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MESSENGER NAVIGATION OPERATIONS DURING THE MERCURY ORBITAL MISSION PHASE

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The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is the seventh in NASA's Discovery Program. The spacecraft was launched from Cape Canaveral Air Force Station in August 2004 to begin an interplanetary cruise that culminated in orbit insertion about Mercury in March 2011 for a nominal one-year scientific investigation. An extension to the mission was initiated in March 2012, and in order to optimize the scope and return of the onboard scientific instruments and the stability of the spacecraft orbit about the planet, the orbital period was reduced from 12 to 8 hours in April 2012. This paper describes MESSENGER navigation operations and trajectory estimation performance for the orbital mission phase from Mercury orbit insertion through the end of the primary mission and into the first 9 months of the ongoing extended mission.

INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is being flown as the seventh in NASA's Discovery Program. The MESSENGER mission is led by the principal investigator, Sean C. Solomon, of Columbia University. 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 (SNAFD) of KinetX Aerospace, a private corporation. Navigation for all mission phases makes use of radiometric tracking data from the NASA Deep Space Network (DSN).

The mission timeline of planetary flybys and deterministic deep-space maneuvers (DSMs) from launch through Mercury orbit insertion (MOI) and the end of the primary mission is shown in Figure 1.[1-5] The interplanetary cruise trajectory included an Earth gravity-assist flyby about one year after launch,[6] followed by two Venus flybys[7,8] and three Mercury flybys[9-11] before MOI.[12-14] From orbit about Mercury, as of this writing, MESSENGER continues conducting science observations of the innermost planet more than one and three-quarters Earth years, and seven Mercury years, after MOI. Spacecraft navigation for the entirety of the mission has been handled by the KinetX Aerospace SNAFD team. The KinetX navigation team has worked closely throughout with the mission design team at JHU/APL to optimize trajectory estimates and maneuvers, in order to maximize the scientific return from the spacecraft.[13,15,16]

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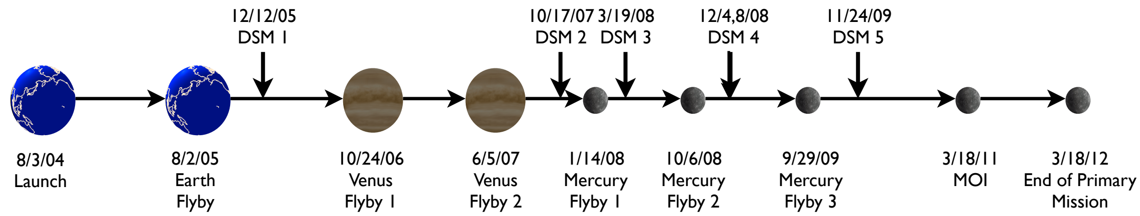

Figure 1. MESSENGER Primary Mission Timeline.

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 re-optimization 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. Each coherent two-way track from a single DSN antenna produces two-way Doppler tracking (F2) data. If a second DSN antenna receives the same downlink (e.g., during a station-to-station handover), then three-way Doppler tracking (F3) is produced. Additionally, most of the tracks for MESSENGER are configured to acquire two-way range data from the DSN Sequential Ranging Assembly (SRA).[17] Delta differential one-way ranging (DDOR) has also been useful for critical portions of the mission, such as planetary encounters and large maneuvers, but has not been used in the orbital mission phase.

Orbital periapsis altitudes have been as low as approximately 200 km, although perturbations from the gravitational attraction of the Sun will eventually decrease closest approach distances below this benchmark and ultimately result in a planetary impact once propellant reserves are depleted.[18] The biggest challenges for trajectory estimation in Mercury orbit involve modeling the accelerations due to the radiation environment. It is around periapsis passages when most of the mission science data are collected, including high-resolution imaging. The most relevant measure of spacecraft navigation performance is how well it enables scientific data acquisition, and feedback thus far has been that trajectory accuracy has exceeded all requirements. However, successful performance did not come without difficulties on a weekly, or sometimes daily, basis for the navigation operations team. As periapsis longitude crosses the Mercury terminator, the modeling of planetary infrared re-radiation during the fit span for orbit determination (OD) can become problematic, and this orbital perturbation, as well as those from direct solar radiation pressure (SRP) and surface albedo, are highly dependent on spacecraft surface properties and attitude. The MESSENGER orbit about Mercury constitutes an extreme environment for radiation and temperatures, both high and low. The OD solution quality, as well as the information content of the tracking data and observability of state parameters, is also an intrinsic function of geometry. Principally the solution depends on the angle between the line of sight (LOS) from Earth and the spacecraft orbit plane, but tracking quality is also degraded during solar conjunctions.

Beyond prediction and reconstruction of the spacecraft trajectory, monitoring of critical events in real time is another important function of the navigation team. Real-time plots have been generated for each of the major maneuvers and flybys as they occurred throughout the mission. These "Quick-Look" reports on maneuver performance were generated throughout the interplanetary cruise phase, as well as for MOI and the post-MOI orbit-correction maneuvers (OCMs). This paper reviews and compares the performance of critical on-orbit propulsive maneuvers that have occurred over the course of the MESSENGER primary mission, along with many other challenging aspects of navigation operations for the first spacecraft in history to achieve Mercury orbit.

MERCURY ORBIT INSERTION

On March 18, 2011, at 01:00:59.77 TDB (Barycentric Dynamic Time), MESSENGER completed its MOI maneuver. Near the end of this complex multi-component propulsive event, the spacecraft was captured into Mercury orbit by the planetary gravitational field. Thus ended the most operationally complex interplanetary cruise trajectory ever navigated through deep space as the primary science mission began. The intense gravity well of the inner solar system had been negotiated after a half dozen planetary flybys, a nearly equal number of distinct deterministic DSMs, and a dozen smaller statistical trajectory correction maneuvers over the span of six years, seven months, and two weeks from launch on August 3, 2004.

Orbit insertion occurred as planned less than two days after Mercury perihelion, and near maximum elongation, as the MESSENGER spacecraft passed over the northern hemisphere of the planet towards its fourth approach at 200 km above the surface in three years and a little less than two months. Over 40 statistical correction maneuvers had been planned, but none were executed in the trans-Mercury regime due to the successful implementation of a solar sailing strategy that facilitated precision flyby targeting without utilizing valuable propellent or risking potential operational mishaps.[9-12] This added margin in the fuel budget could thus be allocated to fulfilling the science objectives of the orbital phase and extending the primary mission beyond the nominal one-year timespan originally planned.

MOI was monitored in real time from the MESSENGER Mission Operations Center (MOC) at JHU/APL. As the track data filtered through, it quickly became obvious that the most critical maneuver of the mission had been executed within specifications. The plot in Figure 2 was generated and displayed during execution of the burn from the incoming Doppler data, and represents the calculated envelope of contributions from OD uncertainties and maneuver execution errors propagated out for near-nominal MOI conditions.

