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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 project is managed by and the spacecraft was built and is operated by The Johns Hopkins University Applied Physics Laboratory. 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 in addition to optical navigation from on-board images of planet flybys. The spacecraft was launched August 3, 2004, to begin its six and one-half year interplanetary cruise leading to rendezvous with and orbit of the planet Mercury beginning in March 2011. Once in orbit, MESSENGER will perform detailed science observations of Mercury for at least one Earth year. This paper gives a description of the navigation system developed for the MESSENGER mission, along with the navigation results obtained thus far for launch and the early interplanetary cruise phase of the mission. Also included are plans for calibrating and testing the navigation system during the remaining years of cruise to prepare for support of the science operations in orbit about Mercury.

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) provided facilities for spacecraft assembly and

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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) in addition to optical navigation from on-board images of planet flybys.

After launch on August 3, 2004, the spacecraft began its six and one-half year interplanetary cruise that will culminate with rendezvous and orbit insertion at the planet Mercury beginning in March 2011. 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 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.

The goal of navigation for the first few weeks after launch was to establish the MESSENGER spacecraft on the proper trajectory to return to the optimal Earth flyby condition on August 2, 2005. The measure used to judge the accuracy of the maneuvers and the subsequent trajectory for the first leg of the mission is the aim point in the so-called 'b-plane' at the Earth flyby. 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 (Earth in this case). The 'S-axis' is in the direction of the incoming asymptote and hence is normal to the b-plane. 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 with origin at the center of the Earth such that $\hat{T} \times \hat{R} = \hat{S}$, where $\hat{T}$, $\hat{R}$ and $\hat{S}$ are unit vectors in each axis direction.

This paper gives a description of the navigation system developed for the MESSENGER mission, along with the navigation results obtained thus far for launch and the early interplanetary cruise phase of the mission. The techniques used for orbit determination and spacecraft model calibration during the first few months of flight are illustrated by both pre-flight simulations and orbit determination and parameter estimation results. Maneuver placement and reconstruction results are shown for the first three trajectory correction maneuvers. Plans for further navigation calibration and tests using the DSN's Delta-Differential One-Way Ranging (ΔDOR) tracking data type and optical navigation during the planetary flybys are described. Finally, a plan is described for calibrating the Mercury gravity field to improve trajectory estimation and prediction in the orbit phase, and simulation results are used to predict the expected navigation accuracy for that phase.

NAVIGATION SYSTEM OVERVIEW

The MESSENGER Navigation team (Nav team) is organized as part of a multi-mission navigation support group so that the Nav team size can be adjusted as mission events dictate. The Nav team is headed by the Navigation Team Chief, Anthony H. Taylor. For MESSENGER launch, the Nav team was made up of eight individuals working in shifts to provide continuous support from twelve hours before launch to about fifteen hours after. This staffing level was reduced to five within a few days after launch, and staffing averages between 1.5 to 3 during most of the interplanetary cruise. Staffing levels will be increased at planetary flybys and propulsive maneuver events to handle the required additional navigation processing and file deliveries. On approach to Mercury Orbit Insertion, the Nav team will be increased to a total staff of five for orbit insertion, and then will be level at about four navigators for the duration of the orbit phase.

As planned, some members of the Nav team were co-located in the MESSENGER Mission Operations Center (MOC) at JHU/APL beginning on July 27, during launch operations on August 3, and thereafter until August 10, when the initial orbit solutions and deliveries to the MOC and DSN were finalized. Since that time, team members have been performing navigation functions at the KinetX, Inc. facilities in Simi Valley, California, and Tempe, Arizona. During critical events such as planet flybys or propulsive maneuvers, members of the Nav team will co-locate in the MOC as they did for launch. Navigation products are delivered to the MOC via electronic file transfer to the same destination computer regardless of whether they are remote or co-located, so that operational interfaces with the MOC are not perturbed when the Nav team changes location.

Navigation interfaces include information transfers with the MOC, the Mission Design team, and the DSN. For the MOC interface, the Nav team supplies estimated trajectories, one-way light time files, and tracking requests while it receives attitude history and prediction files, thruster firing history, and spacecraft time correlation files. For the Mission Design team interface, the Nav team supplies estimated trajectories, trajectory optimization products, and maneuver design products while it receives trajectory design and optimization details and trajectory maneuver design parameters. The Nav team and Mission Design team iterate the design and implementation of TCMs using independent targeting and trajectory tools until the resulting trajectories reach a common aim point. For the DSN interface, the Nav team supplies estimated trajectories to be used for antenna tracking predicts while it receives tracking and calibration data. All these interfaces were tested prior to launch and have been used since launch to provide operational navigation support to MESSENGER. Later in the mission, the Nav team will have interfaces with the MESSENGER Science Operations Center for optical navigation images and laser altimeter data and with the MOC for time-critical optical navigation images.

Orbit determination (OD) computer runs are performed after each tracking data delivery to the Nav team. Various OD strategies are designed beforehand to use different combinations of DSN tracking data types and estimation strategies in order to detect effects due to unknown spacecraft dynamics or DSN tracking issues. The various OD solutions are analyzed and compared in order to determine the current best estimate of the MESSENGER trajectory at any given time. The best estimate trajectory is then delivered to the MOC and to the DSN as required. Each OD solution delivery is given a label, ODnnn, where 'nnn' is the sequence number of the delivery; i.e., OD001, OD002, and so on throughout the mission.

After each OD solution, the Nav team performs a mapping of the trajectory and its uncertainties to the aim point in the b-plane at the next planet flyby. The ideal aim point is determined by optimizing the trajectory over the remaining mission trajectory from the current epoch of solutions up to the Mercury orbit insertion and on into the orbit about Mercury. The goal of maneuver design for TCMs is to stay on or near the optimum trajectory while minimizing the use of propulsive fuel.

NAVIGATION RESULTS FOR LAUNCH AND EARLY OPERATIONS

Significant Launch Day Events for Navigation

MESSENGER launch occurred on the second day of the launch opportunity, August 3, 2004, at 06:15:56.5 UTC. The first radio metric tracking of the spacecraft occurred at the U.S. Air Force Altair site when radar skin tracking verified that the spacecraft had separated from the third stage and the distance between the two was increasing. The range data acquired from Altair were used by analysts of the Lincoln Laboratory, Massachusetts Institute of Technology, at the Marshall Islands Regan Test Site to produce spacecraft position and velocity estimates that were later delivered to the Nav team. While these solutions supplied a backup in case the DSN failed to obtain initial acquisition, successful DSN signal acquisition of the spacecraft precluded the use of these solutions.

