MESSENGER's Use of Solar Sailing for Cost and Risk Reduction

Daniel J. O'Shaughnessy, James V. McAdams, Peter D. Bedini, Andrew B. Calloway
The Johns Hopkins University Applied Physics Laboratory

Kenneth E. Williams, Brian R. Page
KinetX, Inc.

Abstract. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission used six planetary gravity assists in order to enable capture into orbit about Mercury. A key element of MESSENGER's successful trajectory was achieving the proper gravity assist from each planetary flyby. The criticality of the MESSENGER gravity assists levied tight accuracy requirements on the planetary-flyby targeting. Major errors could have precluded Mercury orbit insertion or required modifications to the trajectory that increased mission complexity, cost, and risk by requiring additional Mercury flybys and extending mission duration. Throughout the mission, MESSENGER modified its strategy for achieving accurate planetary flybys. By using solar sailing, the MESSENGER team was able to eliminate all of the flyby approach maneuvers without sacrificing flyby accuracy, thereby saving mission ΔV margin. The elimination of these approach maneuvers also markedly reduced mission risk, as these approach maneuvers were nominally planned during a time of heightened sensitivity to errors and precluded unique flyby science opportunities. The paradigm shift used by MESSENGER may be useful for other interplanetary missions, particularly if their trajectories require gravity assists in the inner solar system.

Keywords: MESSENGER, solar sailing, gravity assists

1. Introduction

On 17 March 2011, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft became the first to enter orbit about Mercury. 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.[1] The Mercury orbit insertion (MOI) maneuver that allowed MESSENGER to be captured into a 12-hour orbit about Mercury marked the end of the 6.6-year interplanetary cruise phase of the mission. This interplanetary trajectory flown by MESSENGER would not have been possible without the equivalent ΔV provided by six planetary gravity assists, an Earth flyby followed by two Venus flybys and three Mercury flybys. These flybys were mission enabling for the Discovery-class mission, as providing this ΔV via chemical propulsion would have resulted in a more costly spacecraft design and would have required a substantial reduction in the mass allocated to the mission payload. As a result, a key element of MESSENGER's successful trajectory was achieving the proper gravity assist from each planetary flyby.

The thermal and radiation environment at Mercury drove the MESSENGER spacecraft design. A large sunshade protects the spacecraft components from the heat and radiation of the Sun, as shown in Figure 1.[2,3] The design of the sunshade allows for deviations of ±10° from direct Sun pointing in rotations around the spacecraft *z*-axis, and ±12° in rotations around the *x*-axis. This Sun keep-in (SKI) zone is a significant constraint on the spacecraft attitude, which in turn affects the science observation opportunities, maneuver design, and momentum accrual due to solar radiation pressure (SRP). The solar arrays are rotated about their centerline to ensure sufficient power generation as well as proper thermal conditioning. MESSENGER carries four reaction wheels for primary attitude control; this makes angular momentum management an essential task, as reaction wheel saturation can lead to a loss of attitude control. To off-load stored momentum and execute ΔVs, MESSENGER has a dual-mode propulsion system with 17 thrusters.

During the interplanetary cruise phase of the mission, the primary goals of the guidance and control system were to maintain the mission safety constraints (most importantly the SKI constraint) and manage the

