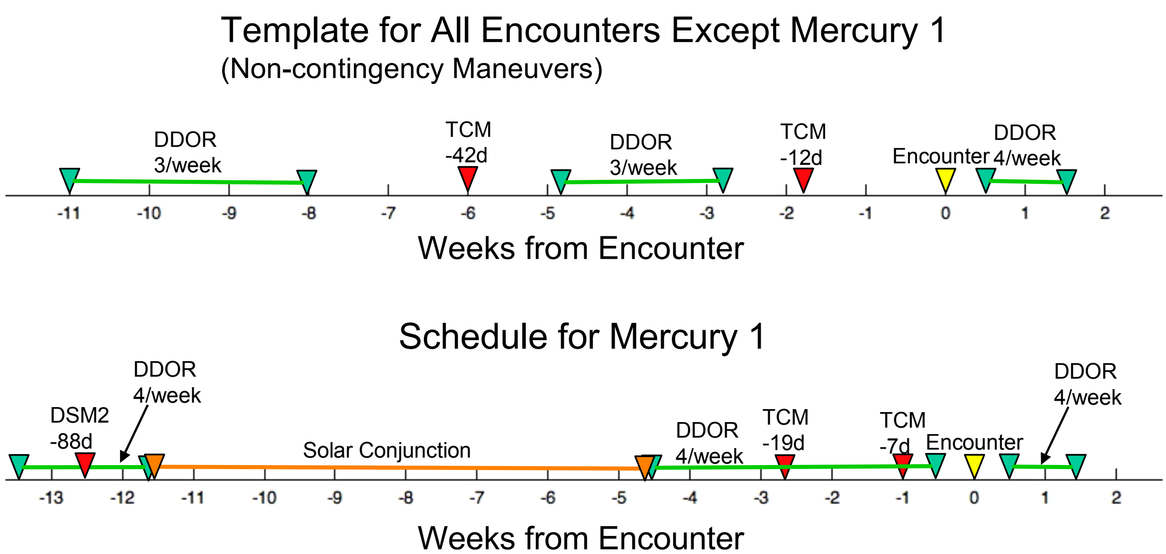

Figure 13. Top Timeline Shows Placement of Targeting Maneuvers and Delta-DOR Tracking for Remaining Flybys of Venus and Mercury. The Bottom Timeline Shows Mercury Flyby 1 Has Time Constraints Due to the Proximity of Solar Conjunction.

The planned OpNav sc**hedule for** Venus flyby 2 is shown in

Table 3. The OpNav plan at Venus flyby 2 is to take images on departure that emulate the apparent size of Mercury that will be seen on approach to Mercury flyby 1. At each planned time, a sequence of OpNav images will be taken. Each OpNav sequence includes nine images made up of NAC and WAC pictures that are taken of stars and the

planet to ensure that sufficient raw information is available for the derived OpNav measurement as described above.

Table 3. Venus Flyby 2 OpNav Plan. The Plan Places Images on Departure from Venus to Emulate the Apparent Planet Size that Will Be Experienced on Approach to Mercury Flyby 1.

Date yymmdd	Time UTC	Time from Flyby	Comments
070606	15:00	+0d15h	Matchs largest Mercury size, M4-2d SPV = 56 deg
070606	15:00	+0d15h	Venus = 480 px, Range = 0.493e6 km
070607	03:00	+1d03h	Venus = 267 px, Range = 0.886e6 km
070607	15:00	+1d15h	Venus = 185 px, Range = 1.278e6 km
070608	15:00	+2d15h	Venus = 115 px, Range = 2.061e6
070609	15:00	+3d15h	Venus = 83 px, Range = 2.843e6
070610	15:00	+4d15h	Venus = 65 px, Range = 3.624e6
070612	15:00	+6d15h	Venus = 46 px, Range = 5.183e6
070614	15:00	+8d15h	Venus = 35 px, Range = 6.734e6
070614	15:00	+8d15h	Matchs smallest Mercury size, M1-5d SPV = 65 deg

Additional planning for OpNavs at subsequent Mercury flybys is shown in Figure 14. During approaches to Mercury, the spacecraft attitude is constrained to keep the spacecraft bus in the shadow of the sunshade. At most, the spacecraft may point up to 12° off-Sun, and the MDIS pivot can be used to point the imagers another 50° toward the Sun or up to 40° away from the Sun. However, scattered light issues could limit the usefulness of OpNavs acquired near the 62° maximum (28° from pointing directly at the Sun) pointing limit. The OpNavs on approach to Mercury flybys will be used to support the design of a contingency maneuver about one day prior to closest approach that would raise periapsis altitude, if needed.

