AAS 11-549

APPLYING EXPERIENCE FROM MERCURY ENCOUNTERS TO MESSENGER'S MERCURY ORBITAL MISSION

Brian R. Page, Kenneth E. Williams, Anthony H. Taylor, Dale R. Stanbridge, Christopher G. Bryan, Peter J. Wolff, Bobby G. Williams*

and

Daniel J. O'Shaughnessy, Sarah H. Flanigan †

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is the seventh in NASA's Discovery Program series. The spacecraft was launched in August 2004 and began an interplanetary cruise that culminated in insertion into orbit about Mercury in March 2011 for a nominal one-year scientific investigation. The cruise phase included six planetary gravity-assist flybys and eighteen propulsive events, which included five large deep-space maneuvers, one in two parts, and twelve smaller trajectory-correction burns. From the approach to the first Mercury flyby through orbital insertion about the innermost planet, an interval that spanned over three years, solar sailing was employed successfully for trajectory correction. This paper describes the navigation performance achieved for the three Mercury flybys and how experiences gained during the mission cruise phase have been applied to support Mercury orbit insertion and maintenance operations during the Mercury orbital phase of the MESSENGER mission.

INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is being flown as the seventh in NASA's Discovery Program series. 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 made use of radiometric tracking data from NASA's Deep Space Network (DSN) as does the continuing primary orbital mission.

After launch on August 3, 2004, the spacecraft began its six and one-half year interplanetary cruise phase that culminated with rendezvous and Mercury orbit insertion (MOI) in March 2011.[1-5] Figure 1 shows the heliocentric geometry for MOI and the mission timeline of planetary flybys and deterministic deep-space maneuvers (DSMs). The interplanetary trajectory also included an Earth gravity-assist flyby about a year after launch[6] and two Venus flybys,[7,8] prior to three Mercury flybys[9-11] and orbit insertion. The MESSENGER spacecraft traversed over ten

* KinetX, Inc., Space Navigation and Flight Dynamics Practice, Simi Valley, California 93065.

† The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland 20723.

heliocentric orbits between the first Mercury flyby and MOI. It should also be noted from the figure that the Earth's location at MOI is just days before the vernal equinox, which makes visualizing where it was during the other Mercury flybys and their associated DSMs, from the dates given, rather intuitive.

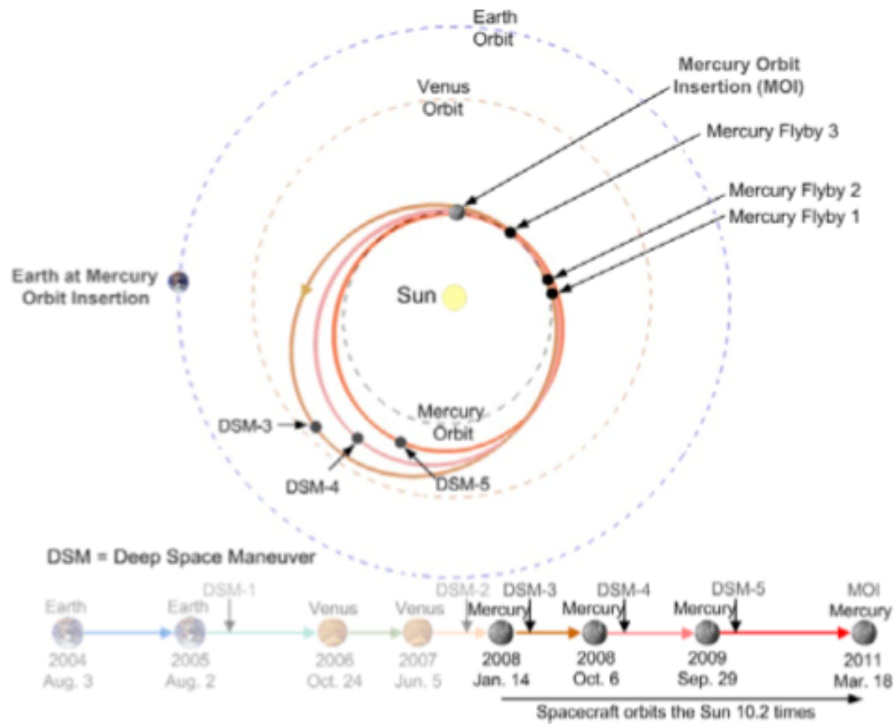

Figure 1. MESSENGER MOI Geometry and Timeline for Planetary Flybys and DSMs.

From Mercury orbit MESSENGER is conducting a campaign of science observations of the innermost planet, nominally for one Earth year.[12,13] Spacecraft navigation during interplanetary cruise involved estimating the trajectory from available tracking data and computing trajectory correction-maneuvers (TCMs) that delivered the spacecraft as close as possible to nominal target parameters at each planetary flyby. Because total fuel usage has been carefully controlled to ensure mission success,[14] the remaining trajectory was reoptimized after each large propulsive maneuver and planetary flyby to accommodate execution errors and trajectory uncertainties. The KinetX navigation team has worked closely with the mission design team at JHU/APL to optimize the flyby targets and to compute the TCMs.

The MESSENGER navigation team has performed trajectory determination and reconstruction of propulsive maneuvers and planetary encounters, and additionally has supported propulsive maneuver design and trajectory reoptimization together with the mission design team throughout the mission. During spacecraft downlink, the DSN acquires radiometric Doppler and ranging data that are passed to the navigation team for processing.[15] Each coherent two-way track from a single DSN antenna produces two-way Doppler tracking data. If a second DSN antenna receives the same downlink (e.g., during a station-to-station handover) then three-way Doppler tracking is produced. Additionally, most of the tracks for MESSENGER are also configured to acquire two-way ranging data from the DSN Sequential Ranging Assembly. Delta differential one-way ranging (DDOR) has also been useful for critical portions of the mission, such as planetary encounters and large maneuvers.

With altitudes at closest approach as low as 200 km, Mercury flybys were generally more demanding than the second Venus flyby at an altitude of 340 km. The measure used to judge the accuracy of the estimated trajectory and TCMs on approach to a flyby is the intercept point in the hyperbolic impact-plane, or B-plane, at the target planet. The proximity of a flyby to the optimized aim point is an indication of the success in modeling the spacecraft trajectory. 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. 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." An illustration of this B-plane definition is given in Figure 2.

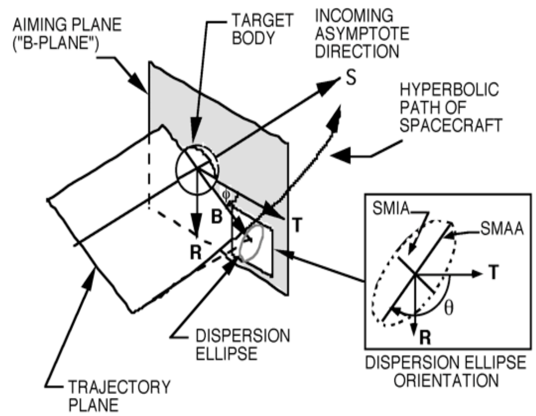

Figure 2. B-Plane Definition with Example Error Ellipse.

This paper compares the Mercury flyby results with each other and with the earlier mission flybys through an examination of B-plane histories and desired aim point targeting performance. Introduction of DDOR prior to the first Mercury encounter provided a substantial improvement in trajectory determination performance.[11] Moreover, the statistical TCMs planned for B-plane corrections were mostly superseded for the Mercury flybys and orbital approach as a result of trajectory adjustments accomplished through solar sailing.[9] This form of trajectory adjustment involves manipulating the forces resulting from solar radiation pressure (SRP) incident on the spacecraft sunshade and solar array panels by varying their respective orientations. The procedures for implementing solar sailing with the MESSENGER spacecraft have evolved over the course of the mission cruise phase. Because spacecraft solar panel attitude is treated as a discrete quantity in the navigation software, a variety of methods were developed to more efficiently represent the changes in panel orientation. These methods were sufficiently accurate to allow for precise targeting of the Mercury flybys through solar sailing without recourse to propulsive maneuvers and the associated expenditure of fuel, which can thus be utilized in support of the primary mission science objectives during the Mercury orbital phase.

Beyond prediction and reconstruction of the spacecraft trajectory, monitoring of critical mission events in real time is another important function of the navigation team. This paper, additionally, reviews and compares the performance of critical events, including planetary encounters and large propulsive maneuvers, which have occurred over the course of the MESSENGER mission.