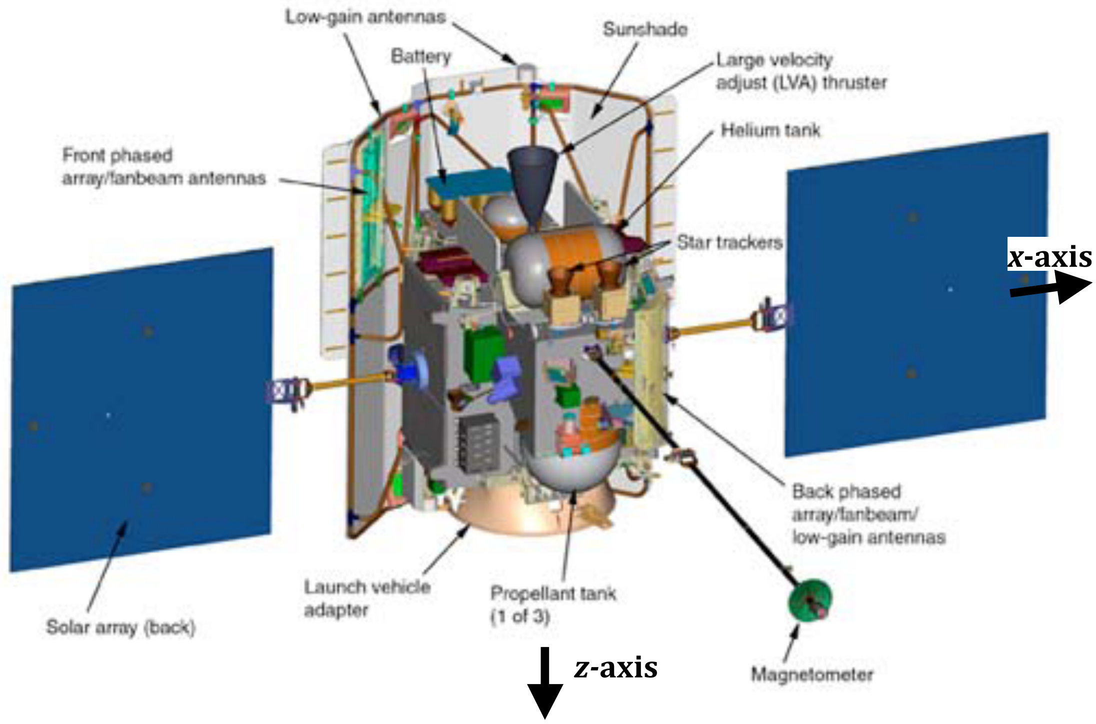

Figure 1. MESSENGER spacecraft components

accumulation of angular momentum. The guidance and control system was also responsible for following the designed trajectory shown in Figure 2 by executing propulsive maneuvers and ensuring the proper gravity assist by achieving the proper flyby targeting. It was also important to satisfy the pointing requirements for spacecraft science and engineering activities, but these activities were of limited duration and scope during cruise. Each pair of planetary gravity assists was typically separated by a deterministic maneuver, termed a deep-space maneuver (DSM), which was used to target the subsequent flyby. This timeline of maneuvers and flybys is shown in the lower portion of Figure 2. Table 1 shows the total ΔV provided by each gravity assist and the ΔV for each of the DSMs. The table demonstrates that the gravity assists from the flybys provided the vast majority of MESSENGER's ΔV, thereby highlighting the criticality of each flyby to a successful mission; the ΔV attained by any single flyby exceeded the total deterministic maneuver budget for the entire mission. Further, accuracy at the flybys was paramount, as major errors in the flyby targeting can easily exceed the mission reserve ΔV capability.

Precision targeting at each flyby was critical, as without the velocity change provided by each gravity assist, MESSENGER would have been unable to be captured into the required orbit. The Mercury flybys

Table 1. ΔV imparted for each critical trajectory event

Flyby	ΔV (m/s)	Maneuver	ΔV (m/s)
Earth flyby (Aug. 2005)	5966.3	DSM-1 (Dec. 2005)	315.6
Venus flyby 1 (Oct. 2006)	5522.5	DSM-2 (Oct. 2007)	226.0
Venus flyby 2 (June 2007)	6937.8	DSM-3 (Mar. 2008)	72.2
Mercury flyby 1 (Jan. 2008)	2304.0	DSM-4 (Dec. 2008)	246.7
Mercury flyby 2 (Oct. 2008)	2452.6	DSM-5 (Nov. 2009)	177.8
Mercury flyby 3 (Sept. 2009)	2836.1	MOI (Mar. 2011)	861.7