The first DSN radio metric tracking that was used in the MESSENGER orbit determination process came from the Goldstone, California, complex about two hours after launch. Prior to this there was some one-way tracking from Canberra, Australia, during the initial low-elevation, short-duration (about 11 minutes) pass from Deep Space Station 34 (DSS 34), but the one-way data were not used by Navigation. The unusual first rise situation (most deep space probes launched from Cape Canaveral are initially acquired by the Canberra tracking station) was caused by the large MESSENGER launch azimuth of 107°. The first pass of Goldstone tracking data initially included antenna angle pointing measurements from the 26-m antenna, DSS 16, and two-way Doppler measurements from the 34-m antenna, DSS 24. Tracking data files were delivered to Navigation by the DSN Radio Metric Data Conditioning (RMDC) team every thirty minutes for the first five and one-half hours to support initial deliveries to the MOC and to the DSN. After this, tracking data deliveries were made less frequently and were tailored to coincide with navigation events (e.g., TCMs) or the end of tracking passes.

The first range points were acquired, after being enabled by up linked ground command, by DSS 24 at the Goldstone, California, complex about three and one-half hours after launch.

First acquisition of the downlink carrier at DSS 24 was much weaker than expected, and this prompted the DSN to question the antenna pointing predicts based on the a priori trajectory supplied by the Nav team. The initial DSN predicts were based on Boeing's Best Estimate Trajectory (BET) initial states that were delivered to the Nav team prior to launch on July 23. The predict files used by DSS 24 were verified in real-time by direct interaction of the Nav team with the DSN predicts generation team. Later reconstruction of launch events showed that the weak signal was caused by both a larger than expected spacecraft injection velocity error (about two and one-half σ low) and by DSS 24 locking up on a side lobe of the transmitted signal. The Nav team responded to a DSN request and supplied a trajectory update about two hours earlier than planned so that the DSN predicts generation team could improve the antenna pointing and frequency predicts for the next station (Canberra, Australia) rise. The new trajectory estimate and associated antenna predicts improved the received signal strength, and as the data arc for OD became longer, the accuracy of subsequent trajectory deliveries for DSN antenna predicts improved and the problem was resolved.

Figure 1 shows the solved-for location of the trajectory mapped to the b-plane for trajectory estimate OD003, which was used to determine the first TCM, TCM-1. Earth is located at the origin, and the expected aim point location for perfect realization of the launch Best Estimate Trajectory (BET) quantities is below and to the right of the origin. The very long, thin BET 1-σ error ellipse shows up as the line surrounding the BET aim-point. The BET location is not the same as the desired Earth flyby aim point because the optimal trajectory included a deterministic maneuver at about 56 days after launch that is not included in this trajectory propagation. The fact that the solved-for target is about twice the distance from the nominal position as compared to the 1-σ error ellipse indicates that the injection errors were about 2-σ.

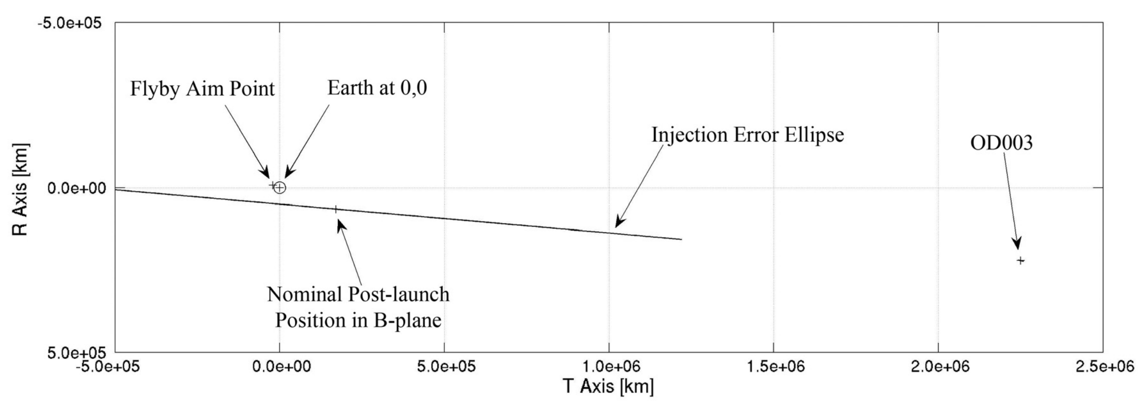

Figure 1. Launch Vehicle Best Estimate Trajectory (pre-launch BET) and OD003 Solution for the Earth Encounter B-plane on August 2, 2005.

After processing the first couple of hours of tracking data, it became obvious that the DSS 16 antenna pointing angle tracking data were inconsistent with the DSS 24 Doppler and ranging measurements. After analyzing and comparing OD results, the decision was made not to deliver any of the trajectories that included the angle data. Hence, all trajectory deliveries made to the MOC and DSN were based on estimates using only DSN Doppler and ranging.

Spacecraft Modeling Results

To account for the effects of solar radiation pressure (SRP), the MESSENGER Nav team uses a model made up of ten idealized flat plates that are oriented so as to approximate the SRP characteristics of the MESSENGER spacecraft bus (six plates) and the two articulating solar arrays (four plates for front and back of the independently pointed solar panels). The Nav team model was calibrated before launch against the more detailed SRP model used by the MESSENGER Guidance and Control team and the resulting SRP forces matched to one percent or better. During the OD process, scale factors for each of the plates in the SRP model are estimated along with the other spacecraft and observation model parameters. The SRP scale factor estimates depend on the spacecraft orientation model, which is driven by the attitude history and prediction file provided by the MOC. The initial post-launch spacecraft attitude is to orient the +y spacecraft axis (opposite the sunshade[1]) so that it points generally towards the Sun. The spacecraft orientation has actually been variable since launch and included an early slow spin about the Sun direction, as well as subsequent pointing with small attitude rates about the Sun line to keep the appropriate antenna pointed toward Earth.