MERCURY FLYBYS

The first MESSENGER Mercury flyby occurred on January 14, 2008, with closest approach at 19:05:45 TDB (Barycentric Dynamical Time), which would place the Earth at around the eleven o'clock position in Figure 1. This timing provided a good line of sight for tracking and favorable geometry separating Mercury from the Sun for viewing the flyby. During the interval leading up to this event, the primary goal of the KinetX navigation team was to carefully determine and control flyby conditions to ensure successful completion of the remainder of the cruise phase.[11] Throughout the mission cruise phase, the spacecraft attitude was modeled for navigation purposes on the basis of telemetry and solar panel angle command uploads provided by the MESSENGER Mission Operations Center (MOC) team at JHU/APL, and SRP parameters were estimated along with the spacecraft position and velocity using the available DSN radiometric track data. DDOR measurements, in particular, were a critical component of this trajectory estimation process, as they provided an independent data type in a plane perpendicular to the direction observable by Doppler and ranging.[15]

The operational ephemeris update sequence leading up to the initial Mercury flyby is illustrated in Figure 3. Beginning with the estimation solution identified as orbit determination #94 (OD094) and its delivery to the MESSENGER MOC, which included the first post-Venus #2 flyby track data, an updated ephemeris was delivered on a nominal bi-weekly basis. Special mission events, such as DSMs and superior solar conjunctions, periodically interrupted this sequence but deliveries were kept as regular as possible. These ephemeris deliveries were, and still are, uploaded to the MESSENGER spacecraft and also used for DSN tracking. The plot in Figure 5 shows the evolution of the fit span as the solid lines associated with each OD delivery lengthen and the prediction spans are correspondingly shortened such that the overall trajectory estimation/prediction span is held fairly constant just on the other side of the Mercury flyby #1 optimized arrival time. The 'x' marks on the plot indicate where the propagation span was cutoff for deliveries to the MOC. This is typically done to preclude predicting beyond critical mission events such as DSMs or flybys. The critical mission events included on this plot for reference are indicated in red by the vertical lines: Venus flyby 2 (V2), DSM-2 (DSM2), the late-2007 superior solar conjunction (CONJ) and Mercury flyby 1 (M1).

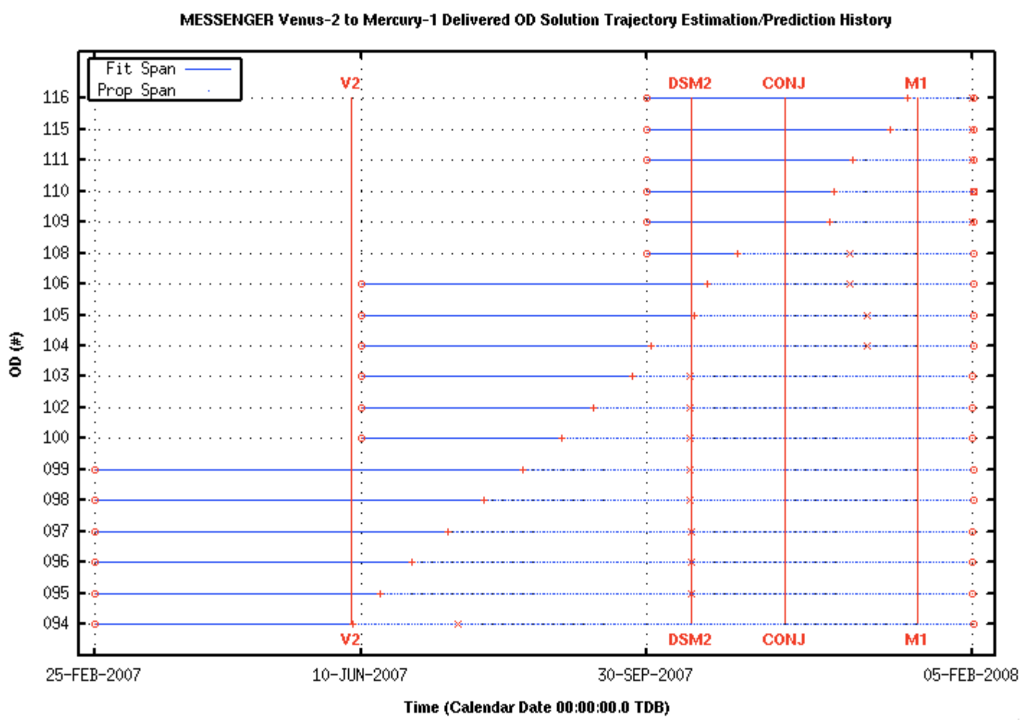

Figure 3. MESSENGER Navigation Operations Mercury Flyby 1 Ephemeris Update Delivery Sequence.

The OD numbering sequence on the plot in Figure 3 is not sequential because these numbers are generated internally by the KinetX navigation team. Not every solution is used for MOC or DSN deliveries because some are produced strictly for analysis purposes. The dates displayed on the time axis are those associated with the estimation epochs and the end of the prediction span, and from these it can be seen why and when the epoch was advanced twice between the second Venus flyby and the first Mercury flyby. After a good reconstruction of the final Venus flyby was achieved, the epoch was advanced to a point just outside of the Venus gravity well, and advanced again to a point in time closer to DSM-2 after that maneuver was executed.

The result of TCM-19, the post-DSM-2 cleanup maneuver on the targeted B-plane is shown in Figure 4, with velocity change (ΔV) cost contours overlaid for emphasis. TCM-19 was executed on the opposite side of a superior solar conjunction from DSM-2, which left the trajectory on a collision course with Mercury for the interval of the conjunction. This was not a problem so long as the MESSENGER spacecraft remained healthy and able to communicate with the MOC through this temporary blackout, which it did. Beyond that, which was, undeniably, a critical juncture in the mission, the importance of TCM-19 was that it was the final small propulsive TCM of the MESSENGER cruise phase. Having successfully completed the coarse targeting of the initial Mercury flyby, all future course corrections through MOI were accomplished with solar sailing.

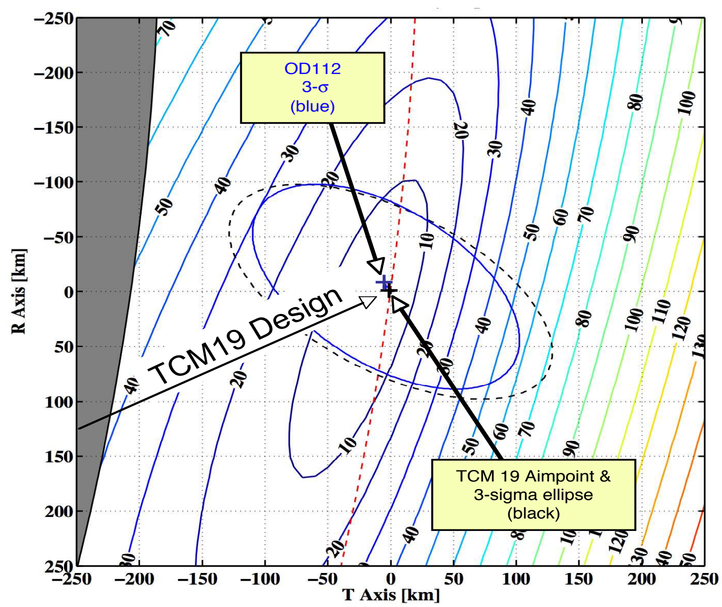

Figure 4. MESSENGER Mercury Flyby 1 B-Plane Showing Effect of TCM-19.

The late-2007 superior solar conjunction was quite deep, with a minimum Sun-Earth-Probe (SEP) angle of 0.6°. There is no, or very little, tracking data available at SEP angles less than 3°, which is why there is a sudden jump in the fit span between OD108 and OD109. Tracking data are reduced in relative weight by the estimation filter once the SEP falls below 10°. This procedure helps to compensate for undesirable interactions between the spacecraft signal and the solar plasma that tend to degrade the data throughout this interval. Perihelion passages of the MESSENGER spacecraft during mission cruise phase also tended to produce residual disturbances within the fit span and thus were an additional motivating factor in periodically advancing the estimation epoch.

In close coordination with the MESSENGER guidance and control (G&C) team at JHUAPL, a strategy was implemented for the initial Mercury flyby that replaced statistical TCMs on approach to the planet with solar sailing for controlling the trajectory within the region of the targeted B-plane.[9-11] Instead of a bang-bang type of controller, as would have been provided by executing the planned TCMs, a more continuous incremental method was made available by periodically updating the spacecraft body sunshade and solar array orientations relative to the Sun. These attitude changes were managed within the constraints of spacecraft torque and momentum requirements by the G&C team[16,17] and the final results were quite good, as shown in Figure 5.

