

## FIRE SAIL: MESSENGER'S USE OF SOLAR RADIATION PRESSURE FOR ACCURATE MERCURY FLYBYS

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MESSENGER (MErcury Surface, Space ENvironment, GEOchemistry, and Ranging) has successfully completed its first four years of flight operations following launch on 3 August 2004. As part of NASA's Discovery Program, MESSENGER has executed the first two of three Mercury flybys, leading to an eventual orbit about Mercury in March 2011. Accuracy at these Mercury flybys is critical, as the flybys provide a significant portion of the  $\Delta V$  required for the mission. Due to MESSENGER's proximity to the Sun, solar radiation pressure is the dominant perturbation on the spacecraft. With intelligent planning and management of the spacecraft attitude and solar array articulations, the solar radiation pressure can be used to improve the accuracy of these flybys. MESSENGER uses this disturbance to help control the growth of spacecraft angular momentum, minimizing the perturbations due to thruster momentum off-loads. The force due to solar radiation pressure is also used directly as a precision trajectory control for the Mercury flybys. This method reduced the amount of propellant required to navigate the first and second Mercury flybys.

### INTRODUCTION

On 14 January 2008 MESSENGER (MErcury Surface, Space ENvironment, GEOchemistry, and Ranging) became the first spacecraft to fly by the planet Mercury since the third Mariner 10 flyby in March 1975. Designed and operated by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in Laurel, Maryland, MESSENGER is led by the Carnegie Institution of Washington with key flight and science operation contributions from KinetX, Inc., NASA's Jet Propulsion Laboratory (JPL), Goddard Space Flight Center, and numerous universities, research institutions, and subcontractors. MESSENGER completed a second Mercury flyby on 6 October 2008, and the spacecraft will make a final flyby on 29 September 2009 prior to orbiting Mercury for one Earth year beginning in March 2011. Precision at these flybys is critical, as without the velocity change ( $\Delta V$ ) provided by each gravity assist, MESSENGER would be unable to capture into the required orbit. The Mercury flybys are nominally at 200 km altitude, and a low flyby could result in impact. Less spectacular, but equally damaging to the mission, if the flyby is too distant from the planned aim point at closest approach, MESSENGER could be forced to use its reserve propellant. Depending upon the flyby targeting error, limited propellant reserves might

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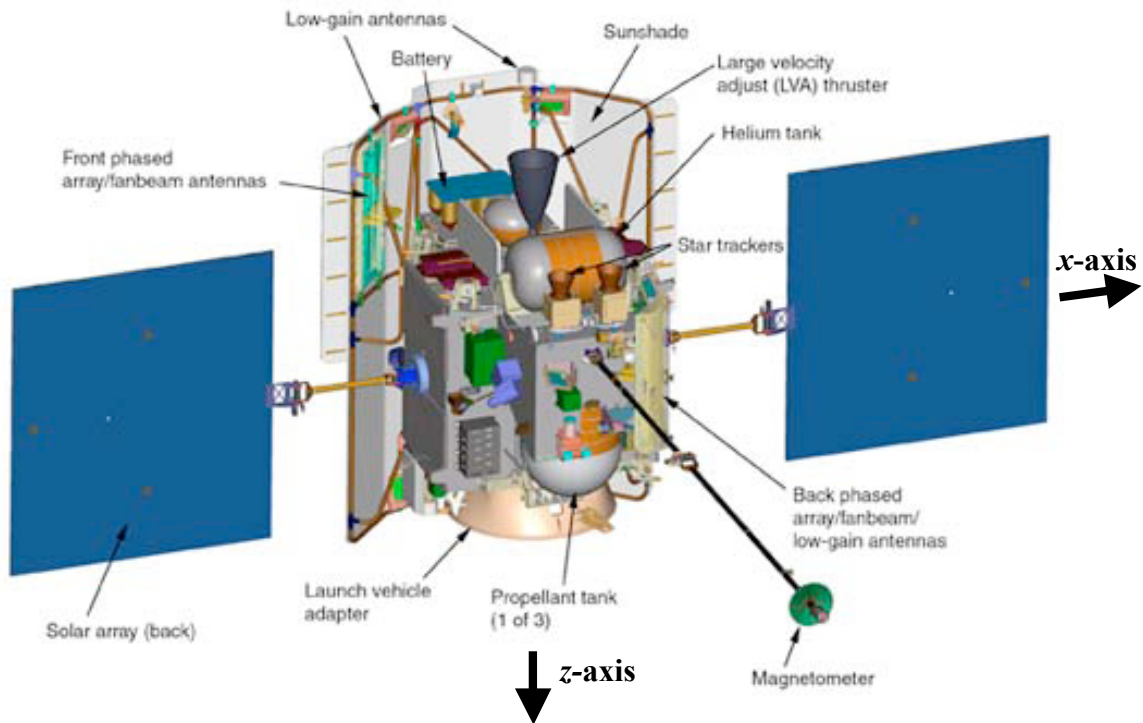
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not allow MESSENGER to continue on its nominal trajectory. Significant errors might preclude Mercury orbit insertion or might require modifications to the trajectory that are undesirable due to complexity or extended mission duration. Further, the Mercury flybys will assist in developing the science data collection process for the year-long orbital portion of the mission, as well as provide unique opportunities for observations not possible while in the Mercury science orbit.<sup>1</sup>

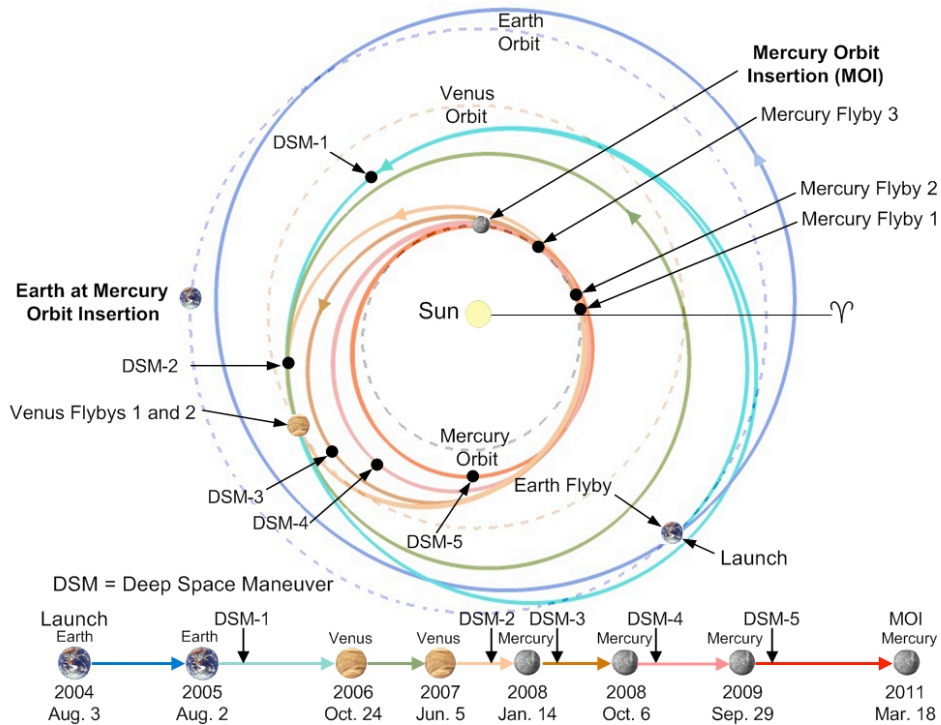
The thermal and radiation environment at Mercury drives the spacecraft design. A large sunshade is used to protect most of the spacecraft systems from the heat and radiation of the Sun as shown in Figure 1.<sup>2,3</sup> The shade must be kept between the Sun and the main body of the spacecraft whenever MESSENGER is within 0.85 AU of the Sun. The design of the sunshade allows for deviations of  $\pm 10^\circ$  from direct Sun pointing in rotations around the spacecraft  $z$ -axis, and  $\pm 12^\circ$  in rotations around the  $x$ -axis. This Sun keep-in (SKI) zone is a significant constraint on the attitude, which in turn affects the science observation opportunities, maneuver design, and momentum accrual due to solar radiation pressure (SRP). MESSENGER carries four reaction wheels for primary attitude control; this makes momentum management an essential task, as reaction wheel saturation can lead to a loss of attitude control. To off-load stored momentum and execute  $\Delta V$ s, MESSENGER has a dual-mode propulsion system with 17 thrusters.