The scale factors for the illuminated components of the SRP model are estimated parameters in the orbit determination solution for all the delivered trajectories. Estimates of these scale factors during the first few deliveries were about ninety percent of their a priori values. A scale factor of 1.0 indicates the SRP model for that component is 100% effective. After a few weeks of data were collected, however, the estimates began changing with data arc length and became sensitive to data weighting experiments. This was an indication of possible corruption of the solution due to the presence of unmodeled accelerations, so the Nav team began an analysis to check for early out-gassing accelerations that are common immediately after launch. Figure 2 shows the effect of delaying the beginning of the data arc on the SRP scale factor estimates. The solutions tend to stabilize if the data arc excludes all data before about September 10. The SRP acceleration estimates for the illuminated flat plates stabilized between 90 and 96% of their pre-launch values. Similar effects are noted in the corresponding trajectory solutions that are presented later. This evidence by itself is not conclusive of early out-gassing, but it does indicate that the early data are not consistent with the later data when the OD filter estimates parameters in a 'batch mode.' The next step was to include time-varying acceleration parameters with exponentially correlated noise, also referred to as 'stochastic accelerations', in the OD filter to effectively model the early non-gravitational acceleration.

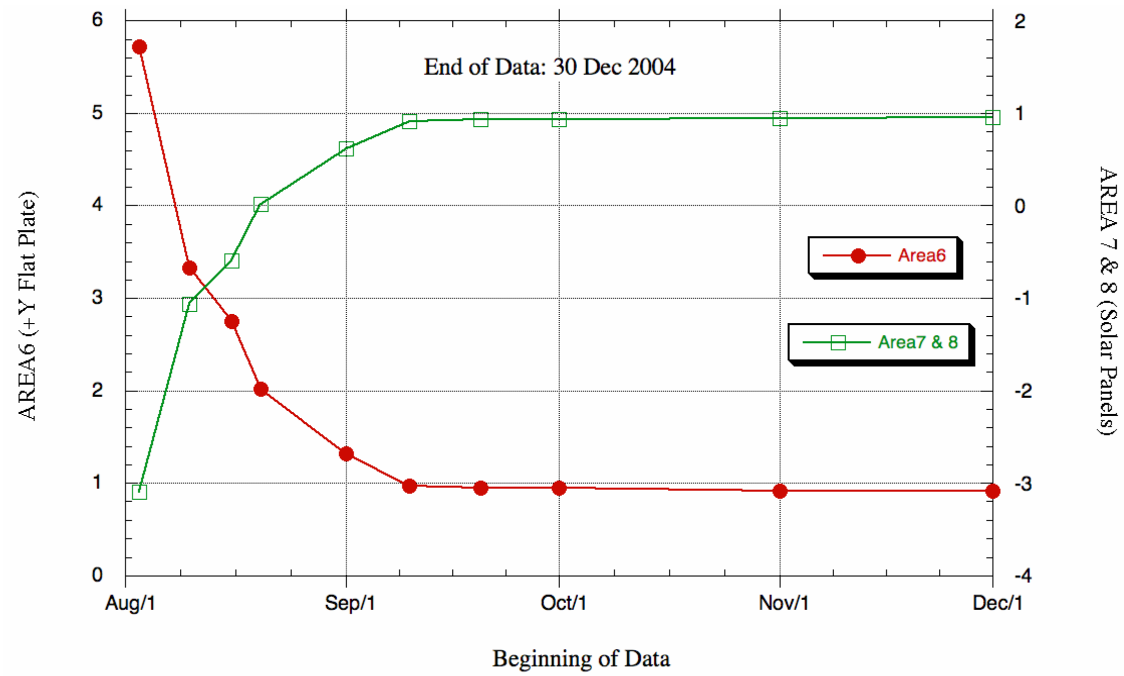

Figure 2. Solar Radiation Pressure Scale Factor Estimates for Various Tracking Data Start Times Showing Stability of Estimates for Main Body (Area6) and Solar Panels (Area 7&8) After Early Data are Excluded.

After experimenting with various OD filter strategies to model the early non-gravitational accelerations, a scheme was devised to fit the accelerations with up to five stochastic accelerations, each having short, one-hour update intervals and each having different correlation times. The correlation times for the five stochastic acceleration vectors were chosen to be 1 day, 2 days, 4 days, 8 days, and 16 days. Each acceleration 'base function' was modeled in three dimensions, so the total number of filter state parameters was increased by fifteen additional parameters. The results of this estimation strategy are shown in Figure 3.

Figure 3 shows the total estimated non-gravitational acceleration, including the solar radiation pressure, using the filter strategy outlined above. The results are shown for the first sixteen days after launch, but the data arc for the fit includes tracking data from two hours after launch until December 2004. The figure shows there were significant levels of acceleration normal to the Sun direction detected during the first week after launch, and that the acceleration appears to decrease exponentially with time. This is a strong indication of initial spacecraft out-gassing (probably due to trapped air and water vapor escaping into the vacuum of space) as has been observed and modeled on other spacecraft immediately after launch.[2] After about two weeks, most of the off sun-line acceleration dies out and only the SRP acceleration remains. Note that the early spacecraft out-gassing is about 25% of the total SRP acceleration. Once these non-gravitational accelerations were separated from the SRP acceleration, the trajectory solution consistency and accuracy improved as shown in the next section.