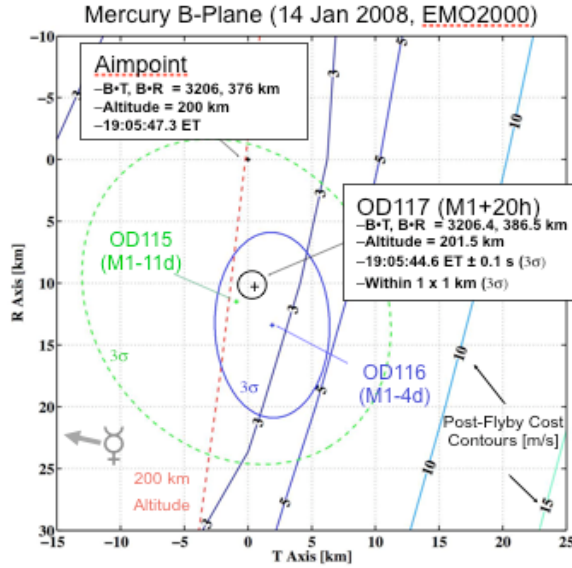

Figure 5. Mercury Flyby 1 B-Plane Reconstruction.

The initial Mercury flyby occurred shortly after a long solar conjunction period, during which the radiometric tracking data were sharply reduced in relative weight to compensate for undesirable interactions with the solar plasma. When it became apparent that errors inherent to the small propulsive correction maneuver needed to retarget the aim point in the Mercury B-plane were of the same order as the maneuver itself, the decision was made to move the spacecraft closer to the optimal flyby altitude by manipulating the attitude to take advantage of the incident SRP. This solar sailing strategy on approach resulted in a miss distance of less than 1 km relative to the modified aim point. The success of this process eliminated the need for future statistical TCMs for the remainder of the mission cruise phase. Most of the details of the initial MESSENGER Mercury flyby, including the performance analysis of DSM-2 and the associated solar sailing strategy for planetary approach, have been discussed in previous technical papers.[9-11]

Mercury flyby 2 provided the first thorough operational test of this new process, and it was also extremely successful. Not only was the altitude corrected this time but the entire set of targeted Mercury B-plane parameters were achieved within 2 km in position and 2 s in arrival time, as is shown in Figure 6. This was well within not only the mission requirements for navigation flyby accuracy but also statistical expectations based upon the incoming three-standard-deviation error ellipse and prior covariance analyses. The approach trajectory was nominal in all respects and the only resultant expenditure of fuel between the first two Mercury flybys was from the deterministic DSM-3, which executed as designed six and one-half months prior to the flyby. During this interval biweekly ephemeris deliveries to the JHU/APL mission operations center allowed the G&C team to develop a continually evolving strategy for maintaining the correct spacecraft orientation necessary to remain on target. The exchange of estimated states, including SRP coefficients, for updated attitude adjustments allowed for the maintenance of spacecraft momentum and a continually optimized trajectory targeted on the Mercury aim point.

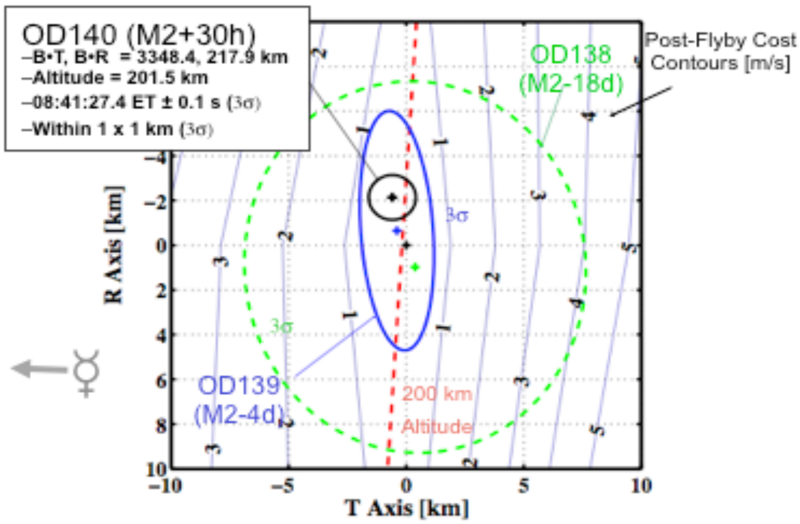

Figure 6. Mercury Flyby 2 B-Plane Reconstruction.

As can be seen from the MESSENGER Mercury flyby 2 B-plane plot in Figure 6, the ΔV cost for maintaining the optimized trajectory was negligible, with respect to the contour overlays, and no post-flyby cleanup burn was needed. Even in the case of the prior Mercury flyby, where the cost contours indicated a cleanup maneuver of a few meters per second, the preferred alternative was simply to re-optimize and use solar sailing to make up any remaining discrepancy. The farther from the next target point and longer the remaining time to arrive, the more effective the solar sailing strategy became.

Closest approach for the second MESSENGER Mercury flyby occurred on October 6, 2008 at 08:41:27 TDB, during an even more favorable period for Earth-Mercury relative geometry. The Earth was around the 02:30 clock position in Figure 1, and while this placed the Sun in the near background field, this posed little difficulty for operations. The ephemeris update sequence for this interval was as indicated in Figure 7. The estimation epoch of the ODs was advanced just twice, first to the other side of the Mercury gravity well and then beyond the early summer superior conjunction. Delivered ephemerides were propagated past DSM-3 only after the maneuver design had been finalized. The length of the trajectory span delivered is constrained by the duration of attitude modeling, which will be described in more detail below. There are also effects associated with perihelion passages, possibly resulting from sublimation of volatile materials, which were difficult to model, adversely affected the filter residuals and impacted estimation accuracy requirements.

Whereas the interval between the Venus and Mercury MESSENGER flybys was around seven months, the interval between the first two Mercury flybys was almost nine months. As more of the trajectory span was taken up by the estimation, a higher fidelity attitude model emerged, as not only was more track data available but attitude history data from spacecraft telemetry progressively replaced attitude predictions. The trade-off is between the fidelity of the attitude modeling and the computed uncertainties of the trajectory parameters being estimated. Since the panel attitude model is an external input to the orbit determination program, these model errors are not incorporated into the formal one-standard-deviation outputs of the estimation process. Consequently, there is difficulty in estimating the optimal point in time for advancing the filter epoch and some subjectivity must therefore be used in determining when this is done.

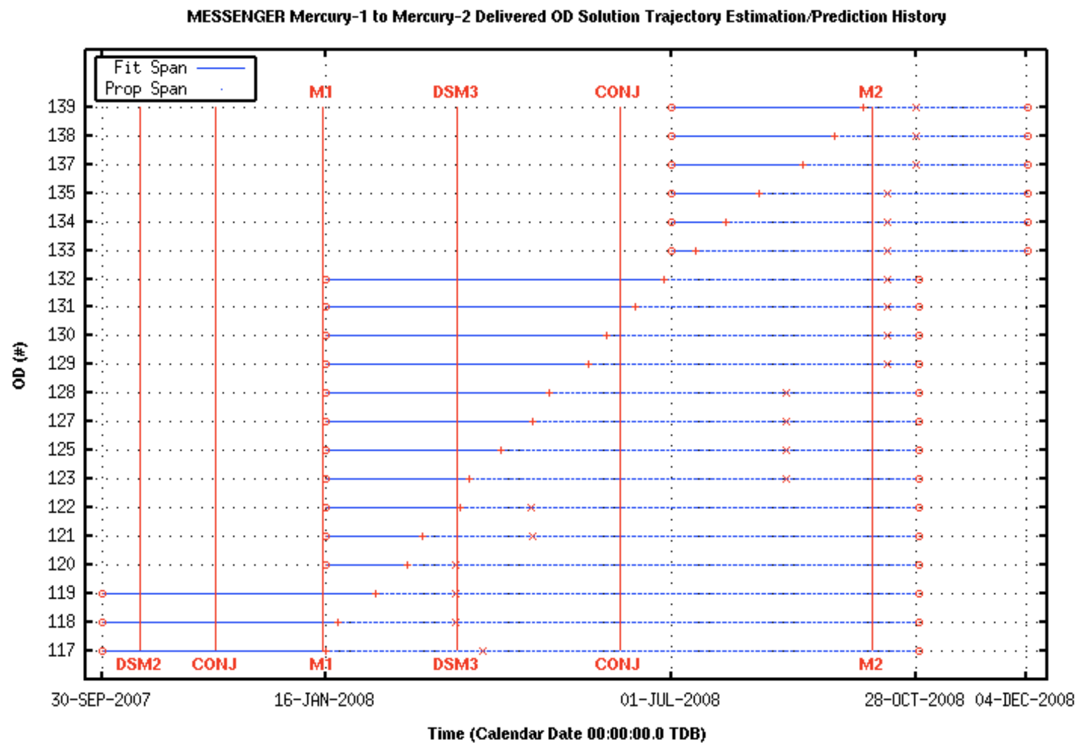

Figure 7. MESSENGER Navigation Operations Mercury Flyby 2 Ephemeris Update Delivery Sequence.