**Figure 1. MESSENGER Spacecraft Components**

During the interplanetary cruise phase of the mission, the primary goals of the guidance and control system are to maintain the mission safety constraints (most importantly the SKI constraint) and to keep the mission on the correct trajectory. It is also important to satisfy the necessary pointing requirements for spacecraft science and engineering activities, but these activities are of limited duration and scope during cruise. To execute the MESSENGER trajectory shown in Figure 2, the guidance and control system must periodically use the propulsion system to execute planned  $\Delta V$  maneuvers called Trajectory Correction Maneuvers (TCMs) and Deep

Space Maneuvers (DSMs). DSMs are large (>50 m/s) deterministic burns that allow targeting of the next trajectory waypoint, e.g., a planetary flyby or the Mercury Orbit Insertion (MOI) maneuver. The TCMs are generally much smaller maneuvers (<5 m/s) employed as corrections to the trajectory; these burns are typically used to clean up errors in the execution of DSMs and to ensure precision trajectory adjustments at the planetary flybys. Each of the planetary flybys provides a critical adjustment to the trajectory; with significant errors at any one of these flybys, MESSENGER would be unable to achieve the required orbit at Mercury.



**Figure 2. MESSENGER Trajectory – Launch through Mercury Orbit Insertion**

**Table 1.  $\Delta V$  Imparted for Each Critical Trajectory Event**

| Flyby                        | $\Delta V$ (m/s) | Maneuver          | $\Delta V$ (m/s) |
|------------------------------|------------------|-------------------|------------------|
| Earth Flyby (Aug. 2005)      | 5966.3           | DSM-1 (Dec. 2005) | 315.7            |
| Venus Flyby 1 (Oct. 2006)    | 5522.5           | DSM-2 (Oct. 2007) | 226.0            |
| Venus Flyby 2 (June 2007)    | 6937.8           | DSM-3 (Mar. 2008) | 72.3             |
| Mercury Flyby 1 (Jan. 2008)  | 2304.0           | DSM-4 (Dec. 2008) | 246.9            |
| Mercury Flyby 2 (Oct. 2008)  | 2452.2           | DSM-5 (Nov. 2009) | 177.6            |
| Mercury Flyby 3 (Sept. 2009) | 2853.5           | MOI (March 2011)  | 859.4            |

The vast majority of MESSENGER’s  $\Delta V$  comes from the gravity assists at the planetary flybys and not the propulsion system. Table 1 shows the total  $\Delta V$  provided by each gravity assist and the  $\Delta V$  for each of the DSMs. This table highlights the criticality of the flybys to a successful mission, as the  $\Delta V$  attained at each flyby exceeds the total deterministic maneuver budget for the entire mission. Further, accuracy at the flybys is paramount, as significant errors in the flyby targeting can easily exceed the mission reserve  $\Delta V$  capability.

## EARLY MESSENGER PLANETARY FLYBYS (THE OLD APPROACH)

For MESSENGER, a typical planetary gravity assist begins with a deterministic trajectory change many months prior to the planetary flyby via a DSM, as shown in Figure 2. (To make the following approach more general, this deterministic trajectory change is not limited to a maneuver, but could be the result of launch or a prior gravity assist.) This DSM is implemented such that the MESSENGER trajectory will achieve the desired flyby location at some future time. Although these DSMs are very accurate ( $< 0.2^\circ$  direction error and  $< 0.1\%$  magnitude error), maneuver execution errors translate into errors at the flyby location (or time). Prior to the Mercury flybys, MESSENGER used a sequence of TCMs to clean up the errors in the DSM execution, as well as remove navigation errors in the trajectory. These navigation errors arise from unmodeled or poorly modeled disturbance forces and orbit determination errors, the largest of which is the uncertainty and variation in the SRP. These clean-up TCMs, referred to as approach maneuvers, are used to achieve the necessary precision targeting at the planetary encounter. Approach maneuvers are subject to their own execution errors, thereby forcing MESSENGER to use multiple approach maneuvers to reduce the flyby targeting error to a tolerable level. Each mission has different tolerances for flyby errors, which generally depend on the amount of reserve propellant and the sensitivity to targeting at the gravity assist. Because MESSENGER carries very limited reserve propellant, and preservation of propellant is desirable to enable a possible extended mission, accuracy at the flybys is paramount. Once an acceptable error has been achieved via the sequence of approach maneuvers, the spacecraft stops adjusting the trajectory and coasts past the planet. The remaining small error in the inbound trajectory causes corresponding errors in the gravity assist. This error in the trajectory must be cleaned up after the flyby with another propulsive maneuver, termed a departure maneuver. This standard flyby approach requires the complication and risk of executing several propulsive burns in rapid succession (usually within weeks of one another). Further, each of the approach and departure burns consumes propellant.

The following set of steps summarize the standard flyby approach.

1. Execute a DSM several months prior to flyby.
2. Execute a DSM clean-up maneuver  $\sim 30$  days after the DSM. At this point, the trajectory is usually close enough to the flyby aim point that there is no immediate need for a correction, although flyby uncertainties are large.
3. After several months of flight, errors have accumulated due to unmodeled (or poorly modeled) disturbances and orbit determination errors. Execute an approach maneuver (or a series of approach maneuvers) within  $\sim 6$  weeks of the flyby to reduce the flyby targeting error to an acceptable level.
4. About a month after the flyby, correct the remaining flyby targeting error with a departure maneuver.