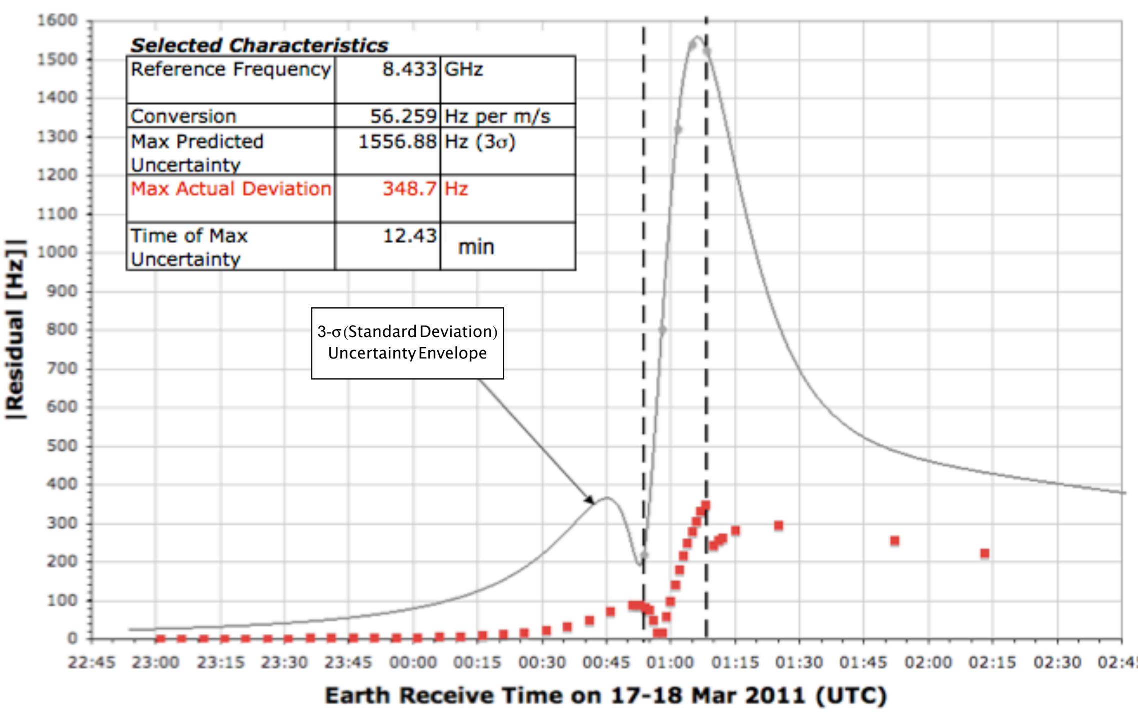

Figure 2. Doppler Residual Prediction Envelope and Actual Doppler Residuals for MOI.

The continual receipt of residual data suggested nominal maneuver execution, as any safe-mode response by the spacecraft to a detected burn anomaly would interrupt this flow. Since all of the residuals were within the three-standard-deviation envelope and telemetry was nominal, all indications were that MOI execution was nominal as well, which was subsequently confirmed. The spacecraft had been captured into orbit about Mercury.

Table 1. MOI Reconstruction Results.

Mercury Equatorial-Centered MOI Target/Achieved Orbit Parameters			
Phase/Parameter	Target	Result	Difference
Change in-Velocity (m/s)	861.166	861.714	0.548
Altitude (km)	200.000	206.770	6.770
Period (h)	12.000	12.073	0.073
Inclination (deg)	82.50	82.52	0.02
Periapsis Latitude (deg)	60.00	59.98	0.02
Argument of Periapsis (deg)	119.13	119.16	0.03
Right Ascension of the Ascending Node (deg)	350.17	350.17	0.00
Eccentricity (dimensionless)	0.74	0.74	0.00

Quantification of the success of MOI has been reported in numerous previous technical papers,[12-14] so those details will not be presented here except to note the injection periapsis orbital elements, which are listed above in Table 1.

The mission plan for the Mercury nominal orbital phase called for periapsis altitude to be maintained between 200 and 500 km, as shown in Figure 3.[2] This plan also originally called for a two part MOI sequence, although this sequence was eventually re-optimized before arrival to provide the desired orbit insertion parameters with a single continuous burn of the thrusters. The perturbation environment tends to drive up the periapsis altitude between OCMs at these altitudes, as shown in Figure 3. The latitude of periapsis, an important element in science planning, drifts up from around 60°N to upwards of 72°N over the course of the nominal primary mission, whereas the orientation of the orbit in inertial space remains relatively fixed as Mercury revolves about the Sun and rotates beneath it, allowing detailed scientific observations and measurements to be taken of the entire planet during cumulative periodic circumnavigations.

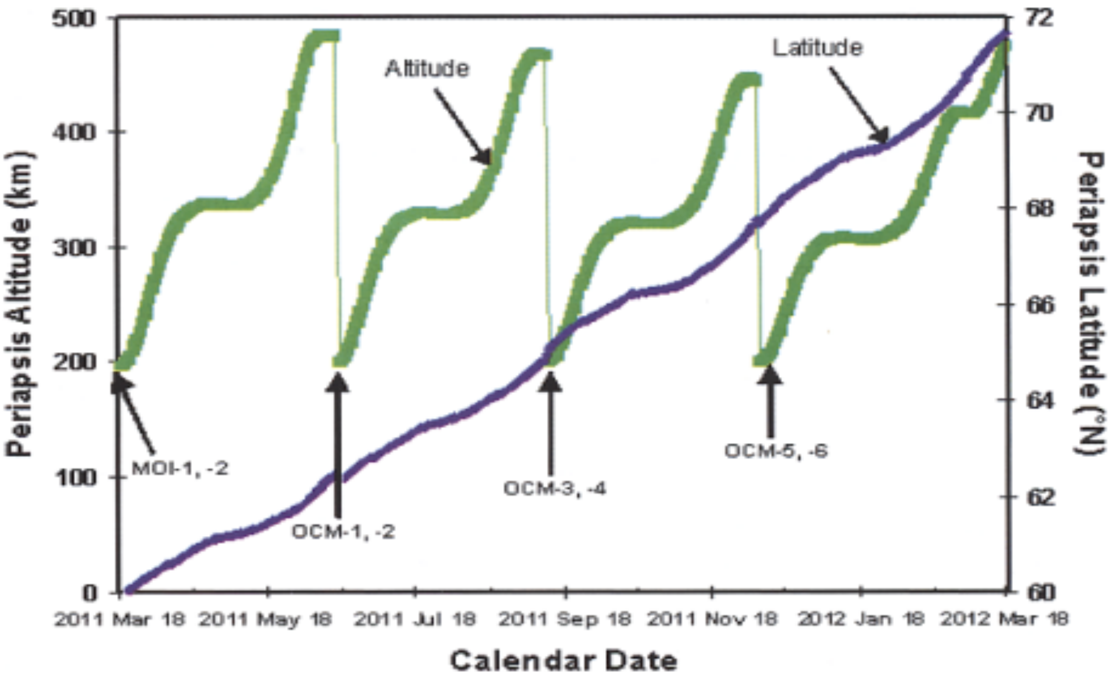

Figure 3. Planned Periapsis Evolution during the Orbital Phase of the Primary Mission.

PRIMARY MISSION ORBITAL PHASE

After MOI, the orbital mission phase proceeded nominally, although radiation pressure perturbations had now increased in complexity and the new force models used for OD were initially problematic. Planetary radiation pressure (PRP) accelerations, in the form of a simple albedo model with a uniform *a priori* value for the sunlit surface of Mercury combined with a spherical harmonic infrared planetary re-radiation model of degree and order 10, are utilized to estimate a combination of spacecraft surface reflectivity coefficients and scale factors in order to fit the tracking data. However, many of these parameters, as well as those for the direct SRP model, were given such wide latitude for filter modification by the associated *a priori* uncertainties that they had a tendency to take on negative, physically unrealistic, values during the estimation runs. The workaround for this problem was to reduce the *a priori* uncertainties as needed so that this did not occur. The problem with this approach was that reducing the uncertainties on one set of parameters typically caused others to go in turn negative. Converging to a realistic solution in this manner was extremely difficult.

MESSENGER spacecraft attitude is modeled by the navigation operations team for the purpose of estimating the radiation perturbations experienced over the course of each Mercury orbit. Separate specular and diffuse reflection components of incident radiation are modeled for SRP, and the analogous albedo and infrared PRP from Mercury's surface, using a 10-flat-plate spacecraft model representing the sun shade and articulated solar array panels, as well as the top, bottom, sides and back of the bus. Figure 4 displays illustrations of the spacecraft to give a feel for the orientation of these plates. Attitude history, derived from telemetry, along with a short-term attitude prediction file defined by the current science plan and a long-term attitude prediction file roughly coinciding with the requirements for spacecraft momentum management, are provided to the navigation operations team by the JHU/APL guidance and control team through the MOC. The history is updated on a daily basis while the short-term predictions are updated weekly and the long-term predictions are regenerated every month or so.