The third MESSENGER DSM, executed between the first two Mercury flybys, was designed by the KinetX navigation team and the mission design team at JHU/APL to target the optimized Mercury flyby 2 B-plane aim point. Also, DSM-3 was a relatively small deterministic maneuver, so this was selected as a good opportunity for an initial operational test for the turn-while-burn strategy in preparation for MOI. It was executed on March 19, 2008, and the relatively small resultant maneuver execution errors, combined with the inevitable but also small trajectory estimation errors, placed the spacecraft slightly off course with respect to the desired Mercury B-plane target. Biweekly ephemeris update deliveries fed into periodic commanded attitude updates to quickly place the trajectory back in synchronicity with the aim point. This process was refined continually as it was developed. There was no plan to do any solar sailing prior to the onset of the mission. Rather, the idea was developed by Daniel O’Shaughnessy and his JHU/APL G&C team in coordination with the mission design and KinetX navigation teams. Several earlier papers have been written about the evolution and history of this idea, specifically with respect to the MESSENGER program.[9,16,17]

The reconstruction of the second MESSENGER Mercury flyby validated the implementation of this novel solar sailing approach to interplanetary targeting within the inner solar system. In hindsight, use of solar radiation forces as an alternative to TCMs for trajectory correction should not have been surprising. However, the ability to use these forces to manipulate the spacecraft trajectory to the degree that it was accomplished was not foreseen prior to entering the trans-Mercury regime. The accuracy of MESSENGER spacecraft attitude modeling became more and more of an issue as the mission progressed, and it was evident that attitude prediction discrepancies could have a major affect on the OD filter when they found their way into the fit span. During the period of the Venus flybys and after the first DSM had been executed using the large velocity adjust thruster,[14] an extreme spacecraft tilt[18] exposed the interior of the thruster bell to sunlight, which resulted in the burn-off of residual propellant and created a spike in the estimated data residuals. When this sequence of events was pieced together in the subsequent analysis of the resultant anomalous filter behavior, the extent of the sensitivity of the OD to attitude modeling was made apparent. The processes involved in modeling the MESSENGER spacecraft attitude for the purposes of trajectory estimation have evolved markedly since the beginning of the mission.

The spacecraft itself is modeled in Mirage using 10 flat plates at appropriate relative orientations to represent the sunshade (3), the top, bottom, back, and side decks of the bus (3), and the front and back sides of both solar arrays (4). Figure 8 provides an illustration of the MESSENGER spacecraft for visual reference. Since only five of these surfaces are ever supposed to be exposed to the Sun, these are typically the only associated SRP coefficients that are estimated within the OD filter. The closer the mission trajectory brought the spacecraft to the Sun, the more it became evident that these attitude modeling limitations would indeed hamstring OD accuracy on Mercury approach, and just as likely during the orbit phase when all 10 plates would be needed to estimate not only SRP but the additional radiation pressure from planetary albedo and infrared re-radiation of sunlight from Mercury's surface.[19]

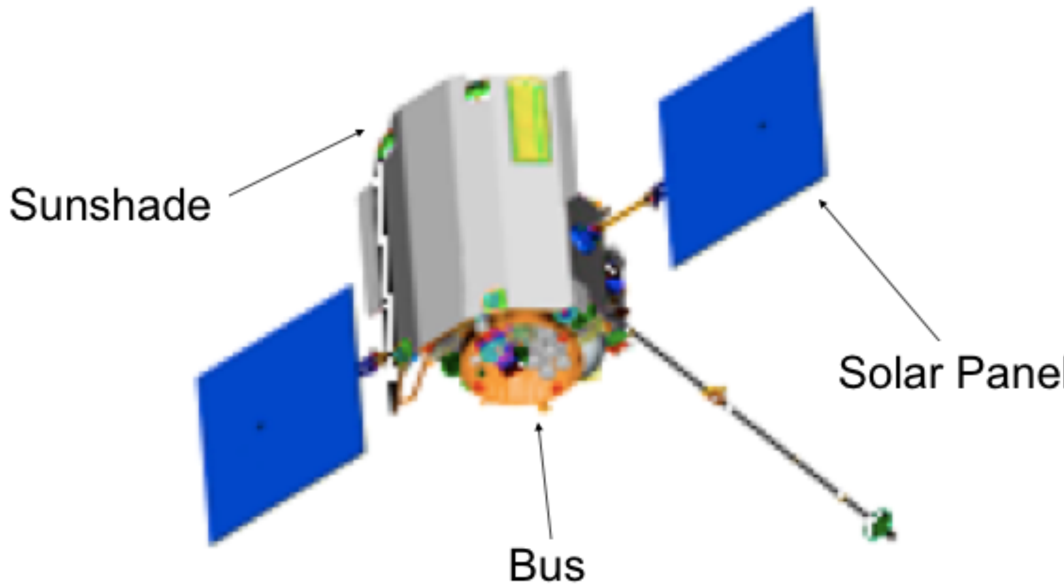

Figure 8. The MESSENGER Spacecraft.

A workaround was developed fairly early in the trans-Mercury cruise phase that allowed the spacecraft body attitude to be effectively modeled continuously, but the solar panels use 200 discrete orientation changes per trajectory span. These were initially determined in a body-relative frame but eventually it was decided, in coordination with JHU/APL mission operations, that both commanded and hence estimated attitude measurements would be better accommodated by using a Sun-relative model. However, such a choice does not completely alleviate the associated problems for the OD filter when estimated trajectory spans are propagated out for six months or more during cruise, or six weeks or so on orbit. Four successive generations of panel attitude models have been incorporated into the OD filter to progressively reconcile the discrete attitude changes allowed to the continuous motion inherent in each orientation maneuver. During MESSENGER interplanetary cruise, particularly for some spacecraft instrument calibration tests and acquisition modes, the solar arrays may be required to reorient themselves continuously for long periods of time. Although this situation presents a difficult challenge for the use of discrete modeling parameters, it has been handled with increasing efficiency throughout the duration of the mission.

The MESSENGER spacecraft solar panel attitude modeling has evolved through an initially random sampling and interpolation process with the available data to a more advanced selection procedure that bypasses the need for interpolation and filters the resulting measurements and predictions on the basis of specified angular dead-band and persistence of orientation thresholds.

Because the solar array position measurements are accurate to within about half a degree, this is the typical change in gimbal angle required to initiate a new discrete attitude record. The persistence filtering is a function of the time a particular panel angle orientation is maintained before a new discrete record is found outside of the specified angular dead-band. These two filtering mechanisms can be tuned to optimize the task at hand, creating a 200-record model that describes the motion of the solar arrays in the discrete steps that most closely approximate the actual series of panel-attitude change events. While it certainly would be better to be able to use all of the panel attitude records available, as has been possible since earlier in the mission for the spacecraft body attitude, the current method of modeling solar array orientations works quite well in practice.

MESSENGER's third Mercury flyby occurred on September 29, 2009 at 21:56:02 TDB and demonstrated the continued success of the solar sailing strategy. The Earth-Mercury geometry was favorable for this encounter, with the Earth just slightly counterclockwise of the 03:00 location in Figure 1. DSM-4 had been performed less than two months after the second Mercury flyby. It was executed in two parts, to accommodate another turn-while-burn test in preparation for MOI, on December 4 and 8, 2008. The solar sailing tuning process had evolved to include a routine set of minimal steps by this point in the mission, and the procedure was used to creep up on the aim point as the flyby approached. The trajectory re-optimization subsequent to DSM-4 resulted in a modified aim point with a targeted altitude of 228 km, a bit above the 200 km originally planned. As can be seen in Figure 9, the refined solar sailing strategy resulted in a reconstructed flyby trajectory that was within 4 km in position and 2 s in arrival time of the re-optimized target aim point at Mercury.

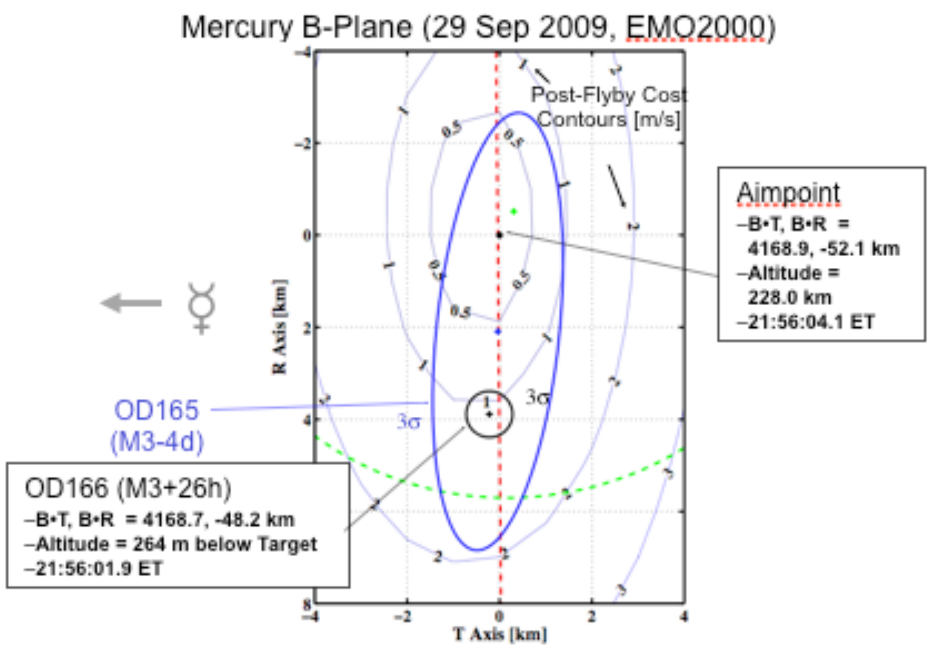

Figure 9. Mercury Flyby 3 B-Plane Reconstruction.