This sequence of steps led to the  $\Delta V$  costs for each flyby shown in Table 2. The first Venus flyby had particularly high penalty, which was the result of execution errors in the approach maneuvers. Compounding the cost was the mission's first long solar conjunction during and after the flyby, which shifted the final approach maneuver earlier and delayed the departure maneuver. Note that the total flyby  $\Delta V$  penalty shown in Table 2 is not just the sum of the approach and departure maneuvers, as errant flybys can affect the size of future deterministic maneuvers as well. The total penalty for each flyby is the sum of the approach and departure maneuvers plus the increase in any future deterministic maneuvers. The last two columns of Table 2 show the results for the first three MESSENGER flybys. Accuracy of the predicted flyby trajectory is

assessed using the B-plane, or hyperbolic impact-plane, intercept at Mercury periaapsis. The B-plane is the plane normal to the incoming asymptote of the hyperbolic flyby trajectory that intersects the center of the target body (i.e., Mercury). The reference vector normal to the B-plane, the “S-axis,” lies along the incoming asymptote. For MESSENGER planetary encounters, the “T-axis” is parallel to the line of intersection between the B-plane and the Earth Mean Ecliptic plane of 1.5 January 2000 (and is positive in the direction of decreasing right ascension). The “R-axis” (positive toward the south ecliptic pole) completes the orthogonal, right-handed “T-R-S” Cartesian coordinate axes. Negative values for the periaapsis altitude offset indicate a flyby at a lower altitude than designed. Using the flyby approach outlined above, the Earth flyby and Venus flybys were within 6 km of the desired B-plane aim point, with costs ranging from 1-40 m/s.

**Table 2. Flyby Costs with the Traditional Flyby Approach**

| Flyby   | Approach Maneuver Cost (m/s) | Departure Maneuver Cost (m/s) | Total Flyby Penalty (m/s) | B-plane Target Miss Distance (km) | Periaapsis Altitude Offset (km) |
|---------|------------------------------|-------------------------------|---------------------------|-----------------------------------|---------------------------------|
| Earth   | 1.3                          | 0.0                           | 1.7                       | 22.1                              | +1.0                            |
| Venus 1 | 2.8                          | 35.7                          | 40.0                      | 36.0                              | -52.8                           |
| Venus 2 | 0.8                          | 0.0                           | 1.0                       | 5.7                               | +1.4                            |

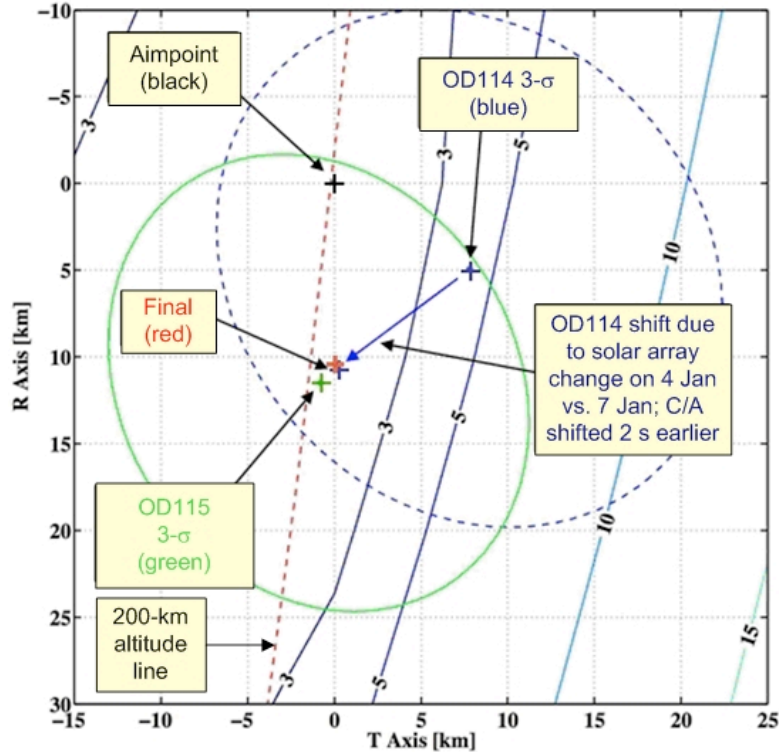
### MERCURY FLYBY 1

The first Mercury flyby for MESSENGER occurred on 14 January 2008. Prior to the beginning of that month, the MESSENGER team used the traditional flyby approach of adjusting the trajectory with propulsive maneuvers to achieve the desired B-plane aim point. The sequence of events for the first Mercury flyby began with the execution of DSM-2 on 17 October 2007. This maneuver was 226.0 m/s, and despite the small execution errors, the trajectory required a further adjustment to achieve the necessary flyby accuracy. An approach maneuver of 0.85 m/s was executed on 19 December 2007 to remove the remaining small flyby targeting error. This approach maneuver executed with very small errors and put the spacecraft within 10 km of the flyby aim point. This can be seen in Figure 3, as the “+” location indicated by orbit determination solution #114 (OD114).

While the solution indicated by OD114 would produce a flyby that was satisfactory for science data collection, the mission  $\Delta V$  penalty of this flyby would be about 4.5 m/s, as indicated by the  $\Delta V$  cost contours in Figure 3. While this does not represent a significant portion of the mission  $\Delta V$  margin, executing a very small maneuver (0.04 m/s) a few days prior to the flyby could reduce this penalty. However, a maneuver of this size could have substantial execution errors, and an anomalous maneuver could jeopardize the mission-critical science at the flyby. Further, the desired maneuver direction required the use of MESSENGER’s least reliable thruster set. So while the benefit to the propellant budget of a second approach maneuver was clear, the risks associated with the maneuver made the decision difficult.

It was at this point that MESSENGER engineers realized that there was another option to achieve the necessary trajectory correction. The required  $\Delta V$  for this second approach maneuver was comparable to the disturbance introduced by the SRP force acting over a few days. Since the vast majority of the desired approach maneuver was in the sunward direction, a reduction in the spacecraft Sun-facing area would allow the change in the SRP force to approximate this maneuver. This prompted the team to adjust the solar array angle three days earlier than originally planned, serving to reduce the SRP force over those three days. This change caused the B-plane intercept to move closer to the Sun (and Mercury), but shifted the intercept slightly farther from

the aim point (11 km), indicated by the green “+” in Figure 3. While this shift increased the B-plane targeting error, the total mission  $\Delta V$  penalty was reduced to  $\sim 1.5$  m/s as this solar array change moved the flyby altitude very close to the target altitude, shown as the red dashed line in Figure 3. This simple solar array change saved  $\sim 3$  m/s of mission  $\Delta V$  and moved the spacecraft within 2 km of the desired flyby altitude.



**Figure 3. B-plane for MESSENGER’s First Mercury Flyby in EMO2000 Coordinates**

### ROLE OF SOLAR RADIATION PRESSURE IN MESSENGER’S MERCURY FLYBYS

The success of Mercury flyby 1 convinced the MESSENGER team that the heliocentric orbit can be controlled with the use of SRP. Because the SRP forces acting on a spacecraft are (in general) quite small, the resulting control authority on the orbit is also small. This means that for most missions the utility of using SRP to reduce total mission propulsive  $\Delta V$  (and reduce mission costs) is minimal. However, planners can reduce the statistical fuel penalty for interplanetary missions significantly if this technique is applied to improving the accuracy of planetary flybys. For a mission that uses planetary flybys for gravity assist, precision targeting of the flyby location is critical to achieving the desired change in the spacecraft trajectory. The force due to SRP can be used to improve the accuracy of these flybys, thereby significantly reducing the amount of propellant required to navigate the mission. By using SRP forces in lieu of propulsive forces to improve flyby targeting, reducing the burden on ground personnel, and eliminating the fuel cost for navigation.