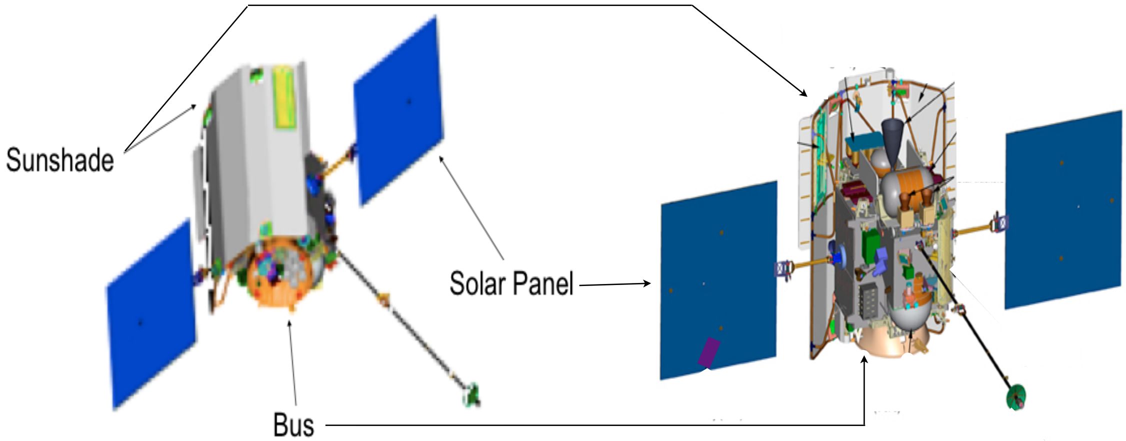

Figure 4. The MESSENGER Spacecraft.

A weekly delivery schedule had been established for the ephemeris updates produced by the navigation solutions, but the first three post-MOI solutions were treated as special cases. The first OD solution delivered on-orbit by the navigation operations team was OD number 204 (OD204). This OD was delivered using track data from the first 12 hours after MOI, just prior to the initial orbital periapsis of MESSENGER about Mercury. The final residuals for OD204, displayed in the upper half of Figure 5, are of relatively poor quality.

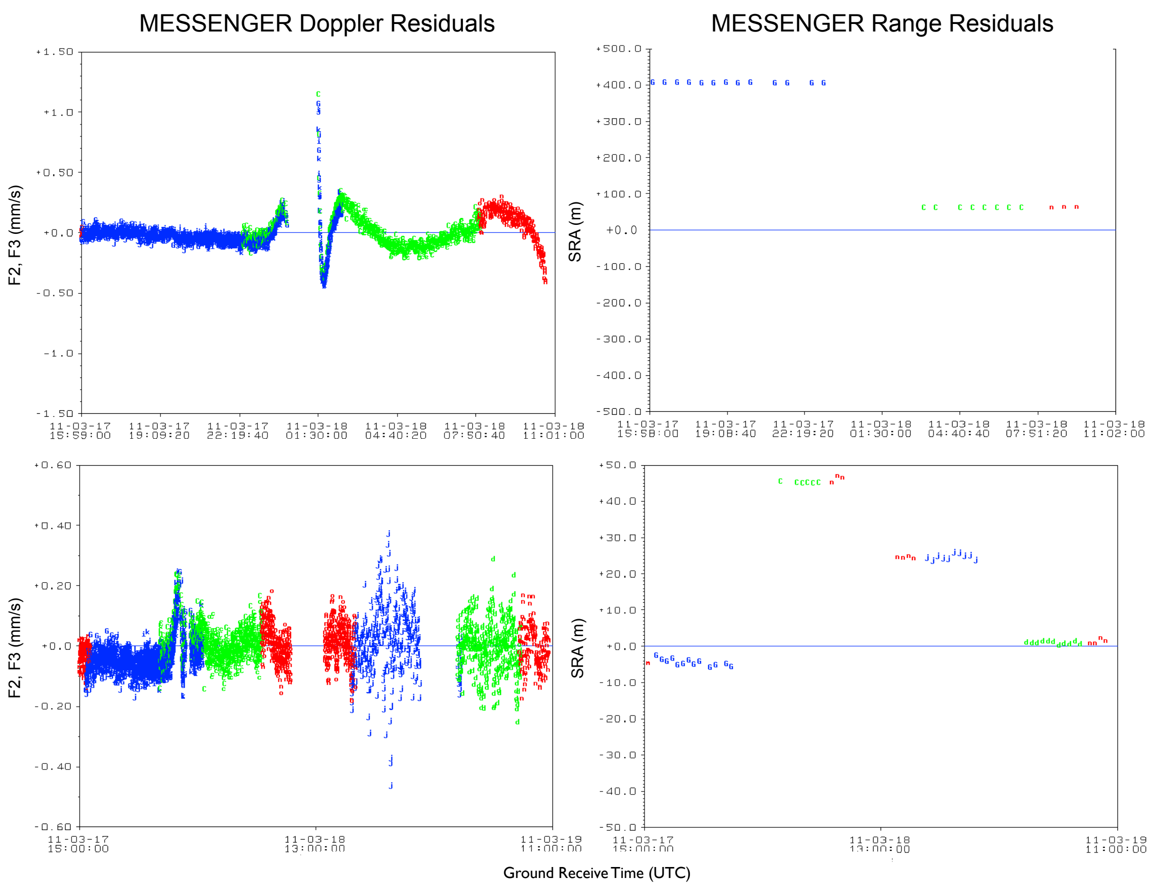

Figure 5. Doppler [mm/s] and Range [m] Residual Plots for OD204/205 (Upper/Lower).

The first week after MOI was one of the most hectic of the entire mission for the navigation team, along with launch and spacecraft deployment. This period included a very short delay, on the order of hours, for the delivery of the second post-MOI solution, OD205 (Figure 5). OD205 used an additional 24 hours of track data, and OD206 incorporated data through eleven-plus orbits. Together, these three solutions encompassed the better part of the first week of post-MOI data and constituted the first "weekly" orbital phase ephemeris update solution for the MOC, and for the MESSENGER Science Operations Center (SOC) as well.

Determining the initial post-MOI OD solution was a tedious process, and it was not until the Set-3 planetary ephemeris parameters for Mercury were added to the OD206 solution that the situation improved. Even then, the radiation parameters had to be closely monitored from iteration to iteration, because once a negative parameter was fed back into the filter the process quickly diverged. Subsequent reconstruction of the spacecraft trajectory, using all available track data for the first Mercury sidereal day (approximately 57 Earth days) of the orbital phase, yielded an improved 20×20 planetary gravity model. This model replaced the initial *a priori* set, generated prior to MOI from reconstructed trajectories for MESSENGER's three Mercury flybys combined with the available Mariner 10 gravity estimates. The PRP infrared model was also refined, and the combination of these enhancements improved the situation markedly. These latter two tasks were accomplished over the course of the first two months in Mercury orbit.