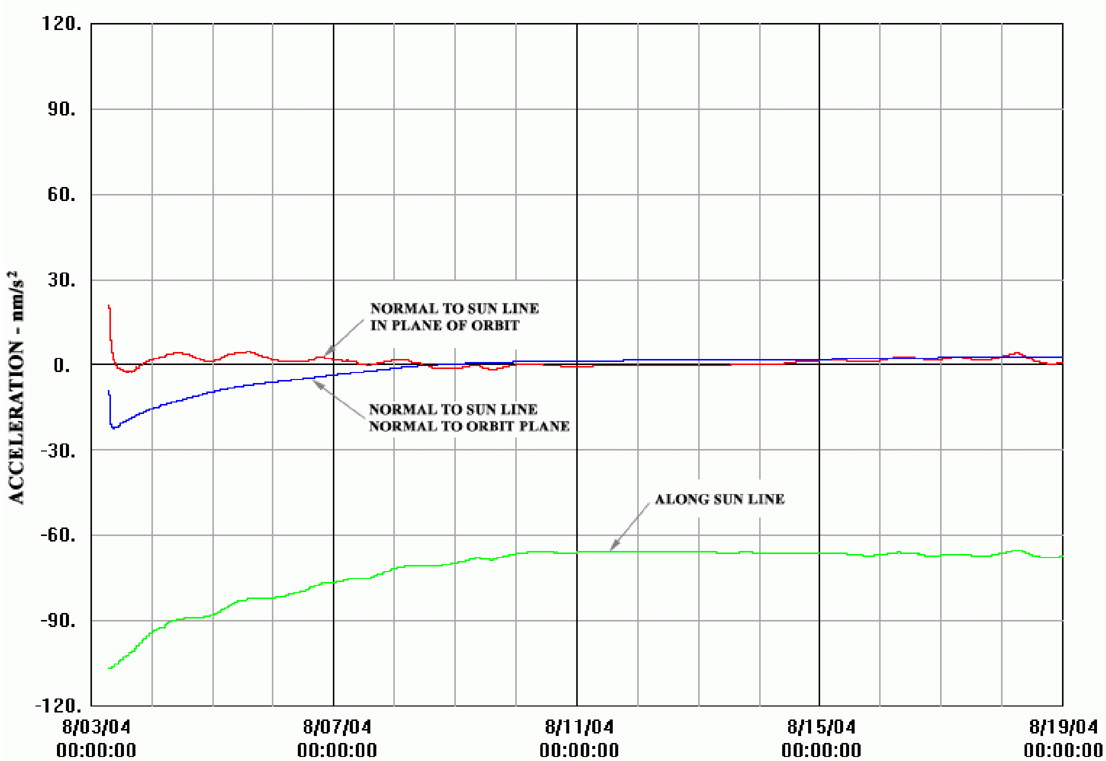

Figure 3. Estimation of Non-Gravitational Accelerations Showing Evidence of Post-Launch Out-Gassing.

Orbit Determination Results

Prior to launch, an OD covariance analysis was performed to predict navigation performance using the Nav team operational filter model and the expected DSN tracking data coverage. The results for the first leg of the mission from launch to Earth flyby are shown in Figure 4. The trajectory errors are presented in terms of the size of the semi-major and semi-minor axes of the error ellipse in the b-plane and the along-track component normal to the b-plane in the $\hat{S}$ direction. The plot shows error as a function of data cut-off time before closest approach at Earth. The 'step' increases in error at 250, 30 and 10 days before close approach are due to modeled TCM execution errors at the planned TCM locations. The slight variations in uncertainty about 100 days before closest approach are believed due to non-optimal OD filter effects and tracking geometry that results from this particular simulation. As shown in the figure, the trajectory uncertainties decrease rapidly on approach to Earth, and the formal delivery errors are less than 10 km for the final targeting maneuver at encounter minus 10 days.

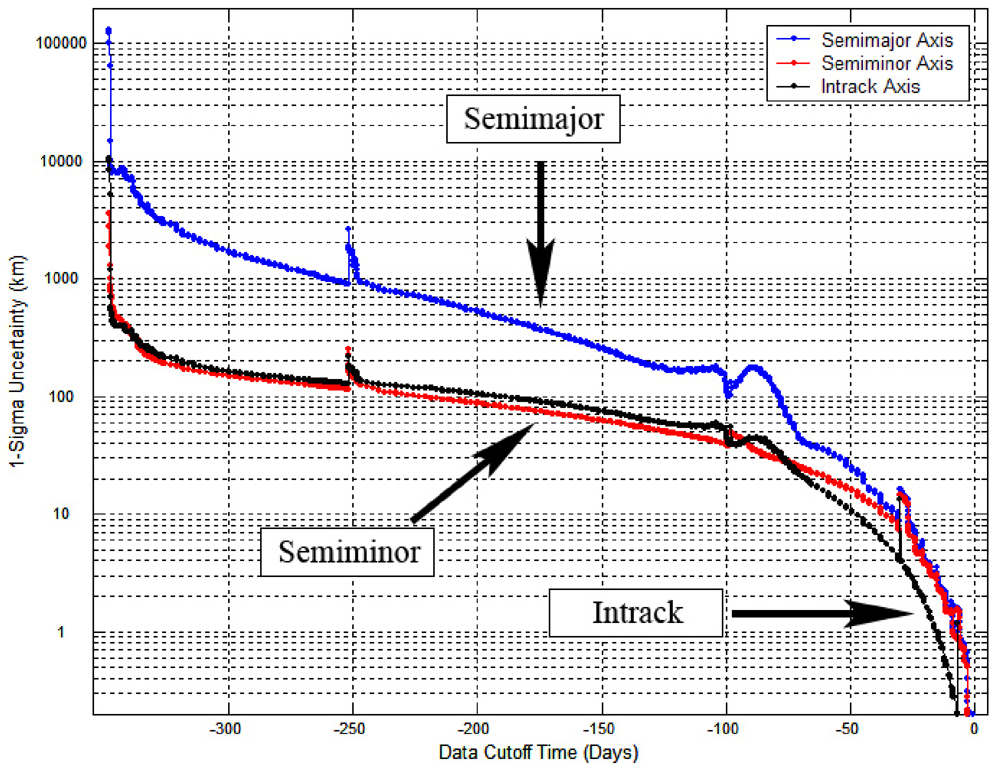

Figure 4. Trajectory B-plane Error Covariance Analysis Results for First Leg of MESSENGER Mission from Launch to Earth Flyby on August 2, 2005.

The current estimate of the Earth b-plane encounter condition, OD019, and associated 1-σ error ellipse, are shown relative to the optimal aim point in Figure 5. The solution OD019 is based on a Doppler and ranging data arc from September 20 to December 30. The area of the b-plane shown in Figure 5 is an enlargement of the region around the flyby aim point shown in Figure 1. Also shown in the figure is the Earth impact radius for this flyby. The Earth is centered at the origin (not shown on the figure). The remaining difference between the current trajectory and the aim point could be removed by a TCM of about 1 cm/s executed at the next planned TCM time of March 12, 2005, but the correction will probably be applied sometime later in May 2005 when the solution error is smaller (as shown in Figure 4). Two more opportunities for TCMs are planned at encounter minus 45 days and encounter minus 10 days to remove trajectory and navigation errors on approach to the Earth flyby. These maneuver opportunities will be used to remove any significant trajectory errors as the solutions become more precise on approach. If the TCM calculated at any of these times is statistically insignificant in terms of execution and trajectory errors, then the project has the option of canceling the TCM.