Most missions treat the force that results from SRP as a disturbance. Because this force is generally quite small, infrequent propulsive events are sufficient to overcome the disturbance. MESSENGER used this strategy for the first three planetary flybys by using the approach maneuvers. Similarly, the low level of force offers limited ability to adjust the trajectory. Missions with large Sun-facing area or missions that operate near the Sun are exceptions. Since

the SRP force changes with the squared distance to the Sun, this technique is mostly beneficial to missions inside the Earth's orbit, which makes the technique particularly powerful for MESSENGER. However, since SRP affects all spacecraft exposed to sunlight, it can be beneficial to nearly any mission. This requires only that the spacecraft be able to vary the Sun-facing area and/or the orientation of the surfaces with Sun exposure. This variation is usually accomplished via articulation of appendages (solar arrays), attitude changes, or both.

The solar radiation pressure also influences the momentum growth on MESSENGER.<sup>4</sup> Because the spacecraft uses reaction wheels for attitude control, these wheels continually absorb angular momentum resulting from the SRP torque. To prevent wheel saturation and a possible loss of attitude control, MESSENGER must periodically use its thrusters to dump momentum. These thruster dumps are undesirable, as they introduce a parasitic  $\Delta V$  that perturbs the orbit, exacerbated by uncoupled thrusters. This perturbation on the trajectory can adversely affect the accuracy of the flybys if a momentum dump must occur in close proximity to the flyby. Further, each momentum dump consumes propellant, which is undesirable. Much in the same way that the disturbance force due to SRP can be used to benefit the trajectory, the SRP torque can be used to manage the momentum passively.

### Solar Radiation Pressure Model for MESSENGER

In order to accomplish the passive trajectory and momentum management, an accurate model of the disturbance forces and torques due to SRP is required. In the nominal cruise configuration, MESSENGER keeps its sunshade pointed toward the Sun. This provides a relatively simple set of surfaces for which the SRP forces can be calculated. These surfaces include the cell side of the solar arrays, the facets of the sunshade, the Sun sensors and the radio frequency components on the sunshade, and for large sunshade tilt angles, exposure of the LVA bell or Magnetometer boom are also included in the model. All of these components are modeled as a series of flat plates using the standard flat-plate equation<sup>5</sup> for SRP:

$$\mathbf{F} = -PA \cos \theta \left[ (1 - C_S) \mathbf{S} + 2 \left( C_S \cos \theta + \frac{1}{3} C_D \right) \mathbf{N} \right] \quad (1)$$

$$P = \frac{F_e}{c} \quad (2)$$

where  $P$  is the mean solar momentum flux,  $F_e$  is the solar constant ( $1358 \text{ W/m}^2$  at 1 AU),  $c$  is the speed of light,  $A$  is the plate area,  $C_S$  and  $C_D$  are the specular and diffuse reflective properties of the plate,  $\mathbf{S}$  is the Sun direction unit vector,  $\mathbf{N}$  is the outward plate normal unit vector, and  $\theta$  is the angle between  $\mathbf{N}$  and  $\mathbf{S}$ . By summing the force components over all the plates in the model, the net force on the spacecraft due to SRP is:

$$\mathbf{F}_{SRP} = \sum_{i=1}^n \mathbf{F}_i \quad (3)$$

where  $\mathbf{F}_{SRP}$  represents the instantaneous force due to SRP on the entire spacecraft,  $i$  represents the  $i$ th plate, and  $n$  the total number of plates in the spacecraft model. For MESSENGER, the sunshade and Sun-facing components are modeled as 65 flat plates, where each plate has its own area, reflectance properties, and normal vector, as shown in Equation (1). Equation (2) provides the instantaneous force, and from the temporal evolution of the plate normal vector and the Sun vector (both of which change due to changes in plate attitudes), a time history of the force due to SRP can be computed.

From the physical properties of these surfaces and their size and orientation, the net force due to SRP at any given time may be calculated. This modeling includes several known approximations, including: the reflectance properties of the modeled surfaces are based on pre-launch ground estimates, the modeled plates are approximated in some cases, and secondary reflections are not included in the model. Despite these simplifications, the SRP model has provided an accurate prediction of the time history of the resultant force observed on MESSENGER.

Using the plate model described above, it is straightforward to calculate the predicted torque at any given time. In addition to the size and orientation (attitude) of the plates in the SRP model, to compute the torque it is necessary to know the location of the center of mass (CM) and the geometric center of each plate as:

$$\mathbf{T}_{SRP} = \sum_{i=1}^n \mathbf{r}_i \times \mathbf{F}_i \quad (4)$$

where  $\mathbf{F}_i$  is the SRP force on the  $i$ th plate in the model and  $\mathbf{r}_i$  is the location of the center of pressure (CP) of the  $i$ th plate relative to the spacecraft CM.

While it is a simple matter to compute the net torque on the spacecraft for a known CM, determining the current CM location is less straightforward. Significant energy has been devoted to estimating the time history of the MESSENGER CM.<sup>6</sup> The MESSENGER CM is not static, as the propellant is free to move inside the main fuel and oxidizer tanks. In general, the surface tension forces in these tanks are sufficient to prevent motion of the propellant between thrusting events. However, any time thrusters are used, they can shift the CM location. Under some conditions, this CM motion may be predictable, although this is generally not the case. The uncertainty in the post-maneuver CM leads to significant uncertainty in the SRP torque and the resultant momentum accumulation. This is another strong reason for managing the momentum without propulsive dumps, as any propulsive dump can produce a change in the CM and attendant changes in the evolution of the system momentum.

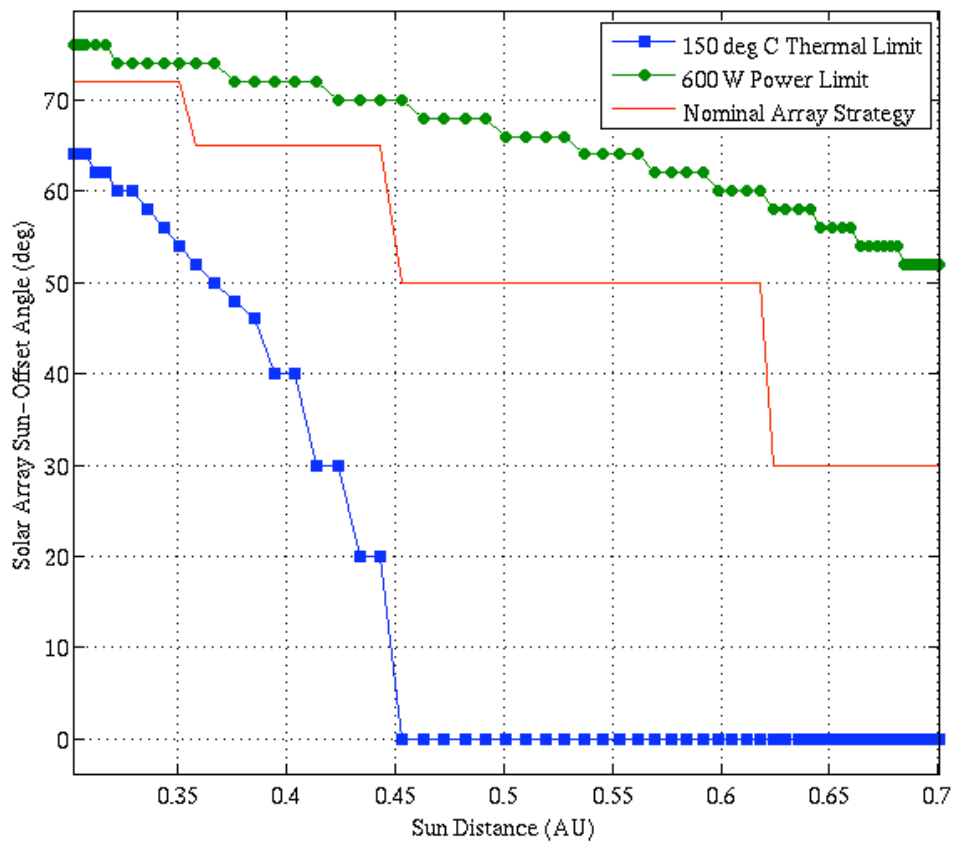
### **Long-Term Attitude and Articulation Plan**