The improvements gained through estimating the planetary ephemeris are evident in the bottom half residuals of Figure 5. As may be seen, the residual scale on the dependent axis is about an order of magnitude better for SRA and about three times as good for F2/F3 for the same starting point, some fourteen hours before the MOI. An extra day of tracking data undoubtedly helped the solution for OD205 converge more smoothly as well, but the inclusion of the planetary ephemeris estimate in the OD filter was of critical import. Despite the initial struggles of the navigation team in driving the track data residuals to more precise results, no adverse impact to the SOC schedule was experienced. Figure 6 displays, in graphical form, the ephemeris update delivery sequence for the weekly OD deliveries leading up to the first OCM (OCM-1).[12]

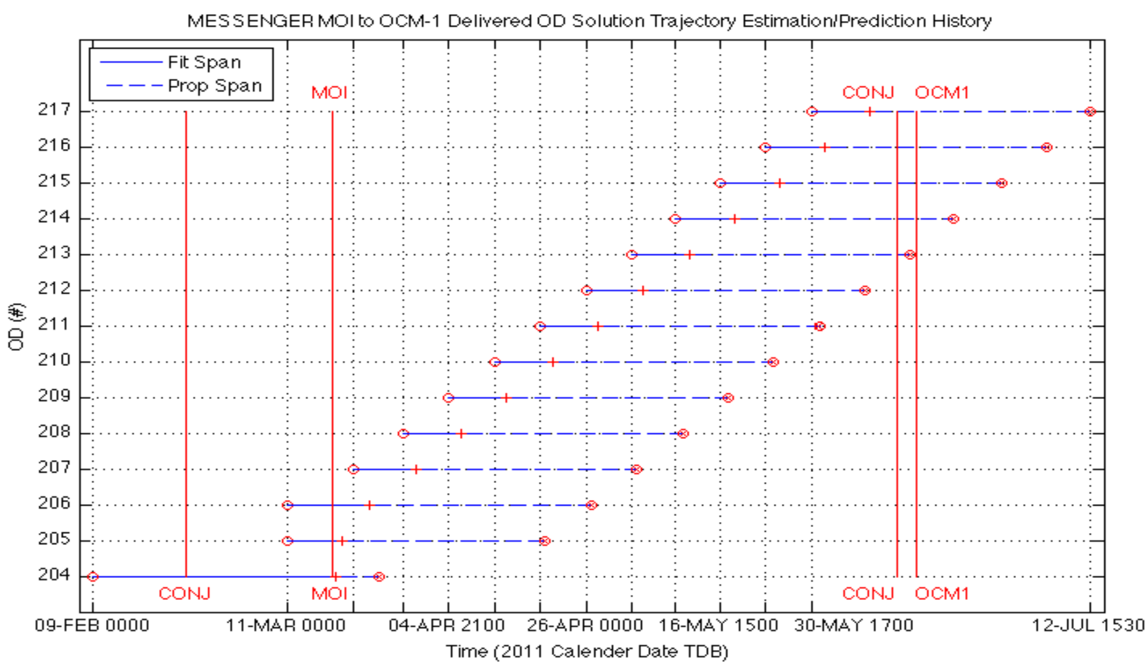

Figure 6. MESSENGER Ephemeris Updates Prior to OCM-1.

This series of deliveries ran sequentially from OD204 through OD217, and the numbering has continued to be sequential throughout the MESSENGER Mercury orbital phase. Figure 6 shows the fit spans in solid blue, the prediction spans in dashed blue, and important mission events as red vertical lines spanning the delivery sequence. These events include MOI and OCM-1, as well as two superior solar conjunctions (CONJ), the first in the month preceding MOI and the second with a minimum separation angle of less than 1° occurring just three days before the OCM. The semi-regular momentum dumps, used to prevent saturation of the four attitude control reaction wheels onboard the spacecraft, are not shown on this timeline, but there have been over 75 executed on-orbit so far, and 13 of them occurred during the interval of this plot.

OCM-1 was executed on June 15, 2011, at 19:40:55.18 TDB, approximately one Mercury year after MOI as designed, and was successful in lowering the MESSENGER orbit periapsis altitude back down to 200 km. The real-time critical mission event plot for OCM-1 is displayed in Figure 7 and shows the predicted envelope of radiometric Doppler tracking data residuals for a propulsive periapsis-lowering orbit-correction maneuver. The OCMs were generated by the JHU/APL mission design team and verified by the KinetX SNAFD navigation team, the converse of how things were generally done during most of the interplanetary cruise phase. There were six OCMs planned for the orbital phase of the nominal primary mission, and they were originally scheduled to execute in pairs, just over a day apart, once every Mercury year. However, that plan was modified prior to arrival at Mercury to allow a six-week interval between paired burns, or approximately one-half a Mercury sidereal year. A Mercury year is just under 88 Earth days long, and because of Mercury's well known 3:2 spin-orbit resonance, one Mercury solar day is two Mercury years long, which means that Mercury rotates fully around its axis three times every two times it orbits the Sun. An analogous resonance scheme had also been a driver in the mission design of the Mercury flybys and their associated DSMs during cruise, such that DSMs 3–5 generated heliocentric orbit resonances between the spacecraft and Mercury of 6:5, 4:3, and 3:2, respectively.[13] OCM-2 was subsequently executed on July 26, 2011, at 21:05:06.18 TDB, and served to reset the orbital period of the spacecraft about Mercury to 12 hours.

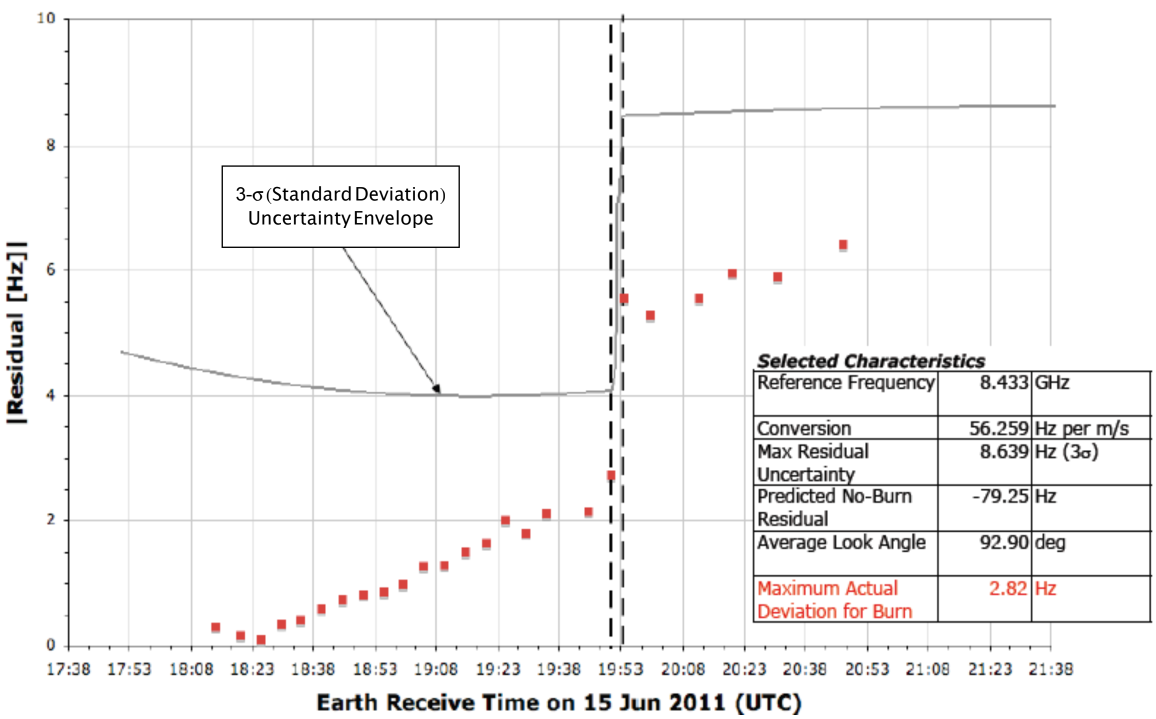

Figure 7. MESSENGER Predicted and Actual Doppler Residuals for OCM-1.

The navigation operations delivery timeline for the orbital phase of the entire mission is shown in Figure 8. Only every fifth OD delivery is displayed on the dependent axis for clarity, and others can be inferred from what is shown. As before, the OCMs and MOI are marked off on the plot as critical mission events, along with the end of the nominal mission (EONM) and the currently projected end of the extended mission (EOEM); conjunctions have been omitted. Aside from the OCMs, there are regularly scheduled momentum dumps not shown on this graph. They typically generate residual changes in velocity on the order of several mm/s. However, it is important to model them for dynamic completeness. The data available around these momentum dumps, which are typically around a minute in duration, are generally deleted so as not to disrupt filter processing. This step requires incorporating the one-way light time delay into the spacecraft referenced start and stop times of the dump to account for the offset with the Earth ground receive time of the track data. The superior solar conjunction periods are usually devoid of useful tracking data when the Sun-Earth-probe (SEP) angle is less than 3°, the MOC threshold for defining superior conjunctions, and track data delivered during this interval are down-weighted to compensate for any potential problematic interactions between the radiometric signals and the solar plasma. A decrease in relative radiometric data weights is prescribed whenever the magnitude of the SEP angle is less than 10°. This decrease is accomplished in graduated intervals such that data weights are minimized below the 3° SEP angle threshold, as was done during the interplanetary cruise phase.