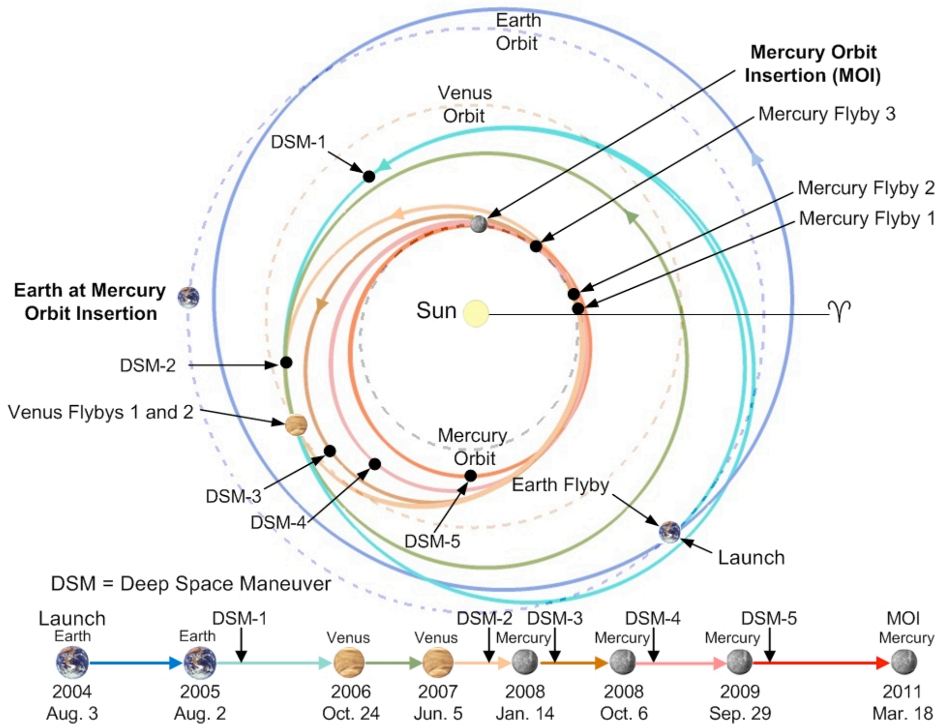

Figure 2. MESSENGER trajectory from launch through Mercury orbit insertion

were nominally at 200 km altitude, and a low flyby carries the additional risk of planetary impact. Less spectacular, but equally damaging to the mission, if the flyby was too distant from the planned aim point at closest approach, MESSENGER could have been forced to use its reserve propellant. In the event of a large flyby targeting error, limited propellant reserves might have prevented MESSENGER from returning to its nominal trajectory. Major errors could have precluded Mercury orbit insertion or required modifications to the trajectory that increased mission complexity, cost, and risk by requiring additional Mercury flybys and extending mission duration. Moreover, the Mercury flybys assisted in developing the science data collection process for the year-long orbital portion of the mission, as well as provided unique opportunities for observations not possible while in the Mercury science orbit.[1] Accurate flybys also preserved reserve propellant use for completion of the mission and for possible mission extension.

2. MESSENGER's Flyby Targeting Approach

Throughout the mission, the MESSENGER team modified its strategy for achieving accurate planetary flybys. In general, a planetary gravity assist was preceded by a deterministic trajectory event (either a prior planetary flyby or a DSM). These events are subject to uncertainty, either as the result of maneuver execution errors or due to errant targeting at the prior flyby. In order to ensure the desired gravity assist at an upcoming flyby, the MESSENGER team would plan for a series of trajectory refinement maneuvers in advance of the flyby to ensure sufficient targeting accuracy. Typically this would include scheduling three maneuver opportunities in advance of the flyby and one maneuver opportunity after the flyby to remove any remaining velocity errors. The approach maneuvers were not costly in terms of propellant, but they added cost and risk to the program because of the substantial effort required to plan and implement these burns. MESSENGER's Earth and Venus gravity assists used this propulsive maneuver paradigm to achieve the desired targeting accuracy. This strategy worked reasonably well for two of these flybys, but the first Venus flyby had a combination of maneuver execution errors, poor orbit observation geometry, and a long solar conjunction following the flyby that delayed the flyby correction. These circumstances led to a flyby cost of more than 35 m/s of mission reserve propellant (approximately 15% of the total mission reserves).