With the equations in the prior section and a plate model for the spacecraft, analysts can predict the instantaneous forces and torques resulting from the SRP. To model the temporal evolution of these forces and torques requires a prediction for the attitude and articulations of the spacecraft and its appendages. Of course, it is not always practical to plan the science and engineering events that require attitude changes well in advance of these events. For the MESSENGER cruise phase, activities are not well defined more than a few weeks into the future, although the concentrated science activities around flybys are a notable exception. Moreover, Deep Space Network (DSN) antenna coverage is well defined only ~6 weeks beyond the current date, which is a further constraint on the attitude. For MESSENGER the attitude and articulation plan is divided into two intervals, a short- and long-term prediction. The short-term plan (STP) is based on well-defined activities and generally spans 2-3 weeks. This STP is based on built and reviewed command loads and reflects a very accurate prediction of the spacecraft activities, unless normal flight operations are interrupted due to an anomaly. The long-term plan (LTP) is based on scheduled events in various states of maturity that occur beyond the STP. Although these events are not always well defined, they represent the best estimate of the spacecraft activities in the future. This LTP generally spans the end of the STP through the next planetary encounter, which could be many months in the future.



On MESSENGER, both the attitude and solar array articulations are subject to constraints. The spacecraft attitude is constrained by the SKI zone, and it is further constrained during DSN passes to allow communication with Earth. The solar arrays are similarly constrained, as they must produce sufficient electrical power for the spacecraft without exceeding thermal limits. In general, while the constraints on each mission are different, they serve to limit the control authority on the trajectory, but they do not preclude the use of SRP as a trajectory (or momentum) control. The attitude and articulation plan can work within these mission constraints, simultaneously providing the necessary force for trajectory control and necessary torque for momentum control.

The LTP follows a few simple guidelines. First, the power and thermal engineers define the baseline solar array articulations. The solar array angles are defined as a sunline-offset angle, and the flight software automatically adjusts the body-fixed position during attitude changes to maintain the desired angle with respect to the Sun. The sequence of Sun-offset angle changes is planned well in advance, and is based on the spacecraft-Sun distance. As MESSENGER approaches the Sun, the arrays tilt away from the sunline to maintain thermal margin. When MESSENGER recedes from the Sun, the arrays tilt towards the Sun to ensure sufficient power. The arrays must operate in this corridor to satisfy both of these limits, as depicted in Figure 4. The red solid line in Figure 4 provides the baseline articulation plan that minimizes the solar array configuration changes; this defines the solar array articulations used in the baseline LTP.



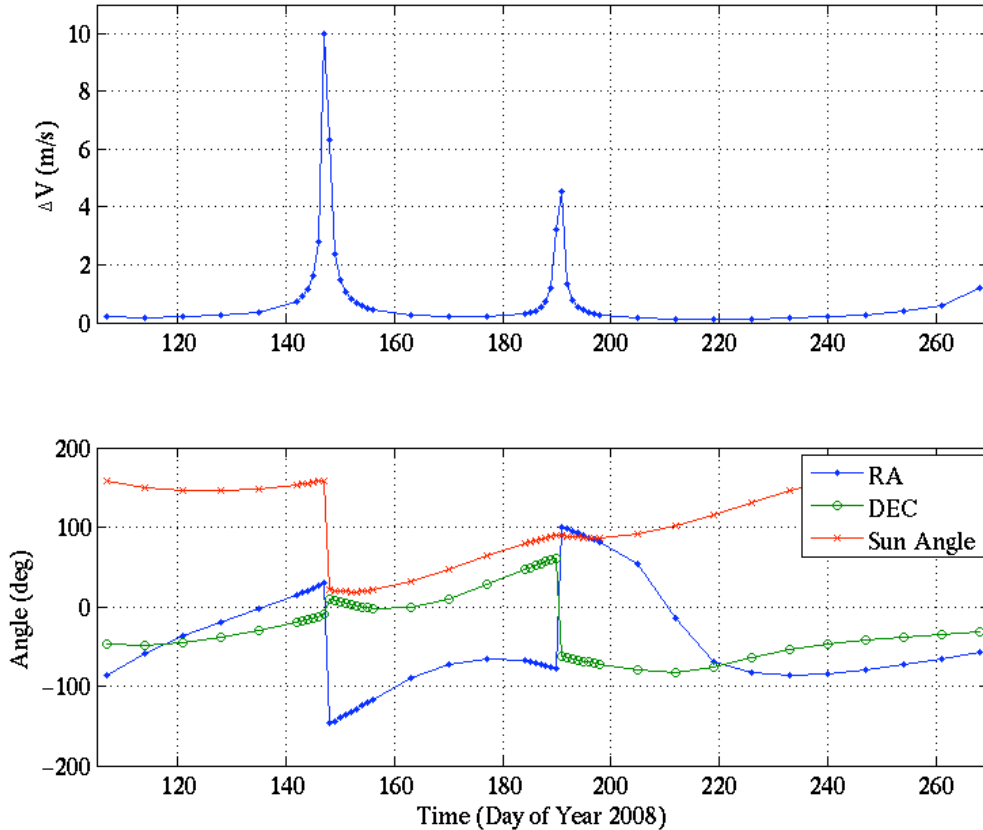
**Figure 4. Nominal Solar Array Sun-Offset Angle Strategy with Power/Thermal Corridor Limits**