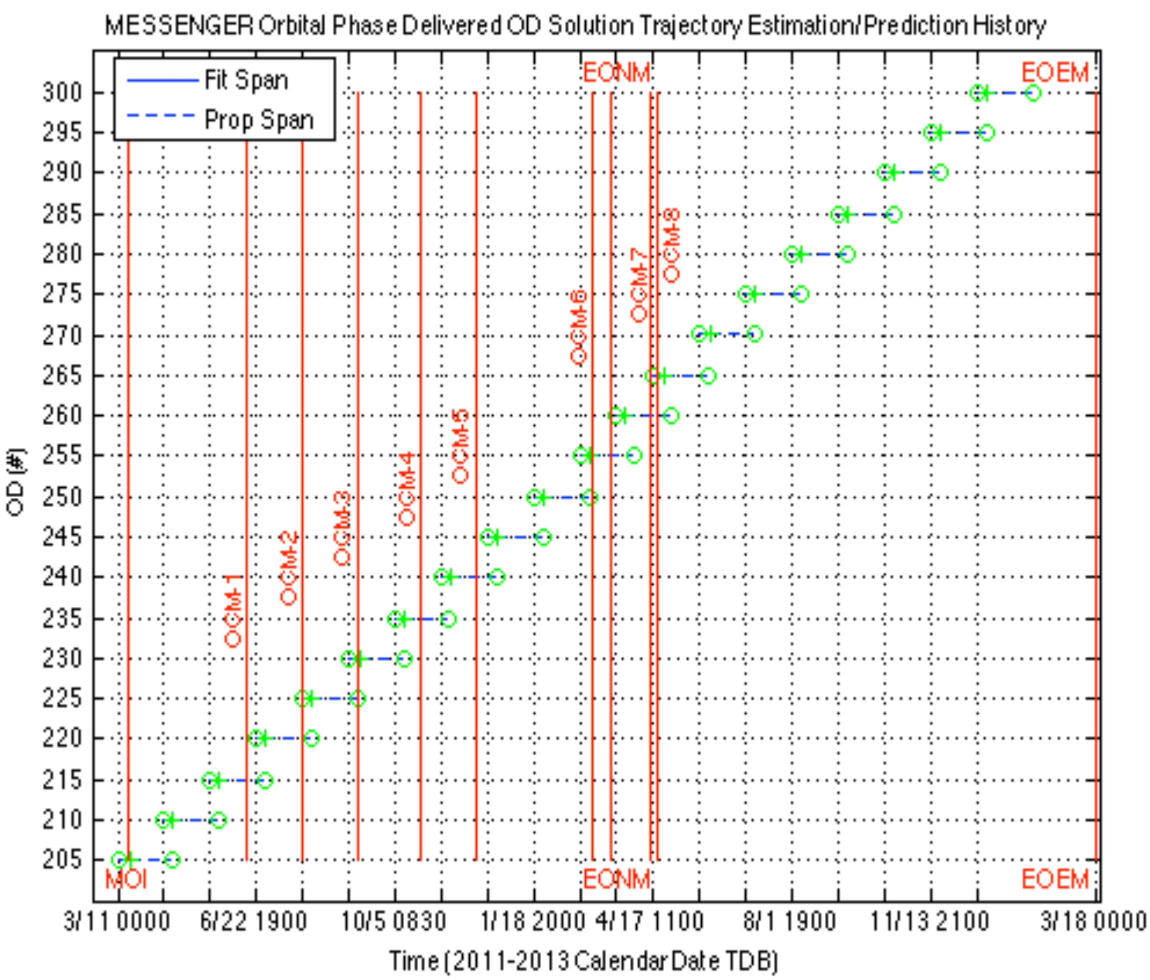

Figure 8. MESSENGER Ephemeris Updates during the Orbital Mission Phase.

The refinement of the initial Mercury gravitational field model for navigation operations was accomplished through reconstruction of the on-orbit spacecraft trajectory. The graphic location of the spacecraft nadir point on the surface of Mercury is a useful visual element for this analysis. Figure 9 shows a mapping of the radiometric data collection to a latitude-longitude grid of Mercury for a week of spacecraft time (SCT) very early in the primary mission orbital phase. The altitudes at which these data were acquired are color coded onto the map, as defined by the color bar to the right of the plot, along with the relative positions of both the Sun and Earth at the beginning and end of the data span. These are all important variables when considering the effect of gravitational perturbations. The early gravity solutions for Mercury were critical inputs to the OD filter for navigation operations and the ease of convergence was greatly facilitated by the initial on-orbit determination of the gravitational harmonic model.

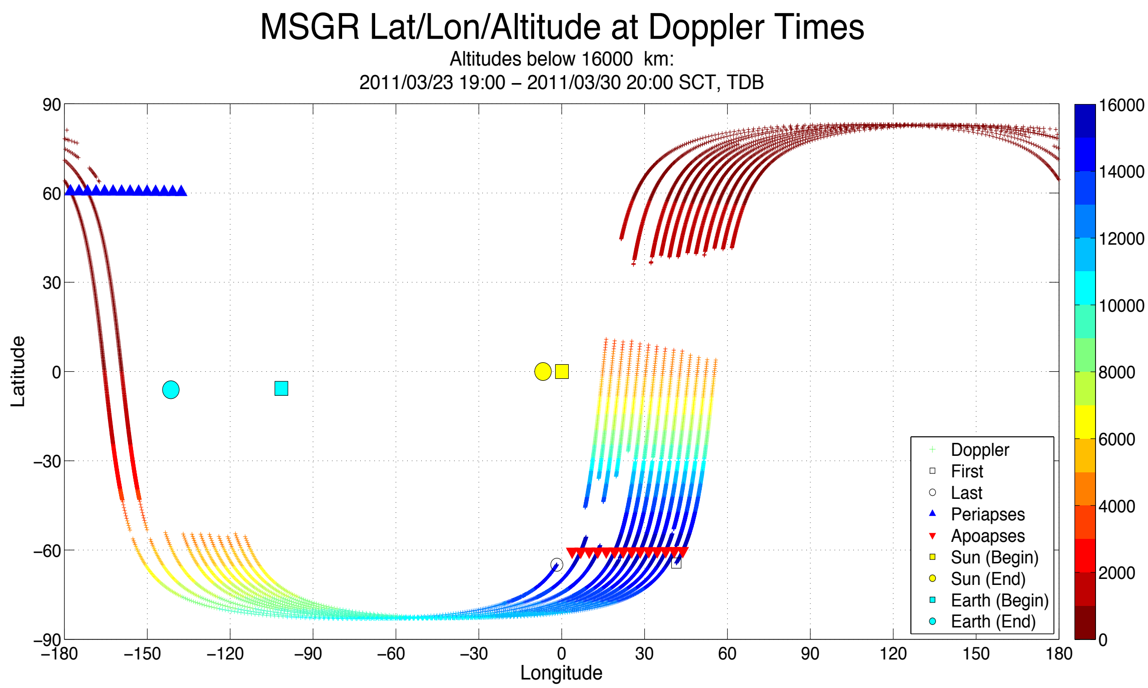

Figure 9. Acquisition of Radiometric Data by Track.

Once the infrared model was refined and the second generation MESSENGER gravity field for Mercury was produced, the OD filter runs converged much easier. Other improvements in data processing that took place during the orbital mission phase included the incorporation of the MOC precise ephemeris time-tag biases for science operations into the antenna motion correction model and sundry other incremental improvements to the modeling of solar array panel attitude. Although the PRP models could potentially be further refined by generating spherical harmonics derived from orbital phase scientific measurements, such a step has not been deemed necessary to date. It is rare to see the radiation pressure scale factors wander outside of their physical limits after these refinements were implemented, and thus the large *a priori* uncertainties for these parameters can be maintained as they were initially constructed to provide filter flexibility in generating converged OD solutions.