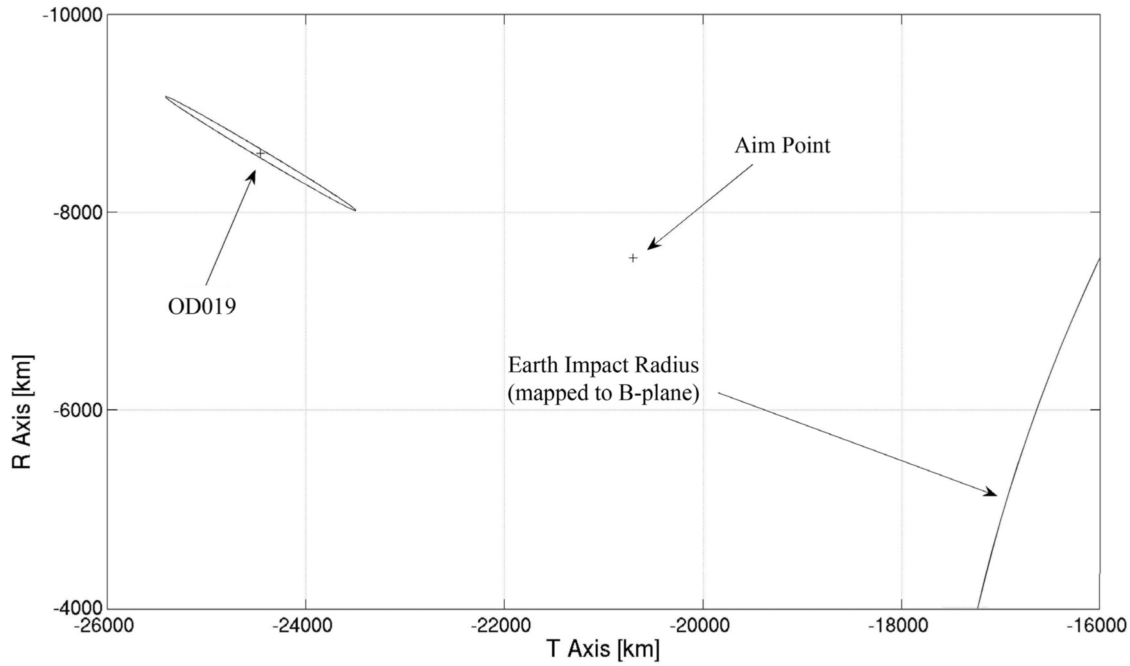

Figure 5. Post TCM-3 Trajectory Solution and Optimal Aim Point for Earth B-plane

After the non-gravitational accelerations on the spacecraft are calibrated, the trajectory solutions tend to stabilize for different length data arcs. This behavior is illustrated in Figure 6 where the trajectory aim point estimates in the b-plane are shown versus the delay in the beginning of the data arc in the OD fit. As seen earlier in the SRP calibration analysis in Figure 2, the trajectory estimates are also more consistent when omitting the early tracking data.

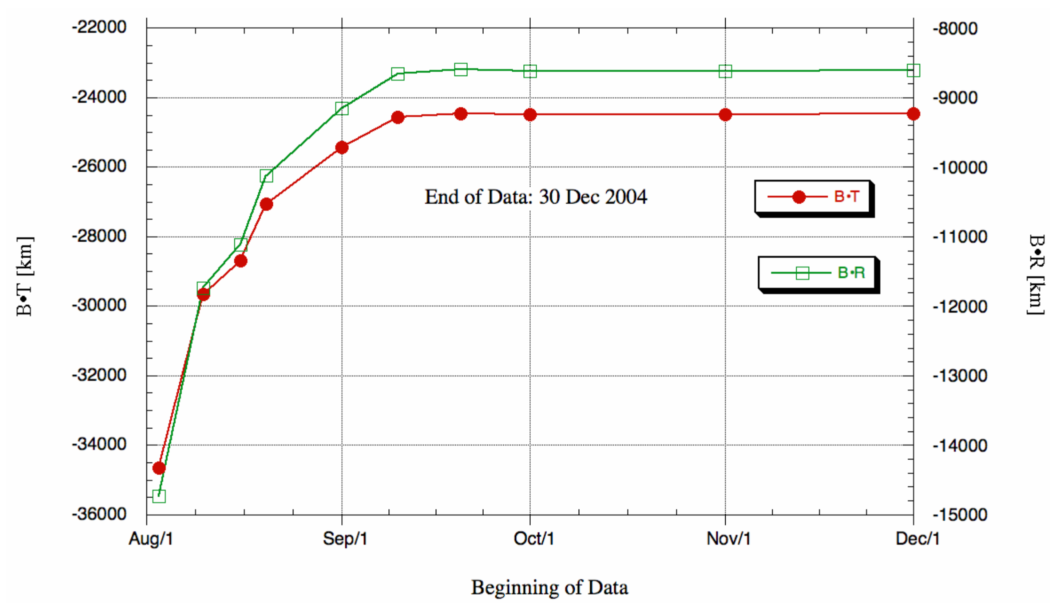

Figure 6. Post TCM-3 Trajectory Earth Flyby Aim Point Estimates for Various Data Arc Lengths During Launch and Early Operations.

Maneuver Design and Reconstruction

After launch, the Nav team began estimating the first trajectory correction maneuver, TCM-1, to correct for injection errors and return the trajectory to the targeted aim point at Earth-1 encounter. The pre-launch trajectory optimization resulted in a deterministic maneuver, originally named TCM-2, scheduled in November 2004. As planned before launch, the Nav team performed a study after launch to analyze options for delaying TCM-1 to allow for more spacecraft checkout before the first TCM. The results of moving TCM-1 later while holding the time of TCM-2 fixed and re-optimizing both maneuvers are shown in Table 1. The trajectory used to generate the values in Table 1 was based on estimate OD003 (data cut-off at 00:14, August 14, 2004). Not shown in the table is the optimal burn direction, which was also recomputed for each case. Notice that the total mission ΔV is practically the same (within 1 m/s) for a large range of TCM-1 locations from 18 days to 58 days after launch. After the design analysis was completed, it became obvious that the optimum fuel-use trajectory was relatively insensitive to the location of the correction maneuver for up to almost two months after launch (as long as the two maneuvers TCM-1 and TCM-2 were designed together). Hence, the location for TCM-1 was chosen on August 24, 2004, about twenty-two days after launch, and that resulted in a design TCM-1 of 21 m/s and a design TCM-2 (on November 19, 2004) of 5 m/s.