As with the first three flybys, the initial approach to the first Mercury flyby used propulsive maneuvers to correct the flyby targeting errors. The initial approach maneuver, conducted nearly four weeks prior to the planetary encounter, left non-trivial flyby errors which would have resulted in a 5 m/s cost to the mission if these errors were left uncorrected until after the flyby. Since it was significantly less costly to correct this error prior to the flyby, some team members recommended making this correction to the trajectory in advance of the encounter to conserve propellant. However, this propulsive correction maneuver was scheduled for only four days prior to MESSENGER's first encounter with Mercury. There was substantial pressure to reduce the mission risk by not executing this maneuver, since any anomalous execution could jeopardize the spacecraft's first opportunity to collect science observations of Mercury. At that point, the team recognized that a simple adjustment of the solar array orientation would change the force due to solar radiation pressure enough to correct the bulk of the flyby errors without introducing any risk to the flyby science data collection. The successful demonstration of correcting flyby targeting errors with solar radiation pressure prompted the team to refine the technique for the second and third Mercury flybys as well as for the approach to Mercury for the orbit insertion maneuver. This paradigm shift eliminated all planned flyby targeting and post-flyby clean-up maneuvers, reducing the flyby cost and decreasing the workload on spacecraft operators. Further, by using solar sailing to correct errors at the flybys, the flyby accuracy was maintained and in some cases improved, as solar sailing offers greater precision than the conventional targeting with trajectory-correction maneuvers.

3. Angular Momentum as a Driver For Solar Sailing

The use of SRP to solar sail MESSENGER to the correct flyby arrival conditions was only one issue of concern to mission operators, as the management of angular momentum by passive means was another significant driver in choosing the orientation of MESSENGER.[4] Of chief concern to MESSENGER operators was ensuring that the angular momentum remained within limits, thereby obviating the need for propulsive momentum dumping. Although MESSENGER carries four reaction wheels, each capable of 7.5 Nms of momentum storage, the operational limit for the total system momentum is 5.5 Nms in order to prevent reaction wheel saturation during high-rate slews. By judiciously choosing the orientation of the vehicle and the solar arrays, the angular momentum vector could be controlled so that there was no risk of violating this momentum limit. Management of the momentum via this passive strategy was effective, but it required substantial time and effort on the part of planners and operators. Spacecraft attitude and solar array articulations had to be carefully planned to remain within the required constraints while simultaneously providing the necessary control on the system angular momentum.

The techniques to maintain the momentum within the required limits have been in use on MESSENGER since launch. Initially, the team adjusted the orientation of the spacecraft sunshade to align the spacecraft center of pressure with the center of mass to eliminate the torque due to SRP. As the mission evolved, the center of mass drifted due to the consumption of propellant during the mission's ΔV maneuvers. These changes moved the center of mass to a location that would no longer allow elimination of the SRP torques by adjusting the tilt of the sunshade, as this angle was constrained by SKI to be less than 12º. At that point, MESSENGER operators managed the momentum by alternating the inertial direction of the SRP torque by periodically rotating the spacecraft around the sunline by 180º. The change in momentum management techniques was primarily driven by several long solar conjunctions that required a robust plan for momentum management that could maintain the momentum for several weeks at a time without ground intervention. These so-called "attitude alternations" allowed management of the momentum despite increasing SRP torques; although as the torque increased, the frequency of the attitude alternations was increased as well.

These techniques were very effective at managing the momentum without the need for propulsive momentum dumps (although every ΔV maneuver contained an opportunistic momentum adjustment). Outside of the ΔVs, MESSENGER used only five dedicated propulsive momentum dumps during the entire 6.6-year cruise phase of the mission, and three of these dumps were tests of the Mercury orbital phase operations.