The LTP for the attitude is developed from the SRP torque model that predicts the time-history of the spacecraft angular momentum. In the absence of any other attitude, the spacecraft LTP defaults to the Earth communication attitude (termed downlink attitude). This attitude points the sunshade directly toward the Sun and rolls around the sunline to put the Earth in either the  $(+x, +y)$  or  $(-x, -y)$  quadrant of the  $x$ - $y$  plane. With this attitude and any defined science or engineering observations, the SRP model provides an estimate of the behavior of the angular momentum. This set of baseline attitudes is modified to keep the momentum below the autonomous momentum dump threshold of 5.5 Nms. Any undesirable trend in the momentum about the sunline (spacecraft  $y$ -axis) can be corrected with small ( $\sim 1^\circ$ ) differential offsets in the individual solar array angles. This technique has been termed “windmilling” the panels, as the sunline-offset angle is slightly different for each array, resulting in a windmill-like configuration of the solar arrays. This technique easily negates any  $y$ -axis torque, thereby balancing the  $y$ -axis momentum. A CM to CP offset on the spacecraft  $x$ - and  $z$ -axes creates large torques (and momentum growth) about the spacecraft  $z$ - and  $x$ -axis, respectively. If the nominal downlink attitude produces momentum growth rates about these axes, the downlink attitude is adjusted to tilt the sunshade to help minimize the CM to CP offset. The sunshade tilt is constrained by the SKI zone to  $\pm 12^\circ$ , so for large CM to CP offsets, this technique is not sufficient to eliminate the torque due to SRP. MESSENGER uses “attitude alternations” to manage the momentum when the sunshade has insufficient control authority to eliminate the torque due to SRP. These alternations have MESSENGER spending half of its time in the untilted downlink attitude, and the other half of its time in an attitude that is a  $180^\circ$  rotation (about the sunline) from the untilted downlink attitude. This allows the  $x$ - and  $z$ -axis momentum accumulated during the time at downlink attitude to be removed while at the alternate attitude. This strategy is very effective at keeping the momentum well below the autonomous dump threshold. The only constraint levied by this approach is that the DSN schedule must cover less than 50% of the time interval for the alternations, as the spacecraft cannot be at the alternate attitude during a DSN contact (i.e., Earth communication is not possible at the alternate attitude).

The solar array position can strongly influence the overall CP for the spacecraft, particularly in the spacecraft  $x$ - and  $z$ -directions. Generally, when the MESSENGER solar array Sun-offset angle is below  $50^\circ$ , the  $x$ - and  $z$ -axis momentum can be managed by tilting the sunshade to minimize the offset between the CM and the CP. When the solar array Sun-offset angle is above  $50^\circ$ , the attitude alternation strategy must be used to manage the momentum. This strategy is paired with the information in Figure 4 to define an LTP for the attitude and the solar array positions. Using the information in this LTP and the SRP model from Equations 1-4, a long-term prediction of the spacecraft system momentum can be generated. If this prediction is found to violate the autonomous momentum dump threshold, the attitude or solar array strategy may be altered (within the applicable constraints) so that the momentum remains below the necessary limit. Developing a LTP that keeps the momentum below the autonomous dump threshold is currently an iterative process that is done manually by the guidance and control team. This planning has proven very effective at preventing propulsive momentum dumps. By using sunshade tilts and windmilling the solar arrays, MESSENGER required only two dedicated dumps during the first 30 months of flight operations. Once the attitude alternations were employed, dedicated propulsive dumps have been eliminated. (MESSENGER pairs a momentum dump with every propulsive  $\Delta V$  for convenience.)

Once an analyst creates a nominal plan that manages the momentum, this plan is used with the SRP model to determine the resultant disturbance force. This SRP force profile is used in the translational equations of motion to propagate the current spacecraft state vector out to the planetary flyby. This integration determines the nominal B-plane intercept, which is, in general, not near the intended B-plane aim point. Iterative adjustments made to the LTP maintain the momentum within acceptable limits and simultaneously drive the B-plane intercept onto the aim

point. These iterations are ad hoc in nature, but formalization is possible, as the equations of motion and constraints are all well defined. At present, an analyst investigates a simple change over a short time period. For instance, the solar array Sun-offset position is increased from the baseline LTP over several days. This modified plan is used in the integration of the equations of motion, and the B-plane sensitivity to this change is studied. By performing this ad hoc sensitivity analysis, an analyst can find a plan that keeps the momentum below the necessary limits and drives the trajectory onto the B-plane aim point. To aid in finding a quick solution to this problem, navigators produced a time-history of the instantaneous desired  $\Delta V$  to drive an off-nominal trajectory onto the B-plane aim point. Figure 5 provides an example of this data.



**Figure 5. Desired  $\Delta V$  Magnitude and Direction (Right Ascension and Declination) for the Trajectory Leg between DSM-3 and Mercury Flyby 2**

Figure 5 shows the instantaneous desired  $\Delta V$  for MESSENGER following DSM-3, as the spacecraft continued towards the second Mercury planetary encounter. By using this as a guideline, it is easy to see when the force due to SRP has the most potential for producing the desired trajectory change. The valleys in the upper figure are the times when a very small  $\Delta V$  would provide the necessary change in the trajectory. These are the optimal times to make changes to the nominal LTP from a trajectory perspective. The attitude and array positions must be modified during these times to push the resultant SRP force along the direction dictated by the lower portion of Figure 5. This information greatly simplifies the procedure to define a LTP that satisfies the momentum and trajectory requirements. Of course, aligning the SRP force with the direction specified in Figure 5 is not always possible given the mission constraints. However, the

information in Figure 5 narrows the design space for choosing an attitude and solar array strategy that produces the desired change in the Mercury B-plane.

The modeling of the spacecraft SRP forces and torques are not perfect, and there are other unmodeled disturbances to the momentum and trajectory. Moreover, refinements of science or engineering events can lead to short-term errors in the LTP. These errors cause the predicted trajectory and momentum profiles to deviate from the actual flight profiles. As these changes evolve, compensating changes are made to the MESSENGER LTP to ensure that the momentum remains below limits and the trajectory remains targeted to the B-plane aim point. The amount of effort required to maintain the actual profiles in a close neighborhood of the predictions is highly variable. For MESSENGER, the momentum model tends to be very accurate over a month or so and then the model predictions begin to deviate from the flight experience. This means that analysts must adjust the SRP model parameters about once a month to keep the predicted momentum trends consistent with the flight behavior. These are minor adjustments, and generally do not require an adjustment to the LTP to compensate for these small modeling imperfections. Similar iterations are required for the trajectory. As the new orbit determination would refine the trajectory estimates, the LTP would require compensating changes to keep the trajectory targeted to the B-plane aim point. In general, these small refinements to the trajectory do not require large changes in the LTP. However, adding a new science observation to the LTP that spans several days can be more disruptive to the LTP. Although each change is different, in general it requires several hours of modifications to the LTP for a single hour of an unplanned event. For this reason, it became very important to include every known science and engineering event, modeled as accurately as possible in the LTP. Further, once the LTP included an event, it was usually better to execute the event rather than remove it from the schedule, since removal would require additional changes to the LTP to preserve the B-plane targeting.