Table 1. Total ΔV Cost and Earth Encounter Aim Point Changes for Delaying TCM-1

TCM-1 location after launch	TCM-1 Magnitude (m/s)	TCM-2 Magnitude (m/s)	$B \cdot T$ (emo)* at Earth Flyby (km)	$B \cdot R$ (emo)* at Earth Flyby (km)	Earth Encounter Time: August 2, 2005	Total Mission ΔV (m/s)
+18d	20.431	5.506	-20888.5868	-8018.3772	19:20:55.0	1901.0
+28d	21.385	4.169	-20869.4614	-8011.0357	19:18:11.0	1899.9
+38d	23.073	2.201	-20852.7503	-8004.6209	19:08:15.9	1899.9
+48d	25.085	0.000	-20833.2654	-7997.1413	19:01:37.4	1899.6
+58d	25.959	0.000	-20798.9727	-7983.9776	19:32:36.0	1900.5

* emo indicates the 'T' axis is parallel and the 'R' axis is normal to the J2000 Earth Mean Orbit Plane

Due to restrictions on the maximum size of the first burn that the MESSENGER Guidance and Control team wanted to perform, and to allow more time for analysis and checkout of the spacecraft systems, the design TCM-1 was split into two burns: the first part on August 24, 2004 was reduced to 18.0 m/s, and the remainder of about 4 m/s (renamed as TCM-2) on September 24, 2004. The location of the design deterministic maneuver, re-optimized for execution on November 18, 2004, was renamed TCM-3.

Monitoring and reconstruction of each TCM using DSN tracking data is the responsibility of the Nav team. During the TCM execution, the Nav team uses the offset in the real-time DSN Doppler tracking data to produce a quick-look estimate of the burn performance. The quick-look estimate is usually delivered within a minute after the DSN has received all the tracking up to the end of the burn (a one-way light time after the TCM ends on the spacecraft). After about two weeks of DSN tracking data have been accumulated following a TCM, the Nav team produces a more precise estimate of the magnitude and direction of the maneuver.

The Nav team reconstruction results for the first three TCMs are shown in Table 2. The time shown for each TCM is the designed maneuver execution time on the spacecraft. Due to initialization and fuel settling burns, the onset of acceleration observed in the received Doppler tracking data is typically delayed by several seconds. The reconstruction accounted for these delays when modeling the TCM acceleration in the OD filter. Table 2 compares the estimated ΔV magnitude and direction, and their 1-σ uncertainty, to the planned design values. For the medium and small sized maneuvers performed thus far, the ΔV magnitudes are one-half of one percent or better and the direction is within a few tenths of a degree. Not shown in Table 2 is the total directional error for each TCM which for TCM-1 was 0.309°, for TCM-2 was 0.274°, and for TCM-3 was 0.342°. The effect of the three maneuvers on the b-plane target for the Earth flyby is shown in Figure 7. An enlarged view of the portion of the b-plane around the current target estimate was shown before in Figure 5.

Table 2. Maneuver Reconstruction for First Three Trajectory Correction Maneuvers (TCMs). ΔV Spherical Components are in Earth Mean Equator of J2000 Coordinate System.

TCM-1 at 21:00:00 UTC, August 24, 2004, Spacecraft Event Time					
	Parameter	Estimated	Planned	Reconstruction Uncertainty (1-σ)	Difference from Planned
	ΔV (m/s)	17.9009	18.0000	0.0017	-0.0991 (-0.55%)
	Declination (deg)	-18.4960	-18.6426	0.0032	0.1466
	Right Asc. (deg)	242.5414	242.8288	0.0032	-0.2874
TCM-2 at 18:00:00 UTC, September 24, 2004, Spacecraft Event Time					
	Parameter	Estimated	Planned	Reconstruction Uncertainty (1-σ)	Difference from Planned
	ΔV (m/s)	4.5886	4.5899	0.0024	-0.0013 (-0.03%)
	Declination (deg)	271.1789	271.3752	0.0096	0.1963
	Right Asc. (deg)	-24.1171	-24.3248	0.0171	0.2077
TCM-3 at 19:30:00 UTC, November 18, 2004, Spacecraft Event Time					
	Parameter	Estimated	Planned	Reconstruction Uncertainty (1-σ)	Difference from Planned
	ΔV (m/s)	3.2473	3.2365	0.0006	0.0108 (0.33%)
	Declination (deg)	315.7591	316.0507	0.0030	-0.2916
	Right Asc. (deg)	-15.2193	-15.4143	0.0152	0.1950

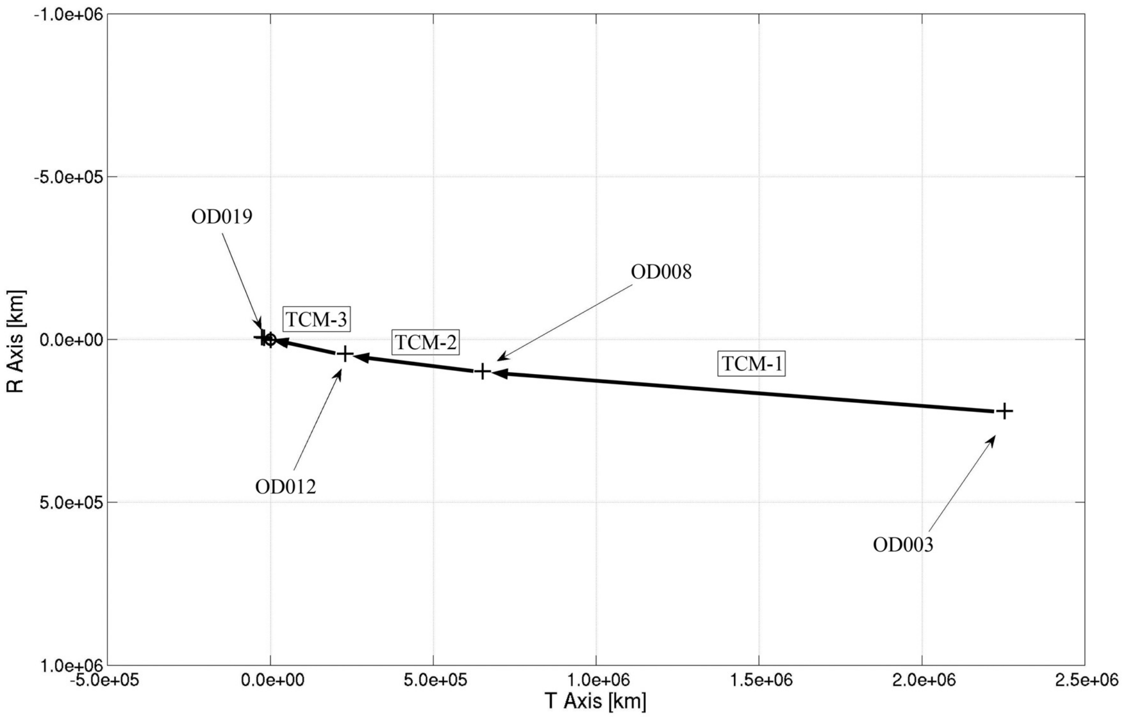

Figure 7. Effect of the First Three Trajectory Correction Maneuvers on the Earth B-plane Intercept Point. The Origin is at the Center of the Earth.