Occasionally there is some difficulty with observability for the radiation pressure parameters in the OD filter, depending on the orientation of the spacecraft orbit with respect to the Mercury terminator, during hot or warm pole crossings or in eclipse seasons. Such geometries can lead to aliasing between estimation parameters. The orientation of the orbit plane to the Earth LOS vector also determines the information content of the tracking data. Obviously when the orbit plane is nearly perpendicular to the LOS there is minimum variability in the F2/F3 and SRA data, and thus the overall information content is degraded. However, this type of situation does not persist for very long, since Mercury orbits the Sun approximately four times every Earth year. As mentioned previously, the MESSENGER orbit plane about Mercury is relatively fixed in inertial space as it co-orbits the Sun with Mercury. It is easiest to separate the signatures of the various radiation pressure parameters during Mercury dark side passages, when the albedo force is zero and infrared perturbations are markedly reduced, and by definition during eclipses when both SRP and albedo accelerations are absent.

Table 2. MESSENGER OD Filter Data Weights and Estimation Parameters.

MESSENGER Mercury Orbital Phase Estimation Controls		
Data Weights		
Phase/Parameter	On-Orbit Nominal	Superior Solar Conjunction
F2/F3 Doppler (mm/s)	0.50	0.70-12
SRA Range (m)	50-75	100-1000

Filter Variables		
Description/Parameter		Model Details
Solved For	Spacecraft Position	Mercury-centered inertial Cartesian components
	Spacecraft Velocity	Mercury-centered inertial Cartesian components
	Radiation Pressure	SRP/PRP specular and diffuse reflectivity coefficients and PRP overall scale factors
	Mercury Gravity	20x20 spherical harmonic coefficients
	Mercury Ephemeris	Solar system barycentric inertial corrections to DE423
	Maneuvers	OCM/MOI component thrust magnitudes/directions, momentum dump delta-velocity components
Considered	Earth Ephemeris	Solar system barycentric inertial corrections to DE423
	Earth Polar Motion	Surface position components and UT1 corrections
	Station Locations	Earth-fixed position component corrections
	Atmospheric Media	Aberration corrections for Earth wet/dry troposphere and day/night ionosphere

The filter data weights along with the solved and considered estimation parameters for the Mercury orbital phase are summarized in Table 2. Outside of superior solar conjunction periods, the radiometric data are weighted consistently, F2/F3 at 0.5 mm/s and SRA at 50 m, although this latter figure was 75 m prior to December 2011 and was tightened after an analysis of the empirical range efficacy. DDOR, which was important in obtaining high-precision OD solutions around critical mission events during the mission cruise phase, has not been used on-orbit, as previous covariance analyses have shown it to be of limited added value during the orbital phase. F2 and F3 are weighted the same, and F2 is by far the dominant data type used in the OD solutions. The track data residuals generated by the estimation filter vary randomly during the best fits in their converged offsets from the expected values but are generally on the order of tenths of a mm/s for F2/F3 and up to around ±10 m for the SRA, much better than in the immediate aftermath of MOI, as discussed above.

The SRP acceleration on the spacecraft is a function of Mercury's heliocentric true anomaly, whereas the PRP accelerations are dependent on the relative positions of the Mercury terminator and the spacecraft orbit plane. Planetary ephemeris corrections are also dependent on the location of Mercury with respect to the Sun. The gravitational acceleration is obviously a function of spacecraft altitude, with higher-order harmonics more easily observable at closest approaches, and is the most easily separable of the solved-for force parameters. The operational gravity model has been through several refinements for navigation purposes so far and is in good agreement with results from the MESSENGER radio science team.[19]

EXTENDED MISSION PHASE

After one Earth year of scientific observations from orbit the MESSENGER primary mission came to an end on March 18, 2012. Since the spacecraft still had sufficient reserve propellant to continue for some time and all the onboard science instrumentation and imaging equipment was functional, a one-year extension to the mission was approved by NASA. In order to further optimize the scope and extent of the science return from the spacecraft and the stability of its orbit about Mercury, it was decided to transfer from a 12 h to an 8 h period at the beginning of the extended orbital phase mission. This change was deemed to yield the best value for the cost of most of the remaining propellant, leaving enough to execute regular momentum dumps and boost the spacecraft back up in altitude before it approaches what would be Mercury impact in August 2014 in the absence of future maneuvers. The solar gravitational perturbations will eventually drive MESSENGER into the planet, but more than 9 months into the one-year extension the mission and navigation operations are proceeding nominally.

The OCM-7/8 pair was designed to reset the MESSENGER spacecraft period about Mercury to 8 h by producing a lowered apoapsis consistent with that period, while keeping the periapsis altitude where it was. This change was planned as the key navigational difference in the extended mission orbit relative to that of the completed primary mission phase. Figure 10 shows the timeline of events from MOI to the projected end of the extended mission, with the eight OCMs specified notionally.

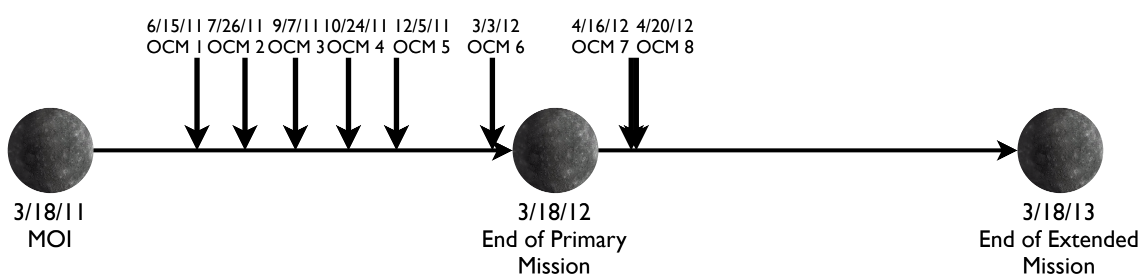

Figure 10. Timeline for the MESSENGER Primary and Extended Mission Phases.

Table 3. OCM Reconstruction Results.

MESSENGER OCM History						
Event/Parameter	Periapsis Altitude Correction (km)			Orbital Period Correction (h)		
	Target	Result	Difference	Target	Result	Difference
OCM-1 06/15/2011 19:40:55.184 TDB	200.000	200.414	0.414			
OCM-2 07/26/2011 21:05:06.184 TDB				12.000	12.000	0.000
OCM-3 09/07/2011 15:09:28.184 TDB	200.000	200.069	0.069			
OCM-4 10/24/2011 22:12:51.184 TDB				12.000	11.999	-0.001
OCM-5 12/05/2011 16:06:34.184 TDB	200.000	200.086	0.086			
OCM-6 03/03/2012 01:45:01.184 TDB	200.000	199.601	-0.399			
OCM-7 04/16/2012 19:14:12.881 TDB				9.083	9.079	-0.004
OCM-8 04/20/2012 23:06:41.093 TDB				8.000	8.001	0.001

The history of the OCMs executed to date is contained in Table 3, which compares targeted design values to estimated post-maneuver reconstruction results. The OCMs are modeled for navigation operations purposes in the same manner as propulsive events were during the mission cruise phase. The input parameters for maneuver generation are provided to the navigation team by the MESSENGER mission design team, and an optimal OCM is produced using independent software and used to verify the mission design result. The maneuver design is used in a trajectory prediction derived from the most recent OD solution to verify the desired orbit correction, and a final version of the OCM is generated and modeled through maneuver execution. After maneuver execution, the maneuver solution is reconstructed in the OD filter and the results are passed back to mission design and the MOC in the form of a maneuver reconstruction report and an ephemeris update that includes the reconstructed burn.