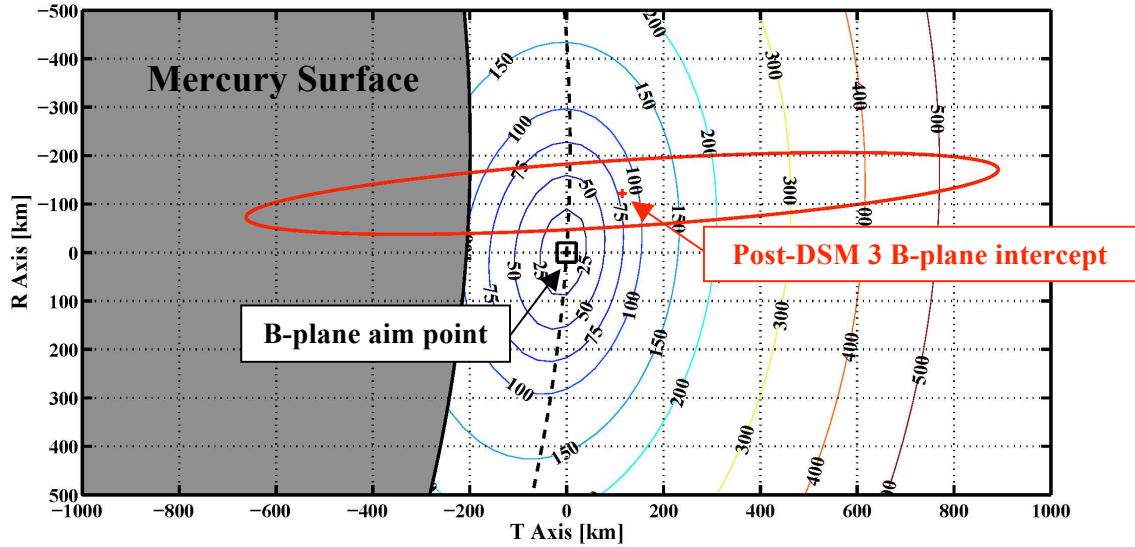
## **MERCURY FLYBY 2**

With the successful demonstration of the use of SRP force to control the trajectory at the first Mercury flyby, the MESSENGER team planned a more extensive use of this technique for the second Mercury flyby in October 2008. Mission planners used the procedure outlined above for this leg of the trajectory. The steps were as follows:

1. Produce an LTP that defines the attitude and solar array position between DSM-3 and Mercury Flyby 2. This plan satisfies the baseline solar array strategy defined in Figure 4 and keeps the momentum below the autonomous momentum dump limit. This plan uses the strategy outlined in the “Long-Term Attitude and Articulation Plan” section of this paper.
2. Design DSM-3 based on the LTP from step 1.
3. Execute DSM-3. Small errors caused the propagation of the post-DSM-3 state vector to miss the B-plane aim point. Figure 6 shows this error.
4. Navigators produce information about the desired instantaneous  $\Delta V$  to achieve the B-plane aim point. Figure 5 shows this information.
5. Modify the baseline LTP from Step 1 to drive the spacecraft to the B-plane aim point. This was an iterative process governed by the information in Step 4.
6. Update the LTP based on the new requirements for science or engineering observations as well as flight telemetry for momentum and orbit determination. Make compensating changes to the LTP to keep the momentum and trajectory managed. Repeat Step 6 as necessary.

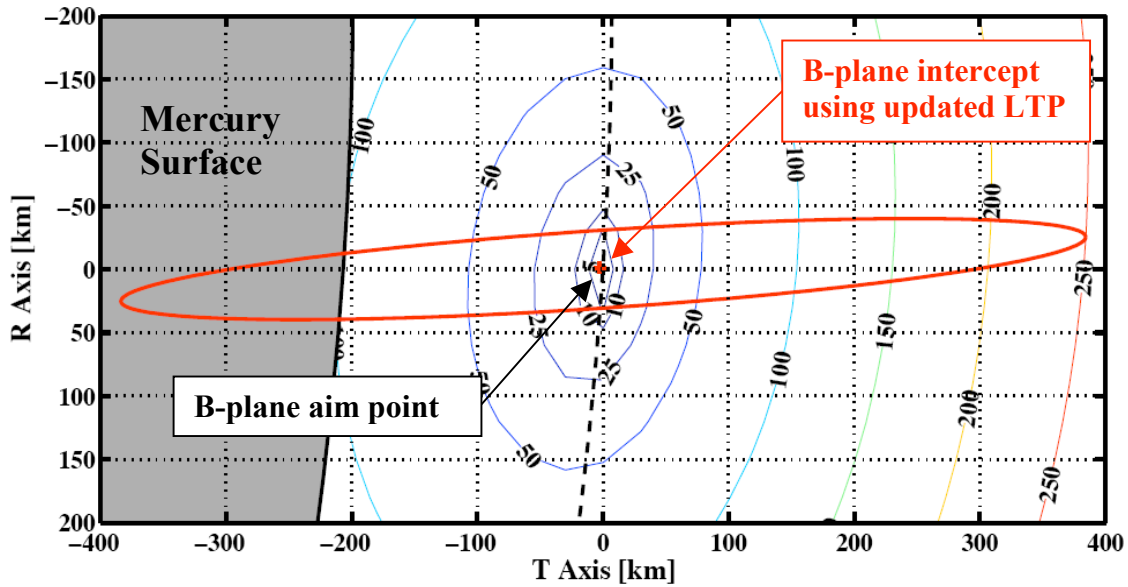
MESSENGER executed DSM-3 on 19 March 2008. This maneuver had extremely low execution errors and left the spacecraft on the trajectory indicated by the red “+” in Figure 6. The red ellipse reflects the navigational uncertainty with this B-plane intercept. Despite the excellent

performance of DSM-3, navigators projected the spacecraft to be ~170 km from the aim point at the time of the flyby, marked by the black “+” in Figure 6. If this error remained uncorrected until after the flyby, the  $\Delta V$  cost contours reveal that MESSENGER would have had to pay a penalty of ~80 m/s.



**Figure 6. Predicted Mercury B-plane Intercept following DSM-3 Execution in EMO2000 Coordinates**

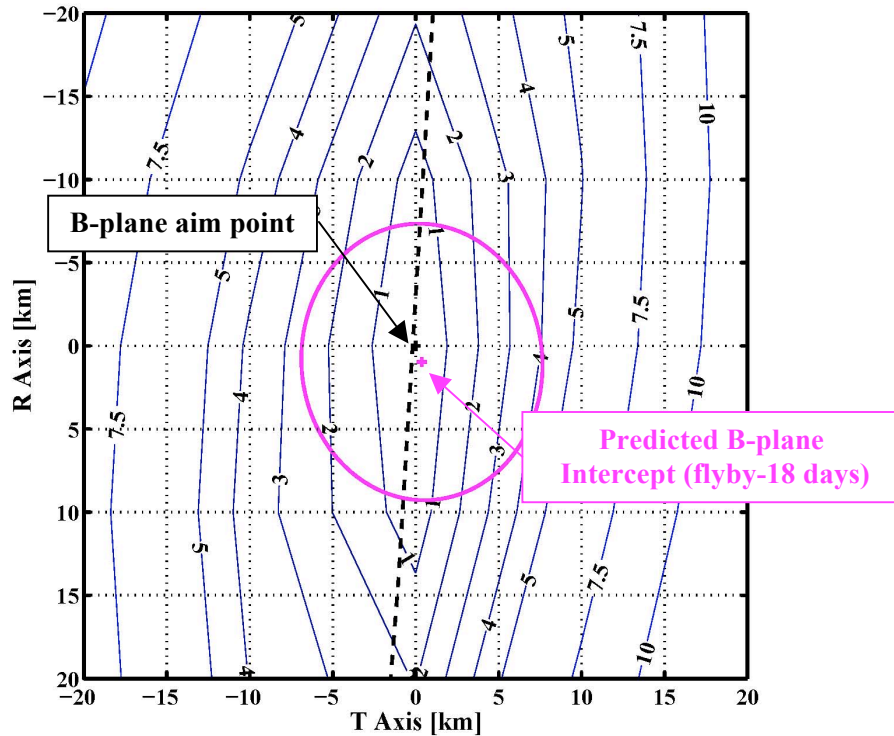
Planners adjusted the baseline LTP (Step 5) on 17 June 2008, which was 111 days prior to the flyby. Based on this updated LTP, the best estimate for the B-plane intercept is at the flyby aim point, as indicated by the red “+” shown in Figure 7. The red error ellipse indicates



**Figure 7. Predicted Mercury B-plane Intercept, 17 June 2008, 111 Days prior to Mercury Flyby 2 in EMO2000 Coordinates**

significant uncertainty in the trajectory, which is the result of uncertainty in the orbit determination as well as the imprecision in the 111-day trajectory propagation. These errors can result in a drift of the B-plane intercept, which require additional corrections by readjusting the LTP (repetitions of Step 6).