FUTURE NAVIGATION TESTS AND CALIBRATION

Calibration and tests of the navigation system are planned during the remaining years of cruise to prepare for support of the science operations in Mercury orbit. Plans include continuing to calibrate the solar radiation pressure model used by Navigation and separating out the effects of spacecraft pointing, solar array incidence angles, and surface degradation over the cruise phase. In addition, orbit determination tests will be performed using DSN ΔDOR tracking data before the first Venus flyby to establish its use on the remaining Venus and Mercury flybys. Other tests include optical navigation tests planned to begin during the Earth flyby in August 2005. Optical navigation will be used primarily to enhance navigation accuracy on approach to the three Mercury flybys and orbit insertion; it will also be tested (but not used to improve navigation delivery accuracy) during Earth flyby and the two Venus flybys. Optical images of landmarks (i.e., craters) will also be used during the Mercury orbit phase to enhance navigation performance as first successfully used on the NEAR project.[3] Once in orbit about Mercury, the Nav team will calibrate the Mercury gravity model to improve navigation accuracy as was done on previous planetary exploration missions. Each of these tests and calibrations are described below.

Plans for Testing Delta Differential One-Way Ranging (ΔDOR)

The use of DSN ΔDOR tracking data has been shown to be an important, independent navigation tracking data type on planetary missions, and it will be used to enhance navigation delivery accuracy for the close Venus and Mercury flybys. The lowest of these flybys will be as close as 200 km above the surface.[1] A single ΔDOR measurement determines the angular position of the spacecraft relative to a baseline between two DSN sites, and hence it contains unique information compared to the line-of-sight measurements of Doppler and ranging from a single station. The baselines typically used are the Goldstone-Australia and the Goldstone-Madrid station pairs.

The DSN long-range planning schedule currently includes periods for obtaining MESSENGER ΔDOR tracking that includes measurements from two different baselines each week (for four weeks total) starting five weeks prior to each Venus and Mercury flyby. ΔDOR tracking taken before the first Venus flyby will be used for after-the-fact data flow and processing tests since the aim point is over 3000 km altitude. At this first Venus flyby, the standard radio metric data types will be sufficient for navigation and the enhanced accuracy available from ΔDOR will not be required. This will allow the Nav team to validate the ΔDOR processing on the Venus flybys in a parallel, non-critical process without affecting the regular navigation orbit determination and delivery process. Subsequent Venus and Mercury flybys will use ΔDOR during the approach phase to determine the targeting maneuvers and estimate the resulting flyby trajectory. For the Mercury flybys, orbit solutions including ΔDOR will be used as an independent data type to resolve any apparent conflicts between the solutions based on radio metric and optical tracking.

Plans for Optical Navigation Testing

The plan is to test optical navigation (OpNav) at the Earth and Venus flybys so that it can be used later to independently determine the miss distance on approach to each of the Mercury flybys. OpNav at the Venus flybys will not be required since the Venus atmosphere limits the precision of finding the planet center; however, the acquisition and processing of images of Venus will provide an excellent end-to-end checkout of the OpNav system. The trajectory solution accuracy using only the radio metric data will be sufficient to accomplish the Earth and Venus flybys.

Tests will include specific image types and a minimum number of each type that will be required at each flyby. The image types include the specification of which imager is to be used; i.e., either the wide-angle or narrow-angle imager. Compression algorithms expected to be used for OpNav images will be used on at least ten percent of the total images taken at each Venus flyby. The imaging goals of each image type include planet image only, planet and background stars, and a range of exposure settings for each image or group of images. The imaging goals will specify that two or more planet images be resolved images of the Sun-lit planet disk with 10 or more pixels extent, so that center finding algorithms may be tested.

The OpNav processing tests scheduled before the first Mercury flyby in January 2008 will demonstrate the following: (1) that OpNav images can be planned, included in the spacecraft sequence, executed on board, and down-linked from the spacecraft for either imager; (2) that images can be provided to the Navigation team through either of the OpNav image processing paths; e.g., images provided via the Science Operations Center processing path or images provided via the MOC critical OpNav processing path; (3) that Navigation can successfully read the image files and form corrected, calibrated images for OpNav processing from either imager through either processing path. If the images are compressed, then de-compression of those images will be demonstrated; (4) that the Navigation OpNav center finding algorithm works correctly on resolved images of Venus; and (5) that OpNav images can be successfully processed in the orbit determination software.

Imager geometric calibrations will also be performed before the Earth flyby. The calibration images will be obtained by pointing both narrow and wide-angle imagers at a specific star field and taking images with at least two different exposure settings. The star fields chosen for calibration images will be dense enough to guarantee several stars will be seen in each image, e.g., by imaging the Pleiades. The star images will be used to determine distortions and geometric calibrations that will be applied to the photometric measurements. In addition, any bias in pointing the imager will be measured and used to calibrate the OpNav processing.

Mercury Gravity Calibration for Navigation During the Mercury Orbit Phase

The orbit determination requirements for the orbit phase are driven by the mission design requirements to maintain the MESSENGER orbit geometry within specifications for spacecraft safety and science measurements. The mission design requirements lead to derived navigation requirements on both orbit period and periapsis altitude. The navigation requirements are to maintain the orbit period to ±1 minute (2-σ), and to control the periapsis altitude between 125 km to 225 km (3-σ) after orbit insertion and after each maneuver to lower periapsis to the nominal target altitude of 200 km. These requirements are met with the current tracking schedule and preliminary navigation performance estimate described below.

A preliminary navigation accuracy analysis has shown that the planned DSN tracking coverage for MESSENGER mission design provides sufficient navigation performance and margin throughout all mission phases, including the orbit phase. The preliminary navigation studies for the orbit phase used DSN Doppler and ranging that were conservatively weighted at 0.5 mm/s and 30 m, respectively, according to the planned DSN schedule of one 8-hour track per day. Table 3 shows navigation orbit uncertainties in three orthogonal directions along the orbit: cross track (radial at periapsis and apoapsis), down track (in the direction of the orbit velocity vector), and out of plane (normal to the plane of the orbit). Table 3 includes uncertainties for three different orbit phases. The phases chosen for the study included the orbits immediately following MOI when the Nav team first starts tuning a model of the Mercury gravity field, the period where the orbits are nearly face-on when viewed from the Earth (near zero inclination to the plane-of-sky), and the period where the orbits are nearly edge-on when viewed from the Earth (near 90° inclination to the plane-of-sky).