4. Solving the Solar Sailing/Momentum Management Problem

With the techniques previously described, managing the momentum became a straightforward, albeit time-consuming, operational activity, but when the control of angular momentum was combined with the control of the trajectory, the problem became substantially more complicated.[5] MESSENGER's mission constraints did not allow decoupling the trajectory control from the momentum control, so these problems had to be solved simultaneously, chiefly because of the inability to align the center of pressure of the spacecraft with the center of mass within the spacecraft attitude constraints.[6]

MESSENGER then faced the problem of minimizing the maximum momentum while simultaneously minimizing the flyby arrival condition targeting error. The control authority to solve this problem was derived from the temporal history of the spacecraft attitude and the solar array orientation, both of which were subject to direct constraints. By manipulating the spacecraft attitude and array orientation, the resultant SRP forces and torques could be steered to achieve the necessary objectives. The flyby targeting was developed in the B-plane[7] for convenience, allowing a linearization of the targeting portion of the problem. Despite this simplification, the problem remained difficult to solve as the angular momentum growth due to SRP is nonlinear and the mini-max nature of the problem makes it notoriously difficult to solve. Further, the dual objectives of the problem are somewhat disjointed as the momentum and trajectory objectives are expressed in different units and do not lend themselves to easy combination into one single objective. These objectives are also sometimes conflicting, as decreases in the angular momentum may lead to increases in the targeting error and vice-versa. Many techniques have been proposed to solve multi-objective parameter optimization problems of this type.[8] As is typical for multi-objective optimization problems, in general there is no global optimal solution, and for MESSENGER it was not necessary to pay the (usually high) computational cost to identify the Pareto frontier, as the real objective was to satisfy the mission constraints and many solutions would meet this goal. For this reason, the objectives were combined into a weighted, scalar metric that determined an overall "solution quality."

Choosing the relative weighting between the momentum and trajectory objectives was subjective and required some engineering judgment. Although the control of the trajectory was useful and the overall aim of the problem, ultimately the momentum management was a notably higher priority, because if the momentum limits were violated, the spacecraft would autonomously execute a propulsive momentum dump. These autonomous momentum dumps have severe penalties as they carry all of the risks of operating the propulsion system, they perturb the trajectory, and they result in a mode demotion of the spacecraft. These activities raise mission risk and consume propellant, which are contrary to the objectives of the problem. However, there was considerable flexibility in the momentum constraint, making this objective easier to achieve. So although minimizing the peak momentum is desirable, a more complete statement of the objective is to reduce the peak momentum to below a prescribed threshold while simultaneously minimizing the flyby targeting error. The weights of the two objectives were then tuned so that the momentum would remain below the desired limit and then the targeting would be more heavily weighted.

It was not tractable to develop an attitude and solar array orientation plan all the way out to the ensuing planetary encounter. This was primarily because the modeling lacked sufficient accuracy to predict the momentum over long time periods. Furthermore, science and engineering activities were often not planned more than five weeks in advance, so these unplanned activities introduced perturbations to both the trajectory and momentum that had to be managed. As a result, the process for planning and implementing adjustments to the attitude was on a 4-5 week design cycle. The process would begin by taking the most recent orbit solution from the navigators, and solving the above optimization problem over a 2-3 week interval, allowing for any planned science or engineering attitude activities during that time frame. Although solving the optimization problem took only a few hours, the process to generate and test the necessary command sequences required 7-10 days. Once the sequence was loaded to the spacecraft and executed, the ensuing orbit determination would begin the process again. This cycle introduced substantial lead time (~5 weeks) to an ability to make adjustments to the trajectory. This process proved insufficient during a planetary approach when the situation was more dynamic. During a flyby approach time period, the feedback loop was shortened by reducing the duration of spacecraft command loads from 2-3 weeks to 1 week, and by the elimination of any unplanned engineering and science activities. These changes helped reduce the design cycle to about 15-20 days, which allowed sufficient control of the trajectory.

5. Flyby Results

With the techniques described in the prior section, MESSENGER was able to maintain flyby accuracy with a reduction in mission risk. Table 2 demonstrates the MESSENGER flyby accuracy, both for planetary encounters controlled by propulsive maneuvers as well as those controlled by solar sailing. The results from the table show that controlling the trajectory with passive means resulted in flybys that were on par with or better than those using a conventional propulsive trajectory control. So while it could be argued that solar sailing improved the planetary flyby accuracy, the real benefit was the reduction in mission risk by eliminating the flyby approach and departure maneuvers. Not only did the sailing approach eliminate the cost and risk of planning and executing maneuvers, it did so at a time when the programmatic risk of executing these maneuvers was high, as the flybys offered unique opportunities for science observations and instrument calibration.