Following three months of small readjustments to the LTP to compensate for unmodeled attitude changes, and to correct for shifts in the orbit determination, MESSENGER was still right on target, as shown in Figure 8.



**Figure 8. Mercury B-plane on 18 September 2008, 18 Days prior to Mercury Flyby 2 in EMO2000 Coordinates**

The situation became more dynamic as MESSENGER approached the planet and the orbit determination errors began to drop. Seven days before the flyby, the orbit solution had drifted about 4 km from the aim point, shown by the blue “+” in Figure 9. Although there was very little time remaining, planners added a simple attitude adjustment to the schedule to correct this error. This change moved the center of the OD uncertainty ellipse to within 1 km of the aim point, indicated by the green “+”, as seen in Figure 9. This late update did improve the final flyby altitude, but it had negligible impact on the flyby location (in terms of proximity to the desired aim point), as the final, post-flyby orbit showed that we were at the location marked by the red “+”. Without the late update, the final targeting error would have been ~2 km in the B·T direction, and with the late update, the targeting error was ~2 km in B·R. This helped to reduce the  $\Delta V$  penalty for the flyby, as the cost contours are much steeper in the B·T direction. This final targeting error was almost exclusively the result of pre-flyby orbit determination uncertainty. Mission designers were able to reoptimize the trajectory based on this flyby location (with altitude close to 199 km), resulting in a net *gain* of 0.7 m/s for the mission! Table 3 shows the

detailed  $\Delta V$  results for both Mercury flybys, clearly illustrating the benefits achieved with the new navigation techniques when compared with the propulsive flybys in Table 2.

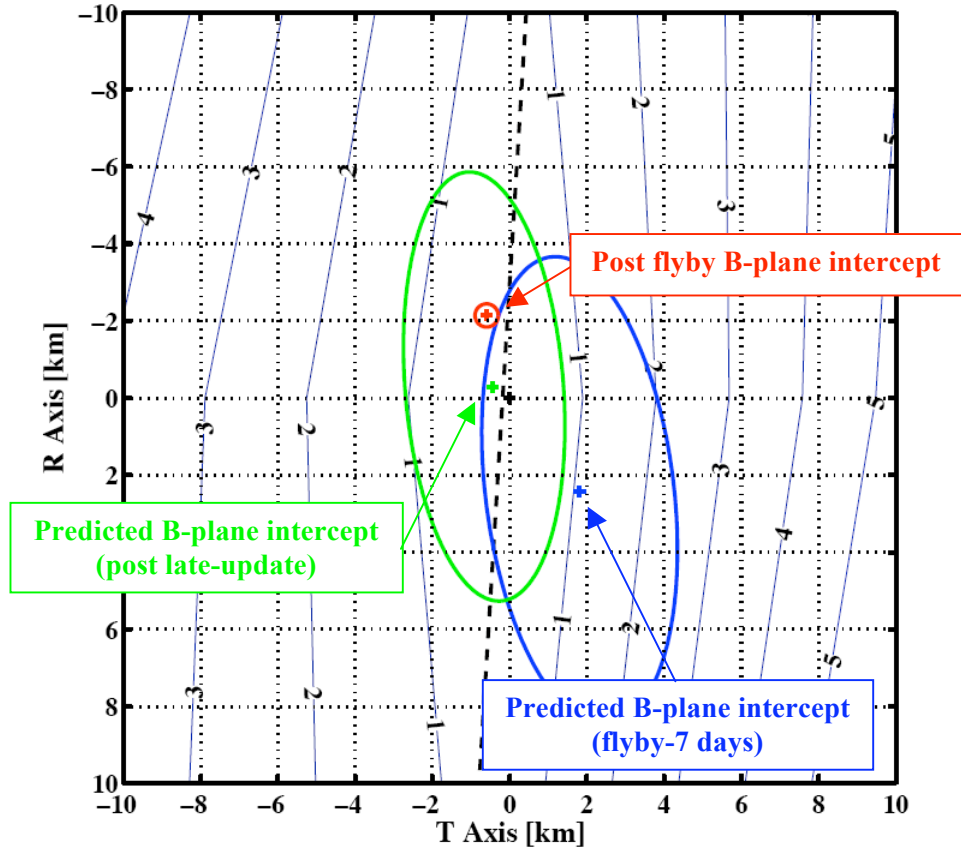


Figure 9. Mercury B-plane before and after Mercury Flyby 2 Closest Approach in EMO2000 Coordinates

Table 3. Flyby Costs with the SRP Flyby Approach

| Flyby     | Approach Maneuver Cost (m/s) | Departure Maneuver Cost (m/s) | Total Flyby Penalty (m/s) | B-plane Target Miss Distance (km) | Periapsis Altitude Offset (km) |
|-----------|------------------------------|-------------------------------|---------------------------|-----------------------------------|--------------------------------|
| Mercury 1 | 0.9                          | 0                             | 2.4                       | 10.4                              | +1.4                           |
| Mercury 2 | 0                            | 0                             | -0.7                      | 2.6                               | -0.8                           |

## CONCLUSION

MESSENGER was able to use SRP successfully to significantly improve the accuracy of the first two Mercury flybys. Although the method was somewhat ad hoc, it is relatively simple to implement and is very low risk. To date, MESSENGER has been able to cancel at least seven propulsive maneuvers due to this technique (two approach maneuvers for Mercury flyby 1, one departure maneuver for Mercury flyby 1, three approach maneuvers for Mercury flyby 2, and one departure maneuver for Mercury flyby 2). The DSM-3 clean-up maneuver was also cancelled, although this was due to the accuracy of DSM-3 rather than the result of the techniques described in this paper.

While the use of SRP to improve the accuracy of the Mercury flybys was very successful, several factors enabled this paradigm shift to a propellant-free flyby. The SRP model and the momentum management with SRP was a proven technique prior to the Mercury flybys. Many of the tools to perform the analysis were a product of the passive momentum management tool set, so there was almost no development cost. Another factor working in MESSENGER's favor is that there is significant margin in the solar array position; this flexibility allows a solar array strategy that meets all the necessary constraints. Of course, MESSENGER's tight fuel budget and history of execution errors on prior small maneuvers made the approach very appealing to program management.

MESSENGER will continue use of this technique for the final Mercury flyby, set for 29 September 2009. This flyby will be slightly more challenging, as the flyby arrival time is more rigid than for prior flybys. This last planetary flyby requires control of this additional variable in addition to the B-plane intercept location, to ensure the necessary orbital conditions at MOI. A refinement in the method to include this extra constraint is underway. There is an obvious parallel between the flyby-targeting problem and many of the low-thrust strategies in the literature, and there is a possibility to leverage this body of work to improve and formalize the approach described here.

## ACKNOWLEDGMENTS

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