As can be seen from the table, OCMs were either targeted to lower periapsis, when they were designed to burn near apoapsis, or to reduce the orbit period through maneuvers around periapsis. The first five OCMs were spaced at approximately equal intervals, half a Mercury year apart, with alternating purposes: periapsis lowering followed by period correction. This pattern was broken for the last three OCMs of the sequence because of extended mission planning. OCM-6 execution was delayed until near the end of the nominal orbit phase so that it could be coupled to the OCM-7/8 pair approximately 6 weeks later to reset the close approach altitude to 200 km and reduce the orbital period to 8 h for the extended mission, while carefully conserving the remaining propellant. All were successful, nominal burns executed as designed.

The weekly spacecraft ephemeris updates provided to the MOC for mission and science operations were consistent in their fit span duration from the second week after MOI through most of the extended orbital phase completed to date. However, recent analysis has motivated a change from a 9- to a 7-day fit with no overlap in the track data between OD deliveries. This process change is still undergoing refinement, but several extended mission ephemeris updates have been delivered with the 7-day fit span, and no degradation in orbit reconstruction nor prediction accuracy has been identified. Besides eliminating the overlap of tracking data in consecutive ODs, this process also reduces the potential for parameter biasing effects and seems to decrease the occurrence of pathological filter behavior in the form of physically unrealistic scale factor estimates in particular. The approximately four-week prediction span, which is propagated out from the end of the resultant fit span, is required for science planning, and thus accuracy is paramount. Prediction accuracy is, of course, predicated on the accuracy of the OD and the process of modeling acceleration perturbations.

Throughout the Mercury orbital phase, ephemeris time-tag biases have been generated for the MOC from offsets between previous predictions and current reconstructions of the orbit. The most significant uncertainties in the propagation span are due to the unknown nature of unbalanced thrusting from future momentum dumps, which are not modeled in the predictions even though they tend to occur on a weekly basis, but are commanded only when the need for reaction wheel momentum desaturation warrants. While these perturbations are typically only on the order of a mm/s, the unmodeled accelerations are a major factor in trajectory differences from one weekly ephemeris delivery to the next. Time-tag biases are generated by comparing ephemerides propagated using current versus recently past OD solutions and are uploaded to the spacecraft by the MOC to facilitate more accurate instrument pointing. The four immediately prior ephemeris updates are processed and compared with the current delivery to produce a table of periapsis time offsets whose trends dictate an appropriate bias to use as a difference applied to the onboard precise ephemeris in the current command load. Figure 11 shows an example of the effect of incorporating such a time time-tag bias to remove predominantly in-track errors from a trajectory estimate that is several weeks old. This serves to smooth the prediction dispersions and facilitates ease of use for planning instrument pointing during periapsis passages. The plot in the top half of Figure 11 shows an ephemeris comparison without the time offset correction between trajectories, and the bottom plot reveals the significant improvements to be gained by incorporating the time-tag bias. The in-track deviations for this example are decreased by several orders of magnitude, which demonstrates why this practice has been used operationally throughout the MESSENGER Mercury orbital phase to update spacecraft command load ephemeris time-tags through the application of a separate time bias upload. Recent preliminary comparisons between independent optical navigation on-orbit trajectory reconstructions generated by the imaging team and the time-tag biased ephemeris updates provided by navigation operations have verified that this process reduces average prediction errors at periapsis to about 50 m down-track, which is the largest component of spacecraft position error.

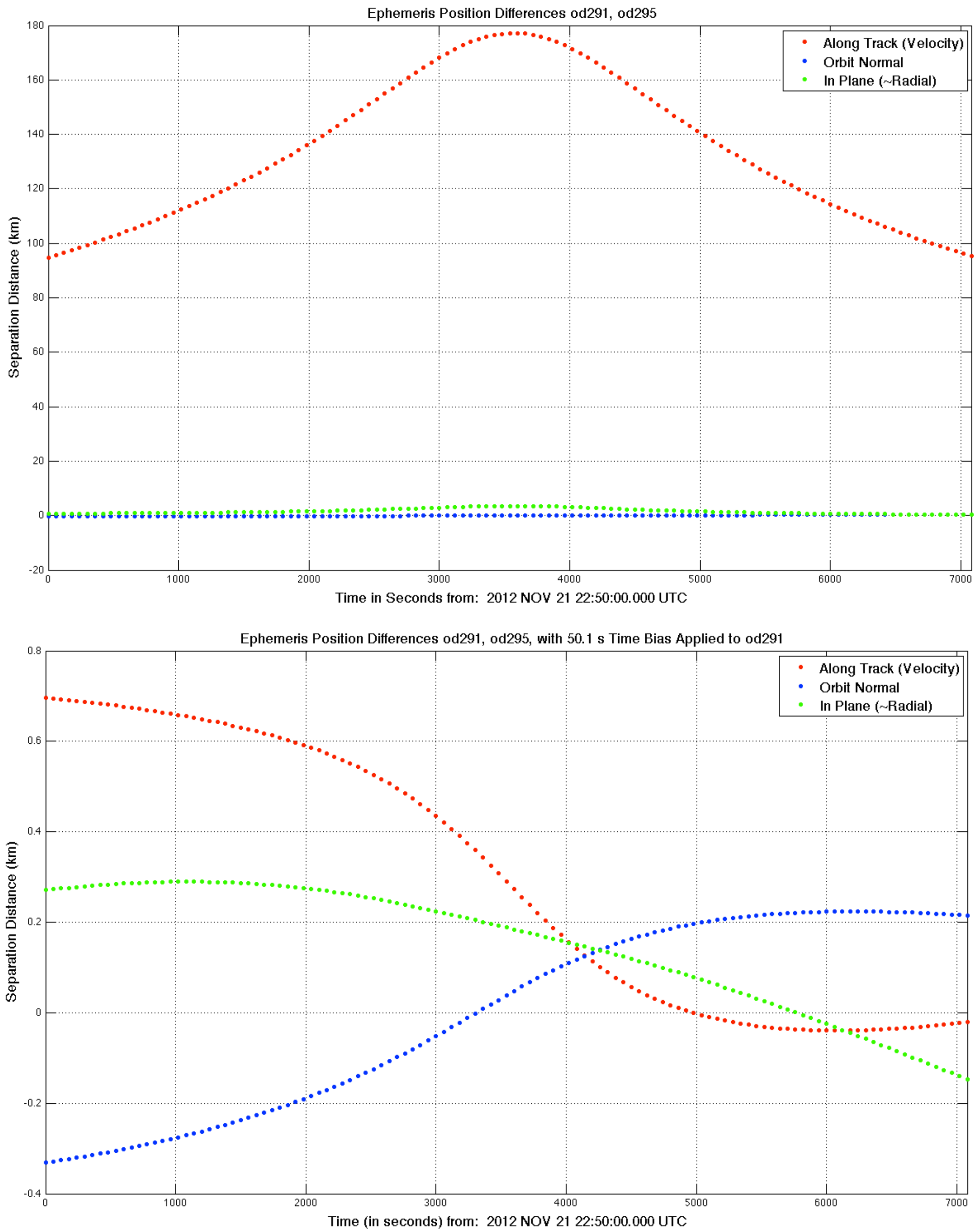

Figure 11. Ephemeris Comparison before and after Operational Time-Tag Bias (Upper/Lower).

The F2/F3 and SRA residuals for a recent operational OD solution generated using both 9- and 7-day fit spans are displayed in Figure 12 on the upper and lower panels, respectively. No major discrepancies between these two methods are evident in the output, although when the overlapping track data deleted from the 7-day fit are included in the residual display, as in the middle panel of Figure 12, a small bias is clearly evident in the excised data.