The MOI approach did have higher errors than prior flybys that utilized the solar sailing approach.

Table 2. Planetary encounter results[5]

Flyby	Approach maneuver cost (m/s)	Departure maneuver cost (m/s)	Total flyby penalty (m/s)	B-plane target miss distance (km)	Periapse altitude offset (km)
Earth	1.3	0.0	1.7	22.1	+1.0
Venus flyby 1	2.8	35.7	40.0	36.0	-52.8
Venus flyby 2	0.8	0.0	1.0	5.7	+1.4
Mercury flyby 1	0.9	0	2.4	10.4	+1.4
Mercury flyby 2	0	0	-0.7	2.6	-0.8
Mercury flyby 3	0	0	-0.5	3.5	-0.5
MOI approach	0	n/a	n/a	8.0	+6.0

There were several complicating factors and a bit of bad luck that caused this circumstance. First, the sailing problem was additionally constrained in arrival epoch (instead of simply the B-plane intercept), as the MOI burn design was predicated on a specific epoch to ensure the correct Mercury-relative orbit. This was an additional constraint in the targeting and required some portion of the control authority to satisfy. Secondly, as the time to MOI decreased, there was a reluctance to make specific modifications because of the volatility of the B-plane solution. This reluctance was due in part to inconsistencies between concurrent orbit determination solutions from radiometric fit arcs of different lengths, affected somewhat by the varying fidelity of the solar panel angles modeled in the navigation software. There was also a superior solar conjunction that occurred 1-2 weeks in advance of MOI, but its effect was mitigated largely by the addition of four passes per week of delta differential one-way ranging (DDOR) during this period. Nevertheless, convergence of the various fit arcs occurred too late to make definitive determination of further solar sailing adjustments prior to MOI. Fortunately, the effect of radial error, as well as error in time of arrival itself, in achieving the ideal B-plane target could be mitigated somewhat by shifting the start time of MOI execution. By shifting the execution time 5 s earlier, the targeted post-MOI orbit period could be more closely achieved with an acceptable increase in achievable periapsis altitude of only a few kilometers. After reconstructing the effects of both B-plane delivery errors and MOI execution errors, the resultant spacecraft orbit achieved a 206.8 km altitude at the first post-MOI periapsis and an orbit period of about 43195 s, determined from the time between the first and second post-MOI periapses. These were about 6.8 km and 261 s longer than planned, respectively, but well within Mercury orbit injection requirements.

6. Extension to Other Missions

The technique developed by the MESSENGER team for ensuring accuracy of the gravity assist is potentially beneficial to other interplanetary missions as well. The net acceleration of the vehicle due to SRP follows an inverse square law[9], so the benefits of this technique are more pronounced as the distance to the Sun decreases. Although the adjustments to the MESSENGER trajectory were typically conducted inside 0.5 AU, the applicability of using SRP to improve flyby targeting for Venus and even Earth gravity assists may be possible as there are a number of issues beyond the magnitude of the SRP force to consider. Of course, as the distance from the Sun increases, the mission must either have a larger cross-sectional area or rely on a longer application time of the sailing technique to effect a similar change on the spacecraft velocity.

The first requirement for a mission to mirror the MESSENGER solar sailing technique is to fly a trajectory that uses gravity assists. The real benefit of the MESSENGER technique is that it achieves accuracy at the planetary flybys, thereby saving statistical ΔV. The imparted ΔV due to SRP remains quite small and is not a useful means of eliminating all but the smallest of trajectory-correction maneuvers, and therefore, is not (in general) useful for reducing deterministic ΔV. As an example, MESSENGER's physical size is typical for interplanetary spacecraft (~5 m^2 Sun-facing area), and its average accumulated ΔV over one day due to SRP was on the order of 1 cm/s, most of which is not useful as a trajectory control as it is directed radially away from the Sun regardless of spacecraft or solar array orientation. The payoff from this technique comes only if the mission benefits from very accurate small ΔVs, as is the case with flyby approach maneuvers.