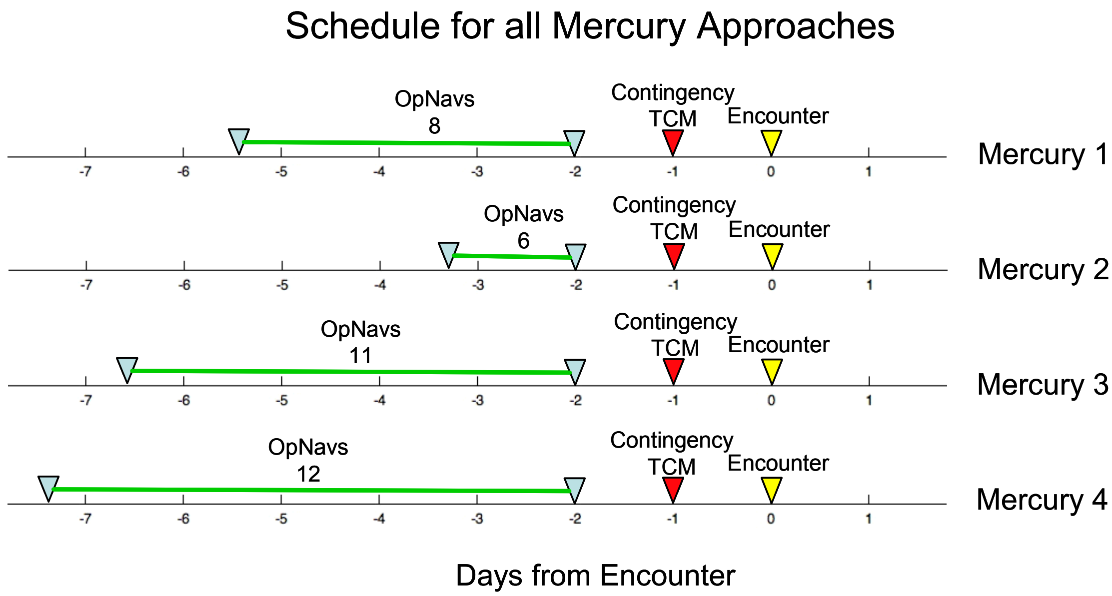

Figure 14. OpNav Opportunities Planned for the Mercury Encounters. Two OpNav Sequences Per Day Made up of NAC and WAC Images. Mercury 4 is the Approach to Mercury Orbit Insertion in March 2011.

SUMMARY

The MESSENGER cruise from Earth to Venus flyby 1 was successful, and several important navigation milestones were completed. The planned tests to incorporate DSN Delta-DOR tracking and OpNav tracking into the MESSENGER trajectory estimates on approach to Venus were successful. The Delta-DOR tests gave such good results that it was validated for navigation deliveries ahead of schedule and will be used more extensively on all future flybys. The OpNav tests were also successful and will be used to design more efficient tests planned for Venus flyby 2 in June 2007 in order to prepare for the first operational use of OpNavs for navigation at Mercury flyby 1 in January 2008.

There were lessons learned during this period that will impact future navigation analysis and operations for the remaining cruise to Mercury orbit insertion. The trajectory correction maneuver execution errors experienced over this period were larger than expected from the pre-launch analysis. This history will be incorporated into future covariance and statistical maneuver analyses. In addition, the project has been advised to schedule backup maneuvers for the last two targeting maneuvers before every encounter to ensure an accurate delivery to the flyby aim point.

The sensitivity of Venus flyby 1 to trajectory errors was discovered only three months prior to encounter. It would have been preferable to have completed the navigation analysis for the entire mission prior to launch, but two delays in launch opportunity and associated changes in mission design led to a decision to complete the analysis during cruise, as needed, before each planetary flyby. The final delivery at Venus flyby 1 was about 60 km from the desired aim point, or about 1-σ based on the error ellipse for the

Doppler and ranging solution. However, because of the sensitivity of the solution this distance error is equivalent to a mission total ΔV cost of about 40 m/s. Because of this experience, additional resources have been made available and navigation analyses are underway to determine ΔV sensitivities well in advance of the remaining planetary flybys and Mercury orbit insertion.

ACKNOWLEDGEMENT

The MESSENGER Navigation Team acknowledges the able and professional support of NASA's Deep Space Network Critical Events Planning Team, the MESSENGER Network Operations Project Engineers, and the Radio Metric Data Conditioning Team for acquiring the tracking data that makes this work possible. Special thanks go to Dr. James Border of the Jet Propulsion Laboratory for planning sequences, choosing quasars, and performing analysis for the Delta-DOR measurements. The Navigation Team also thanks Dr. Louise Prockter of JHU/APL for extensive help to implement the OpNav images in the MESSENGER spacecraft sequences. The MESSENGER mission is supported by the NASA Discovery Program Office under a contract to the Carnegie Institution of Washington (CIW). This work was carried out by the Space Navigation and Flight Dynamics Practice of KinetX, Inc., under a subcontract with CIW.

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