The main purpose of successive Mercury flybys was to decrease the approach velocity of the MESSENGER spacecraft incrementally relative to Mercury in order to achieve a feasible MOI. Consequently, whereas the period between the first two MESSENGER Mercury flybys was a week short of nine months, the interval between the second and third was almost a year. Figure 10 shows the ephemeris update sequence for the approach to Mercury flyby 3. There were no cleanup maneuvers necessary after the second Mercury flyby or DSM-4. The effectiveness of the solar sailing strategy had been well demonstrated by this time and the required corrections resulting from these events were within its capabilities. The estimation epoch was advanced three times during the intervening year, first to the other side of the prior flyby, then to a point between solar conjunctions and finally to several months before the third Mercury encounter. Once again, escaping the deleterious effect on the data residuals resulting from perihelion passage played a role in motivating estimation epoch advancement.

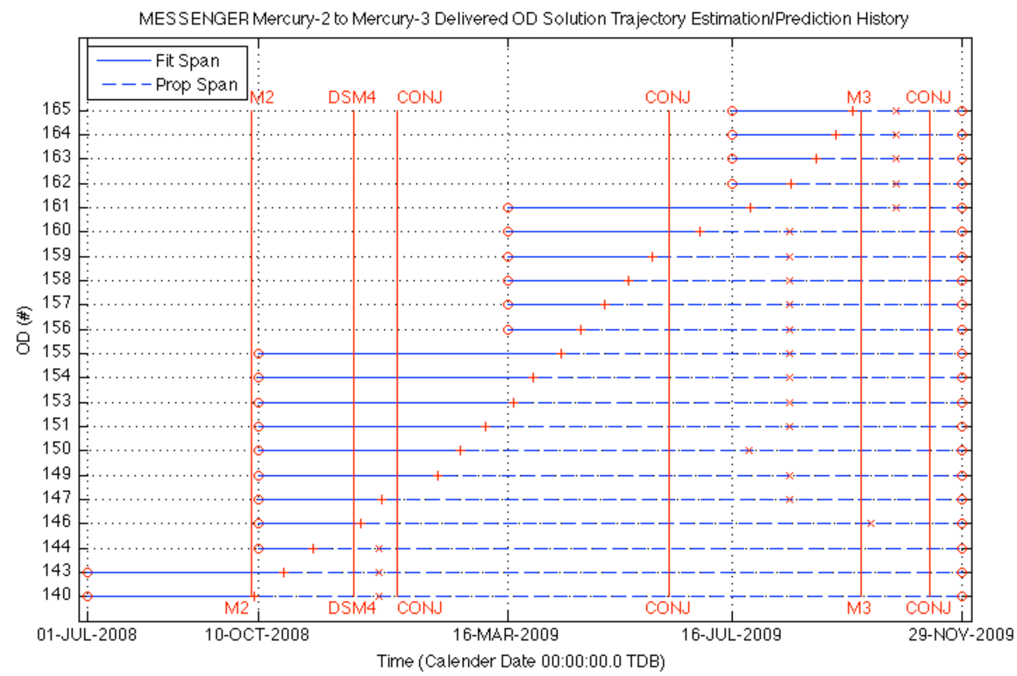

Figure 10. MESSENGER Navigation Operations Mercury Flyby 3 Ephemeris Update Delivery Sequence.

These three Mercury flybys were all made even more successful than their accuracies would indicate by the employment of solar sailing techniques that saved additional fuel for the primary science mission in Mercury orbit. The approach to final Mercury rendezvous and capture via MOI was also greatly facilitated by the refinement of the solar sailing process that was developed to high precision during the prior flybys.[9]

MERCURY ORBIT INSERTION

The most anxiously awaited event of the MESSENGER mission was MOI, and it was successful in meeting mission requirements. The geometry in Figure 1 for this rendezvous was near maximum elongation, as designed. The interval from the third Mercury flyby to MOI was almost one and a half years, with the final DSM executed just two months after the last flyby. The subsequent post-DSM-5 approach trajectory spanned over fifteen months with seven distinct ephemeris segments utilized for operational spacecraft uploads, as can be seen in Figure 11. Once Mercury flyby 3 was reconstructed, the estimated trajectory epoch state was advanced to just a few days past the flyby event and not advanced again until some four months later. The estimation epoch state was advanced again after the final reconstruction of DSM-5, at which time it was pushed forward two months to the other side of the maneuver. At this point the interval from the estimation epoch, through data cutoff, to the end of the propagation span was only a week short of a year. The end of the operational trajectory propagation span remained fixed at three months prior to MOI for almost nine months while the epoch was advanced twice more. This progressive advancement of the estimation epoch then pushed the trajectory to the other side of the penultimate superior solar conjunction prior to MOI.

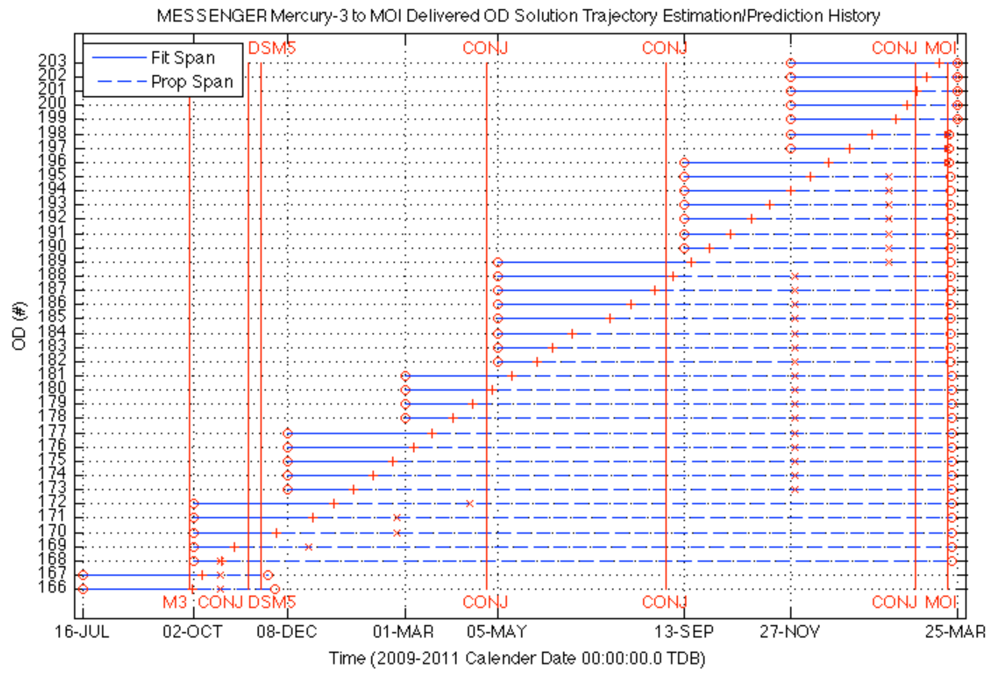

Figure 11. MESSENGER Navigation Operations MOI Ephemeris Update Delivery Sequence.

When the end of the operational ephemeris delivery propagation span was moved forward again, it was placed just six weeks prior to MOI to a point in time between the final pair of pre-MOI superior conjunctions. With the epoch advanced to mid-September, the serious work of planning for the final approach to Mercury capture began. It was during this time period that the final panel attitude modeling process for MOI and beyond was completed. The increased efficiency of modeling the solar array motion using 200 discrete events with this new procedure allowed the ephemeris span generated using the mid-September estimation epoch state to be retained as analysis trajectory up to the brink of MOI, with up to five months of attitude history data accommodated. In fact, the epoch was moved forward only one additional time from there prior to MOI, when it was advanced to the end of November 2010. The Mercury B-plane prediction pictured in Figure12, OD189, was the last solution mapping before the mid-September epoch was initiated, and the first to be delivered with a prediction span running out to early February 2011. The difference between the OD188 and OD189 B-plane mappings was the result of solar sailing, which is obviously more effective the more time is available to command attitude changes prior to arrival at Mercury.