Another issue of importance to using SRP as a trajectory control is the physical shape of the spacecraft. A simple example to consider is a spherical spacecraft, where the direction and magnitude of the SRP force is independent of spacecraft orientation (assuming homogenous composition of the sphere surface), rendering it impossible to sail a spacecraft of this type. At the opposite end of the spectrum is a spacecraft shaped like a flat plate. In this configuration, any attitude changes with respect to the Sun can alter both the Sun-facing area as well as the resultant force direction. Although most spacecraft are not shaped like a flat plate, missions operating in the inner solar system tend to be solar-powered, and articulated arrays make a particularly good sail surface. MESSENGER achieved the bulk of the passive trajectory corrections via adjustments of the orientation of the solar arrays. This technique was helped by the power and thermal design margins on the solar arrays. The MESSENGER arrays were capable of withstanding high temperatures, so the angle between the solar panel normal and the Sun could be small if necessary, even inside 0.5 AU. Conversely, the arrays were sized such that they could produce sufficient power for the spacecraft outside Earth's orbit, so there was significant margin for tilting the arrays away from the Sun inside 1 AU without violating the spacecraft power requirement. This wide band of allowable solar array angles greatly simplified the MESSENGER sailing problem.

Perhaps the most important driver in the use of solar sailing is the location of the spacecraft center of mass. Although it was important for the MESSENGER center of mass to be located near the center of pressure to minimize the growth of angular momentum, the mechanical designers attempted to achieve this alignment during the Mercury orbital phase, when propulsive momentum dumping is unavoidable due to the attitude pointing needed to achieve the science observations. This decision led designers to sacrifice the center of mass location prior to MOI when science pointing was minimal. As a result, the center of mass was not optimal for the solar sailing problem, as previously discussed. Designers of missions who would like to use solar sailing as a secondary trajectory control method should align the center of mass with the center of pressure to the extent possible, thereby reducing the torque due to SRP; this can be accomplished with careful spacecraft layout or with articulated devices dedicated to this purpose. With a more gradual momentum accumulation, the emphasis that must be applied to the momentum constraints can be reduced, allowing more control effort to be dedicated to achieving the right trajectory.

The complexity of the propulsion system was an additional issue that made the use of solar sailing particularly attractive to the MESSENGER team. Because of the substantial constraints on the spacecraft attitude and the wide variety of maneuver ΔV requirements (0.1-862 m/s), no two MESSENGER maneuvers were executed in the same way. This raised the risk of executing these burns, as they nearly always contained unproven elements or sequences. Additionally, even proven maneuver sequences used many different thruster sets and complicated autonomous propellant tank reconfigurations. As evidence of this complexity and risk of using the propulsion system, of the 19 maneuvers executed during cruise, four had anomalies that resulted in a failure to achieve the desired ΔV. Two additional maneuvers had less serious anomalies that did not impact the maneuver execution but resulted in spacecraft safing actions. Although other missions would not intentionally design a needlessly complex propulsion system, for missions like MESSENGER that require substantial complexity to execute the designed trajectory, the risk of flying these complex systems can be mitigated to some extent through the use of solar sailing.

7. Conclusion

MESSENGER has successfully completed the interplanetary cruise phase of the mission, and the desired Mercury orbit was achieved on 18 March 2011. In order to complete this trajectory, the MESSENGER team markedly changed the process for ensuring the necessary accuracy at the planetary encounters by utilizing solar sailing. This helped to greatly reduce mission risk by eliminating 10 propulsive maneuvers without sacrificing accuracy of the arrival conditions for the gravity assists. The solar sailing process was heavily intertwined with the management of momentum, and these problems were combined into a single multi-objective optimization problem to automatically design spacecraft attitude and solar array sequences to achieve the desired targeting while maintaining the momentum within the desired limits. Although the software to solve this problem was reasonably complex, the process of implementing these spacecraft sequences was streamlined and served to reduce mission costs. This paradigm shift demonstrated for the MESSENGER planetary encounters can be extended to other missions and could be even more useful for interplanetary flyby missions if certain parameters, notably the center of mass, are managed carefully during spacecraft design.

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