Table 3. MESSENGER Orbit Uncertainties (1-σ) for a 10-day Arc Solution, Including the Effect of Gravity Uncertainties and Gravity Tuning, Mapped to 10 days After the End of the Arc.

Orbit Phase	Cross Track (km)	Down Track (km)	Out of Plane (km)
Post Mercury Orbit Insertion	2	7	1
Mercury Orbit (face on viewing geometry)	17	100	5
Mercury Orbit * (edge on viewing geometry)	17	32	10

* includes data outage due to spacecraft occultations by Mercury

The two viewing geometries represent near worst-case viewing angles for DSN Doppler tracking data, so these cases help bound the expected errors over the MESSENGER orbit. When viewing the orbit nearly face-on, the Doppler is less sensitive to errors in the down track directions because the line-of-sight to Earth is almost normal to the orbit velocity. This effect is seen in Table 3, where the down track error for the face-on geometry is larger than that for the other two viewing angles. When viewing the orbit nearly edge-on, the Doppler is less sensitive to errors in the out-of-plane direction, as the last column in Table 3 indicates. For other intermediate viewing angles to the plane-of-sky, experience has shown that the orbit errors are generally less than those at the bounding cases for face-on or edge-on geometry. Note that all three cases in Table 3 assume the same starting a priori gravity uncertainties, whereas in reality the last two cases will occur some time after MOI, so some gravity tuning will have occurred and the errors should be less.

For the typical MESSENGER periapsis velocity of 3.8 km/s, the down track errors in Table 3 imply a 1-σ (worst orbit viewing case) navigation timing uncertainty of about 26 s. A typical timing uncertainty will probably be less than 10 s (1-σ). Even when combined with maneuver execution error, the result is within the requirement for maintaining the MESSENGER orbit period to ±1 minute (2-σ). The cross track uncertainties at periapsis indicate the uncertainty in periapsis altitude. Note that the cross track uncertainties for all cases studied from Table 3 meet the periapsis altitude control requirement.

The navigation strategy for the orbit about Mercury includes gravity estimation and localized tuning of a twentieth degree and order spherical harmonic field in addition to the usual spacecraft dynamic parameters and orbit state parameters. The solve-for gravity field has higher degree and order than can be determined from the available tracking so that high frequency signatures in the Doppler data will not alias into the estimates of the low degree and order harmonic coefficients. The uncertainties shown in Table 3 include the a priori gravity uncertainties derived from a scaled lunar field. Since sub-spacecraft periapsis longitude on Mercury moves 360° in 59 days, it will take at least this long to obtain measurements for a global gravity model; hence, determining a series of locally tuned gravity models will be part of navigation operations during the initial orbit phase.

The navigation strategy for orbit determination when MESSENGER is first in Mercury orbit is to perform incremental gravity field tuning as periapsis moves through 360° in longitude. A complete circulation of Mercury by the periapsis point takes 59 days, or about 118 orbits. During this time, the navigation team will estimate spacecraft state and other parameters along with a twentieth degree and order gravity field over 10 day long arcs of Doppler and range data. The harmonic coefficient estimates from these fits will be highly correlated, but experience with other planetary orbiters has shown that this technique fits the short-period gravity perturbations with the least amount of aliasing.[4,5] The gravity field harmonic coefficients from each 10-day arc represent a local fit to the particular orbit data (especially periapsis) and are not valid globally.

This short-arc technique of gravity field estimation uses the Square Root Information Factorization (SRIF) method to separate arc-dependent parameter information from the gravity field information. This technique was developed and used on early planetary orbiters when the planet gravity field was mostly unknown and the sampling was sparse due to high eccentricity orbits.[4,5] Examples are Vikings I and II at Mars (eccentricity ~ 0.8), Pioneer Venus (eccentricity ~ 0.8), and Magellan (eccentricity ~ 0.4). These early planetary orbiter missions had relatively large orbit eccentricity, in most cases even larger than that of MESSENGER (eccentricity ~ 0.7).

Once solutions are available from several 10-day arcs, the information is combined with subsequent 10-day arcs to 'bootstrap' a gravity solution that is valid for MESSENGER over an increasing range of longitudes. This technique extracts both short-period information from the velocity change at periapsis and longer-period orbit evolution information over the 10-day arc. As more data are accumulated, longer or shorter arc fits will be evaluated and included if appropriate to obtain the best navigation gravity model on an ongoing basis. After the periapsis has completed a circulation of Mercury, a tuned gravity solution will be obtained by combining tracking data from the first 118 orbits. This first circulation solution produces a locally tuned field for navigation that will be best determined for a band of latitudes around the mean periapsis latitude for that circulation. Gravity tuning will continue on subsequent data arcs and subsequent circulations of Mercury by the orbit periapsis. Each subsequent gravity tuning will use the a priori gravity information from the previous 'global' field solution to help constrain the final gravity solution.

A covariance analysis was also performed on a typical 10-day arc in the orbit phase by assuming a twentieth degree and order lunar field scaled by the ratio of the radii to Mercury. The resulting gravity field harmonic coefficients were assumed to have an a priori uncertainty of 50%. After processing 10 days of Doppler and range, the low degree and order terms (up to degree and order 3) improved by factors of 2 to 3 times, while the higher degree and order terms did not improve much (<1%) and were highly correlated with each other. The results should improve as data arcs are combined and a more globally valid gravity field estimate emerges.

SUMMARY

The launch and early operations phase has been successful for MESSENGER Navigation. MESSENGER Nav has performed the assigned tasks and delivered the expected navigation products to the other operations team elements as planned. Even with the minor exceptions noted above, the initial acquisition and early operations phase was largely free of problems. The Nav team was prepared for contingency operations and was pleasantly surprised when they were not necessary. In the experience of the Nav team members, which spans the last 30 years of space exploration, MESSENGER has had one of the most trouble-free early navigation phases for a deep-space probe. The cost of correcting the launch injection error (21 m/s) was less than the ninety-nine percentile, worst-case correction computed pre-launch (~38 m/s). The early delta-V "savings" over what could have happened in the worst case, coupled with indications of precision maneuver capability, bode well for having adequate fuel for the remainder of the mission.

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