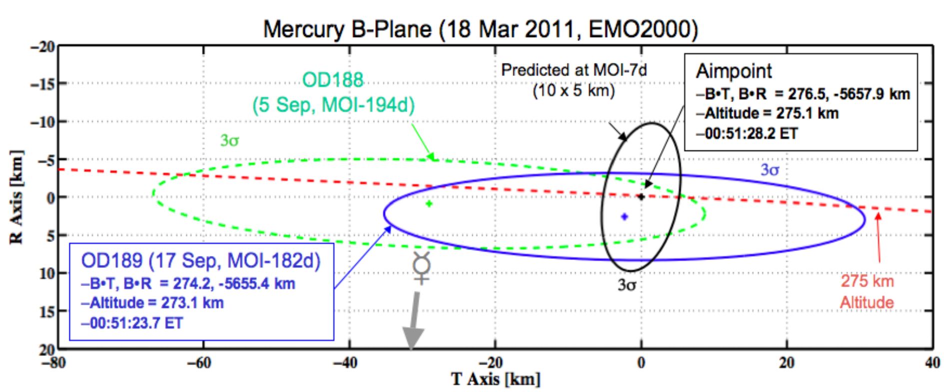

Figure 12. MOI Approach B-Plane Prediction Sequence.

Subsequent to OD189 the operational ephemeris delivery span was held fixed from mid-September to early February for almost two months, when the end of the propagated trajectory delivery was extended to just before MOI. In early January 2011, the epoch was advanced to late November 2010, at which point it was kept through MOI until the initial reconstruction of the planetary orbit insertion maneuver was accomplished. As part of the verification testing and checkout for the current operational version of the panel attitude modeling process, a number of analysis trajectories were generated for evaluation and comparison. An example of the Mercury B-plane predictions for these analysis trajectories is illustrated in Figure 13. The various data arcs associated with the solutions in this plot had epochs ranging from October 2010 through January 2011 and carried from four weeks to four months worth of data, as reflected in the sizes of their respective error ellipses. The central black error ellipse in the figure was generated from an earlier covariance analysis and defines the nominal predicted three-standard-deviation uncertainty at Mercury arrival, which at that point was less than two months away.

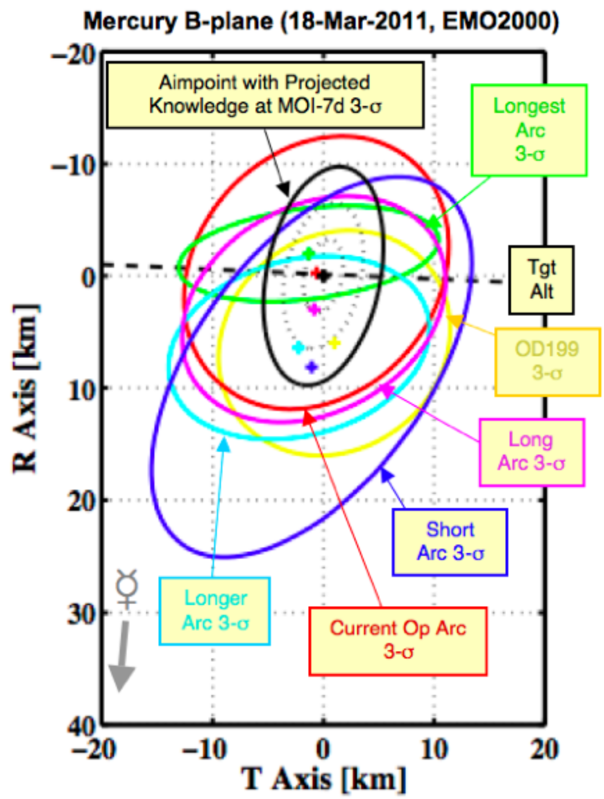

Figure 13. MOI Approach B-Plane Prediction Analysis Trajectories.

In Figure 14, the dotted one, two and three-standard-deviation contours correspond to the central three-standard-deviation error ellipse in Figure 13. This figure shows the progress of the arrival B-plane reconstruction, as if the MOI maneuver had never been executed. This was how Mercury B-plane predictions were generated on approach in order to eliminate the unnecessary complications of including the effects of MOI, which began execution just before the predicted closest Mercury approach. The progression of the arrival B-plane reconstructions is revealed by the shrinking sizes of the corresponding error ellipses associated with each successive operational OD solution. The final results are just over 8 km off in position, much of which can be attributed to small errors in the knowledge of the Mercury ephemeris, among other issues. Still, the resultant initial Mercury orbit was well within operational requirements and no trim maneuvers were deemed necessary.

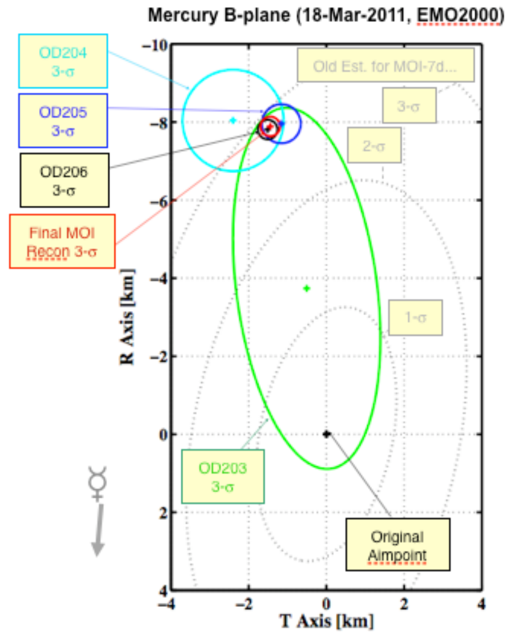

Figure 14. MOI B-Plane Reconstruction.

The MOI arrival time target was modified on approach by uploading a timing bias to compensate for the predicted spatial offsets. This modification reduced the error in the initial post-injection Mercury orbital period and periapsis altitude. This effect is quantized in Figure 15, which shows the aforementioned relationship between arrival time and miss distance. The MOI approach was somewhat more problematic than prior Mercury flybys that utilized the solar sailing approach. As the time to MOI decreased, there was a reluctance to make specific modifications because of the volatility of the B-plane mappings. This volatility was due in part to inconsistencies between concurrent orbit determination solutions from radiometric fit arcs of different lengths, affected somewhat by the varying fidelity of the solar panel angles modeled in the navigation software. There was also a superior solar conjunction that occurred 1-2 weeks in advance of MOI, but this event was largely mitigated by the addition of four passes per week of DDOR during this period.

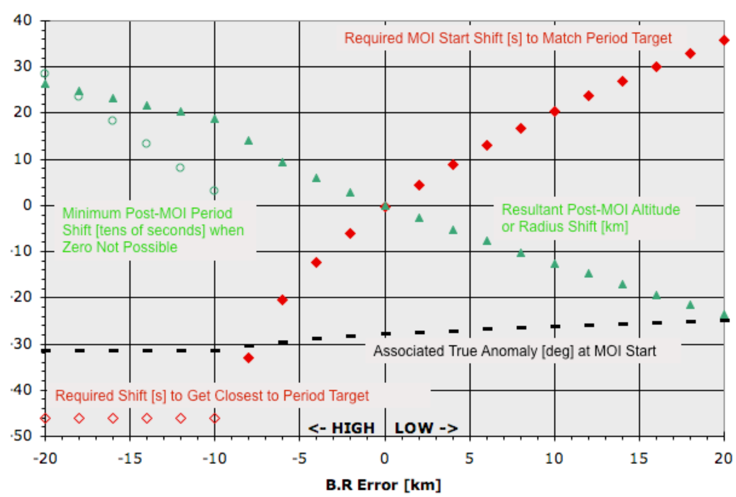

Figure 15. Timing Bias Compensation for Mercury Arrival B-plane Position Errors.

Nevertheless, convergence of the various fit arcs occurred too late to make a definitive determination of further possible solar sailing adjustments prior to MOI. Fortunately, the effect of the radial error, as well as errors in predicting the time of arrival itself, in achieving the ideal B-plane target could be mitigated somewhat by shifting the start time of MOI execution. Figure 15 indicates variations in post-MOI mean orbit characteristics resulting from varying the start time of the MOI sequence based on a fixed MOI design, and Figure 16 shows the cost contours for these parameters. For instance, by shifting the execution time 5 s earlier, the targeted post-MOI orbit period could be more closely achieved with an acceptable increase in achievable periapsis altitude of only a few kilometers. After reconstructing the effects of both B-plane delivery errors and MOI execution errors, the resultant spacecraft orbit achieved a 206.8 kilometer altitude at the first post-MOI periapsis and an orbit period of about 43195 s, based on the time between the first and second post-MOI periapses. These were about 6.8 km greater and 261 s longer than ideal, but well within MOI requirements. The success of this technique is evidenced by the reduced injection errors over what would be expected from inspection of the predicted altitude and period contours of Figure 16.