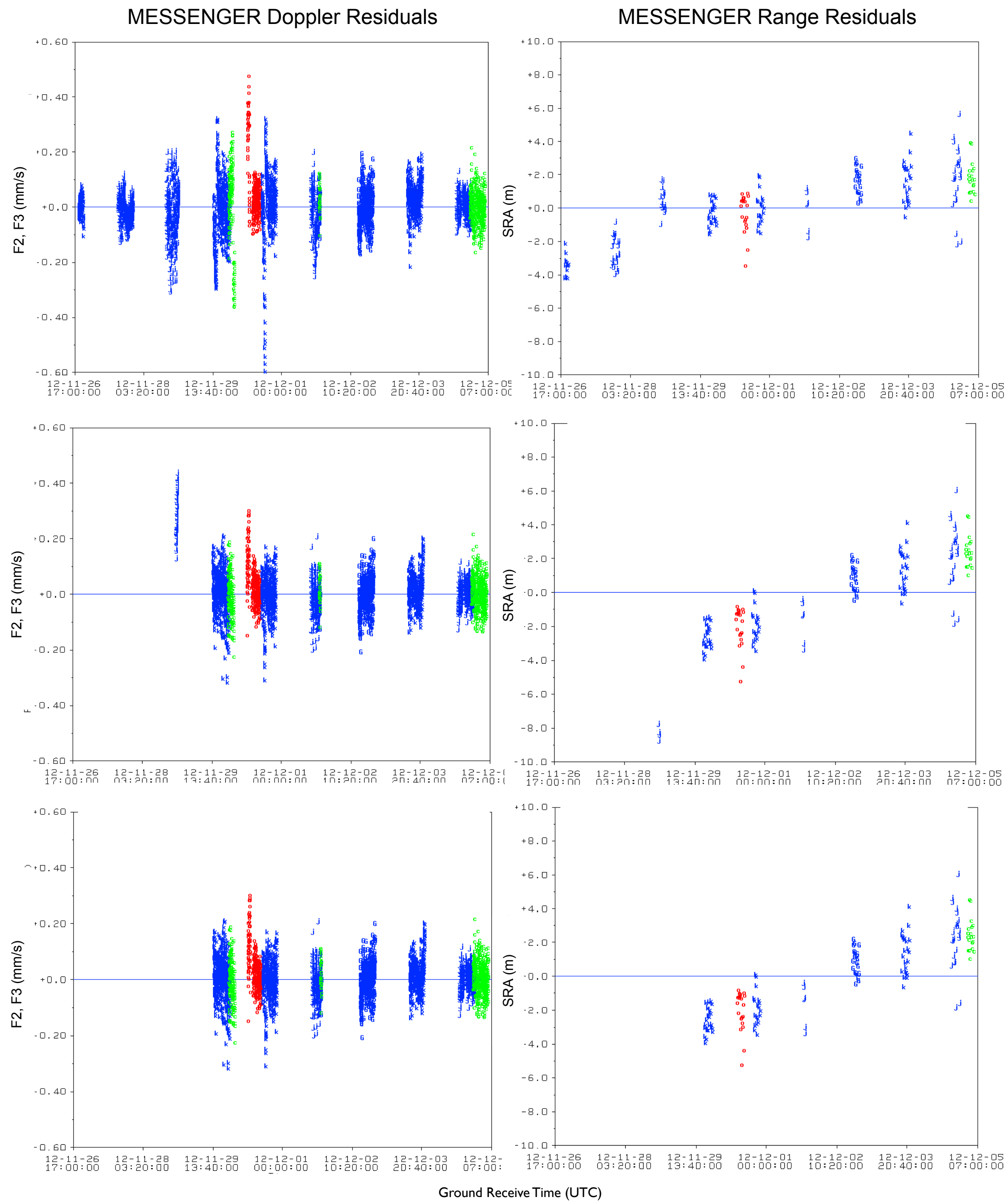

Figure 12. OD297 Residuals for a 9/7/7 Fit Span (Upper/Middle/Lower).

This bias represents a modeling limitation for longer data arc lengths between consecutive solutions, and inclusion of the additional data tends to alias the estimation parameters and resultant spacecraft ephemeris. However, the effect of this biasing is sufficiently small that it does not cause any undue problems for operations, especially with the incorporation of ephemeris time-tag biases in the propagation span. The navigation team has continued to implement improvements in processing and modeling techniques throughout the mission that have resulted in more accurate trajectory predictions.

It has also been noted that the time-tag biases generated from the most recent series of OD solutions and uploaded to the spacecraft for incorporation into the onboard precise ephemeris, reveal a variation with distinct periodicity. This periodic effect seems to be correlated to the true anomaly of the heliocentric orbit of Mercury, with maximum time-bias values occurring near perihelion. The effect was first noted by MESSENGER's Mission Operations Manager, Andrew Calloway, and analysis of this apparent periodic correlation is still in progress. Several other ongoing navigation operations analyses could lead to further refinements of the PRP models, both for albedo and infrared re-radiation, as well as the Mercury gravitational field. The point of diminishing marginal returns for modeling enhancements, however, was arguably reached near the beginning of the primary mission nominal orbit phase. However, this status has not precluded the continual pursuit of process improvements. Mercury gravity field estimation and reconstruction has been an ongoing task of the navigation operations team, and the track data will continue to be analyzed beyond the end of the extended mission to produce a final optimal reconstruction of this and other OD parameters, including the planetary ephemeris. The post-mission reconstructed trajectory should yield a wealth of information about not only Mercury itself but the orbital environment of the closest planet to the Sun, revealing much about the inner solar gravity well and the variables influencing orbits about Mercury for both future deep-space missions and scientific understanding of this particular neighborhood of the solar system. As of this writing, it is not known when MESSENGER mission operations will be completed, although the current extended mission is planned to end on the second anniversary of MOI. However, the manner in which the spacecraft will ultimately meet its final demise is well determined: eventually it will impact the surface of Mercury. This event is not predicted to happen until August 2014 or later, and since it may be quite some time before a NASA spacecraft returns to Mercury orbit again, it would be wise to maximize the return on the investment that has already been made by acquiring as much data as possible while MESSENGER is still functioning and operational.

SUMMARY

Navigation operations in Mercury orbit have been successful by all measures. The MESSENGER spacecraft has not suffered any major operational mission anomalies on-orbit, and the science return, which is enabled by products from the navigation team, has been spectacular and historic. Although operational schedules were hectic immediately after MOI, they never prevented a smooth transition in navigation deliveries from interplanetary cruise to orbit about Mercury. The MESSENGER navigation team ephemeris estimates and deliveries consistently exceeded all requirements for both the MOC and SOC, and allowed them to point and control the scientific instruments to the limits of their capabilities. Continual improvements to the navigation process assures that science collection can and will continue throughout the MESSENGER orbital mission at Mercury.

MOI was very successful, with the initial post-maneuver orbit parameters well within mission design specifications. Ephemeris deliveries on-orbit were initially challenging, but this difficulty was transparent to the rest of the MESSENGER mission team as operational testing, check out, and evaluation proceeded smoothly. A parallel process to reconstruct the Mercury gravity field coefficients by the KinetX SNAFD navigation team quickly produced an effective 20×20 spherical harmonic model, sufficiently accurate for navigation purposes, that has been used throughout both the primary and extended orbital mission by navigation operations. Modeling issues with the infrared radiation accelerations and spacecraft antenna motion corrections shortly after orbit insertion were quickly resolved, though there still remains room for improvements.

The spacecraft antenna motion model was further enhanced by the incorporation of the uploaded ephemeris time-tag biases into the sequences designed and uploaded by the MOC. Estimation of the Mercury planetary ephemeris was essential to tuning the OD filter in the early days after MOI, and it continues to be used to avoid aliasing of other estimated parameters.

The eight OCMs, six during the primary mission and another two so far during the extended mission, have all been designed and executed with no anomalies. All external challenges to navigation operations during the primary mission – superior solar conjunctions, Mercury hot pole and eclipse seasons, and an active Sun – have been met successfully. Although future navigation challenges still remain, such as propulsive maneuvering with nearly depleted propellant tanks and the potential for navigating about Mercury at extremely low altitudes, the process refinements and innovations implemented by the navigation team thus far during Mercury orbital operations will continue to be utilized and further enhanced to successfully support the project. The KinetX SNAFD navigation team has been privileged to support the MESSENGER mission.

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