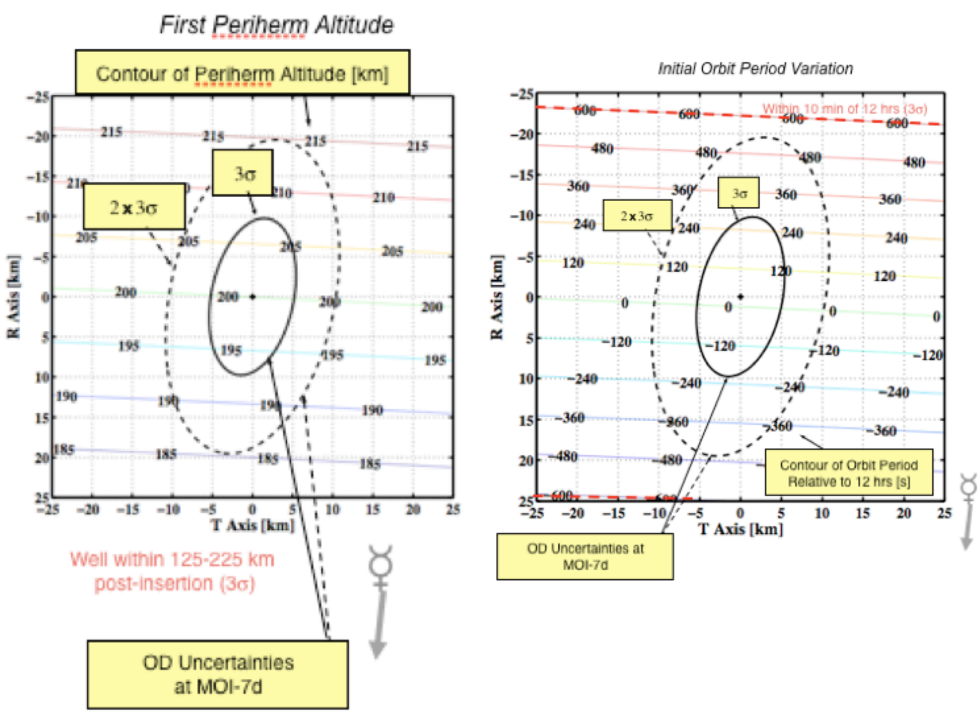

Figure 16. Impact of Pre-MOI Error on post-MOI Periherm Altitude and Period.

Real-time monitoring of the MOI maneuver was performed at the MOC in the presence of most of the MESSENGER operations team. The KinetX navigation team provided the predicted three-standard-deviation Doppler envelope defining an acceptable result for the capture sequence. Figure 17 shows the results, with the red dots in the lower region of the plot representing the measurements received from a DSN two-way link. With the actual data falling well within the expected three-standard-deviation uncertainty envelope, it was evident that MOI was successful and that Mercury orbit had been achieved by the MESSENGER spacecraft for the first time in the history of planetary exploration. Similar real-time monitoring activities were provided for previous mission-critical events, including flybys and DSMs, but this was justifiably considered to be the grand finale to a six and one-half year journey into the deep gravitational well of the inner solar system. The most complicated interplanetary trajectory ever flown had ended with the spacecraft arriving at its destination with stunning accuracy.

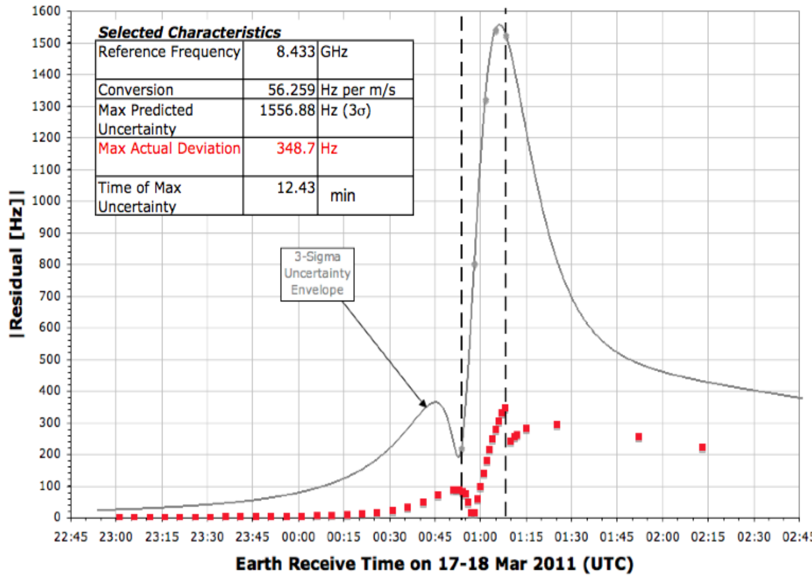

Figure 17. MOI Real-Time Doppler Residuals.

MERCURY ORBIT

On March 18, 2011, at 01:01:00 TDB, upon completion of MOI, MESSENGER became the first spacecraft to achieve orbit about Mercury. Having learned the lessons of a lengthy interplanetary cruise phase, the KinetX navigation team set about implementing revised operational strategies for the nominal one-year orbit phase of the mission. Fourteen ephemeris updates were delivered prior to the initial orbit-correction maneuver (OCM), these are presented in Figure 18. The delivered OD solutions became progressively easier to accomplish as a variety of techniques were refined for modeling planetary radiation forces, extending and refining the gravitational field, and minimizing the propagation span utilized in order to achieve the greatest possible solar panel attitude fidelity within the fit arc. This all led up to the successful completion of OCM-1 on June 15, 2011, which pushed the periapsis altitude back down to about 200 km, the pre-perturbed injection height above the Mercury surface. Having been in orbit for over one Mercury year and having experienced a superior solar conjunction, as well as hot-pole and long-eclipse seasons, the MESSENGER spacecraft and its operations remain nominal. Weekly ephemeris deliveries to both the MOC and DSN have been, and continue to be, on schedule to support ongoing Mercury science operations.

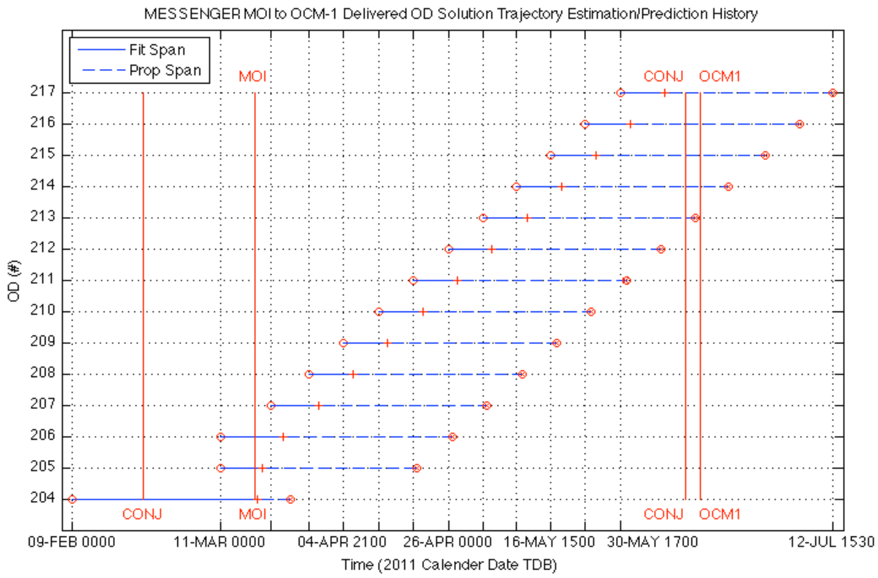

Figure 18. MESSENGER Navigation Operations OCM-1 Ephemeris Update Delivery Sequence.

SUMMARY

The targeting accuracies of the Mercury flybys and the approach to MOI compare favorably to the first three flybys of the MESSENGER mission, as well as to the initial gravity assist gained from passing by Earth a year after launch and the two Venus encounters that occurred within seven and a half months of each other a little more than a year later. The second Venus flyby was the closest of all MESSENGER's planetary encounters to the targeted aim point and may well have been the most accurate deep-space flyby ever executed, but all except Venus flyby 1 were well within statistical expectations from prior covariance analyses. Table 1 compares the results of all six MESSENGER planetary encounters with each other, along with the relevant achieved parameter differences such as flyby altitude and arrival times. It should be noted that the effects of the trans-Mercury solar sailing strategy were indistinguishable from what would have been expected from executing successful statistical TCMs on the various planetary approach trajectories, except of course for the conservation of precious fuel it provided. This latter effect greatly facilitates enhanced science operations during the primary Mercury orbital phase of the MESSENGER mission.

The Table 1 values for "-MOI" reflect the Mercury periapsis that would have resulted had the orbit insertion maneuver not been executed. This virtual periapsis was a computational convenience to avoid the additional complications of including the burn in the targeted aim point optimization, as described previously. The flyby reconstructions were determined using higher data rates and the final predictions were taken from the last delivered trajectory solutions prior to the periapses. Covariance analyses were typically done early in the mission, well before each flyby event, and based upon the originally planned track schedules and data rates.

It is also instructive to compare the results of the DSMs in the trans-Mercury regime to the early mission-critical post-Earth-flyby DSM and the post-Venus-flyby-2 DSM that was the first to target Mercury directly. Table 2 provides a synopsis of the DSM and MOI maneuver results. Maneuver reconstructions also utilized high rate Doppler data and were determined several months after each respective major propulsive event. The a priori uncertainties were used in the OD filter to constrain the estimation of each event for navigation operations.

Table 1. Comparison of Results for MESSENGER Planetary Encounters

Event	Periapse Reconstruction				Periapse Final Prediction				Covariance Analysis (3-sigma)	
	Time (TDB)	Altitude (km)	Posttion Dellta (km)	Time Delta (s)	Time (TDB)	Altitude (km)	Posttion Dellta (km)	Time Delta (s)	Posttion Error (km)	Time Error (s)
-MOI	03/18/2011 00:51:29	278.6	8.3	0.8	03/11/2011 00:51:28	275.8	3.7	<0.1	12.3	0.7
M3	09/29/2009 21:56:02	227.7	3.9	2.2	09/29/2009 21:56:02	228.0	2.1	1.9	9.7	0.9
M2	10/06/2008 08:41:28	199.5	1.7	2.6	10/06/2008 08:41:27	199.7	0.8	2.4	12.7	3.7
M1	01/14/2008 19:05:45	199.1	6.0	-1.3	01/14/2008 19:05:45	203.4	13.5	-1.3	19.5	2.8
V2	06/05/2007 23:09:24	338.2	1.6	0.7	06/05/2007 23:09:24	338.2	1.6	0.8	32.1	5.5
V1	10/24/2006 08:35:05	2987.3	59.8	-84.3	10/24/2006 08:35:05	2992.1	54.3	-83.4	86.6	15.2
Earth	08/02/2005 19:14:13	2347.5	23.7	35.3	08/02/2005 19:14:13	2347.5	23.5	35.3	<30	<3

Table 2. Comparison of Results for MESSENGER MOI/DSMs

Event	Reconstruction			A Priori Uncertainties (3-sigma, Uncorrelated)	
	Delta Velocity (m/s)	Delta-V Error (m/s)	Avg Directional Error (deg)	Delta-V (m/s)	Direction (deg)
MOI (03/2011)	861.7	-0.452	0.0570	2.54	0.354
DSM5 (11/2009)	177.8	0.0325	0.0551	0.618	0.366
DSM4 P2 (12/2008)	24.65	-0.0821	0.101	0.458	1.57
DSM4 P1 (12/2008)	222.1	-0.0784	0.0139	0.0758	0.344
DSM3 (03/2008)	72.25	-0.0053	0.0462	0.319	0.400
DSM2 (10/2007)	227.4	-0.0270	0.208	0.771	0.376
DSM1 (12/2005)	315.6	-0.0866	0.0255	1.06	0.344

One important lesson that was learned is that maintaining an appropriate spacecraft attitude within the inner solar system is critical to mission success. Solar sailing proved to be a vital component of the strong performance of both navigation and targeting for the MESSENGER spacecraft as it repeatedly exceeded expectations for flyby accuracies and planetary capture at Mercury. The flexibility and adaptability of the KinetX navigation team has produced improved modeling of Mercury ephemeris, spacecraft attitude, B-plane mappings, high-order Mercury gravitational fields, spherical harmonic representations of planetary radiation pressure perturbations and spacecraft antenna motion corrections, among other accomplishments. As MESSENGER continues to produce invaluable scientific results with direct applications to not only future planetary exploration missions but also to the history and evolution of our own planet, it is satisfying to reflect on what has been accomplished and what is yet to be achieved by this seventh mission in NASA's Discovery Program series.

ACKNOWLEDGMENTS

The MESSENGER navigation team acknowledges the able and professional support of NASA's DSN Critical Events team, the MESSENGER Network Operations Project Engineers and the Radio Metric Data Conditioning team for acquiring the radiometric data that make this work possible. The navigation team also thanks Dr. James Border of the Jet Propulsion Laboratory for his support in providing processed data from DDOR tracks. The MESSENGER mission is supported by the NASA Discovery Program Office under contracts to the Carnegie Institution of Washington (CIW) and JHU/APL. This work was carried out by the Space Navigation and Flight Dynamics Practice of KinetX, Inc., under a subcontract with CIW.

REFERENCES

[1]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, 43 (5), pp. 1054-1064, 2006.

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

[3]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, 38 (4), pp. 564-571, 2006.

[4]Santo, A.G., et al., "The MESSENGER Mission to Mercury: Spacecraft and Mission Design," Planetary and Space Science, 46 (14-15), pp. 1481-1500, 2001.

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

[6]Williams, B.G., Taylor, A.H., Carranza, E., Miller, J.K., Stanbridge, D.R., Page, B.R., Cotter, D., Efron, L., Farquhar, R.W., McAdams, J.V. and Dunham, D.W., "Early Navigation Results for NASA's MESSENGER Mission to Mercury," Advances in the Astronautical Sciences, 120 (Part II), pp. 1233-1250, 2005.

[7]Taylor, A.H., Carranza, E., Miller, J.K., Stanbridge, D.R., 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, 127 (Part I), pp. 1081-1100, 2007.

[8]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, 130 (Part II), pp. 1113-1132, 2008.

[9]O'Shaughnessy, D.J., McAdams, J.V., Williams, K.E. and Page, B.R., "Fire Sail: MESSENGER's Use of Solar Radiation Pressure for Accurate Mercury Flybys," Advances in the Astronautical Sciences, 134, pp. 1527-1539, 2009.

[10]McAdams, J.V., O'Shaughnessy, D.J., Taylor, A.H., Williams, K.E. and Page, B.R., "Maneuver Design Strategy Enables Precise Targeting of the First MESSENGER Mercury Flyby," 2008 Astrodynamics Specialist Conference, American Astronautical Society/American Institute of Aeronautics and Astronautics, paper AIAA-2008-7367, 15 pp., Honolulu, HI, August 18-21, 2008.

[11]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," 2008 Astrodynamics Specialist Conference, American Astronautical Society/American Institute of Aeronautics and Astronautics, paper AIAA-2008-6761, 20 pp., Honolulu, HI, August 18-21, 2008.

[12]Gold R.E., et al., "The MESSENGER Mission to Mercury: Scientific Payload," Planetary and Space Science, 46, (14-15), pp. 1467-1479, 2001.

[13]Solomon, S.C., et al., "The MESSENGER Mission to Mercury: Scientific Objectives and Implementation," Planetary and Space Science, 46 (14-15), pp. 1445-1465, 2001.

[14]Wiley, S., Dommer, K. and Mosher, L., "Design and Development of the MESSENGER Propulsion System," 38th Joint Propulsion Conference, American Institute of Aeronautics and Astronautics/Society of Automotive Engineers/American Society of Mechanical Engineers, paper AIAA-2003-5078, 20 pp., Huntsville, AL, July 21-24, 2003.

[15]Thornton, C.L. and Border, J.S, "Radiometric Tracking Techniques for Deep-Space Navigation," Deep-Space Communications and Navigation Series – Monograph 1, Wiley-Interscience, pp. 47-58, 2003.

[16]O'Shaughnessy, D.J., Vaughan, R.M., Choinard, T.L. and Jackle, D.E., "Impacts of Center of Mass Shifts on MESSENGER Spacecraft Operations," 20th International Symposium on Space Flight Dynamics, paper 12-4, 15 pp.,, Annapolis, MD, September 24-28, 2007.

[17]Vaughan, R.M., Haley, D.R., O'Shaughnessy, D.J. and Shapiro H.S., "Momentum Management for the MESSENGER Mission," Advances in the Astronautical Sciences, 109 (Part II), pp. 1139-1158, 2002.

[18]O'Shaughnessy, D.J. and Vaughan, R.M., "MESSENGER Spacecraft Pointing Options," Advances in the Astronautical Sciences, 114 (Part II), pp. 747-766, 2003.

[19]Stanbridge, D.R., Williams, K.E., Taylor, A.H., Page, B.R., Bryan, C.G., Dunham, D.W., Wolff, P., Williams, B.G., McAdams, J.V. and Moessner, D.P., "Achievable Force Model Accuracies for MESSENGER in Mercury Orbit," Flight Mechanics Conference, American Astronautical Society/American Institute of Aeronautics and Astronautics, paper AAS 11-548, 20 pp., Girdwood, Alaska, July 31 - August 4, 2011.