ISTS 2006-o-2-09v

MESSENGER OPERATIONS AND CRITICAL EVENTS

James C. Leary[(1)], Robert W. Farquhar[(1)], Mark E. Holdridge[(1)], Robert E. Gold[(1)], Dave G. Grant[(1)], Charlie C. Hall[(1)], James V. McAdams[(1)], Ralph L. McNutt, Jr. [(1)], and Sean C. Solomon[(2)]
[(1)] The Johns Hopkins University Applied Physics Laboratory (APL), Laurel, MD 20723, USA
[(2)] Department of Terrestrial Magnetism, Carnegie Institution of Washington (CIW), Washington, DC 20015, USA
(Email: james.leary@jhuapl.edu)

Abstract

The second year of MESSENGER operations has been highlighted by the first bi-propellant maneuver and planning for the first Venus flyby (non-propulsive gravitational assist) that is complicated by a prolonged solar conjunction and an extended solar eclipse. These engineering-focused critical events provide necessary trajectory corrections as MESSENGER progresses toward Mercury orbit insertion in March 2011, while preparing the team for upcoming science opportunities.

1. Introduction

1.1. Mission Overview

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is NASA's seventh Discovery Program mission [1]. MESSENGER, launched on August 3, 2004, is on a six-year journey to Mercury, where it will become the first spacecraft to orbit the innermost planet (Figure 1). Six planetary flybys are required to enable Mercury Orbit Insertion (MOI) on March 18, 2011 [2]. Following MOI, MESSENGER will perform science measurements for one Earth-year [3].

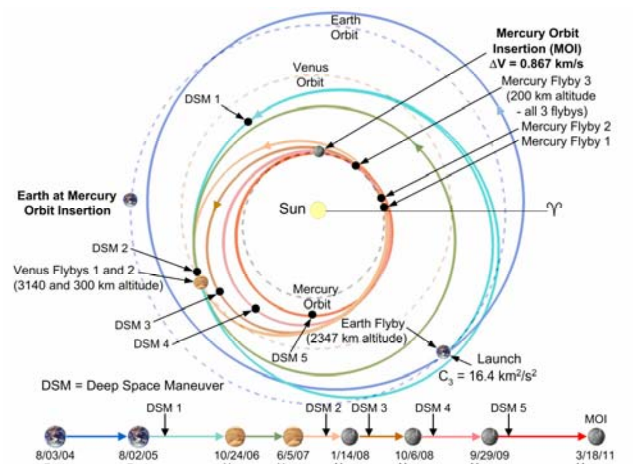

Figure 1. The MESSENGER trajectory (north-ecliptic-pole view)

The second year of MESSENGER operations has focused around the first major maneuver of the mission. This deep-space maneuver (DSM-1) provided a major course correction and targeted a Venus flyby in October 2006. While the second year has continued to involve a significant amount of flight operations (Figure 2), most of the events have been related to health and safety (e.g., instrument calibrations and maintenance). A main processor flight software update in October 2005 was also a first for the mission.

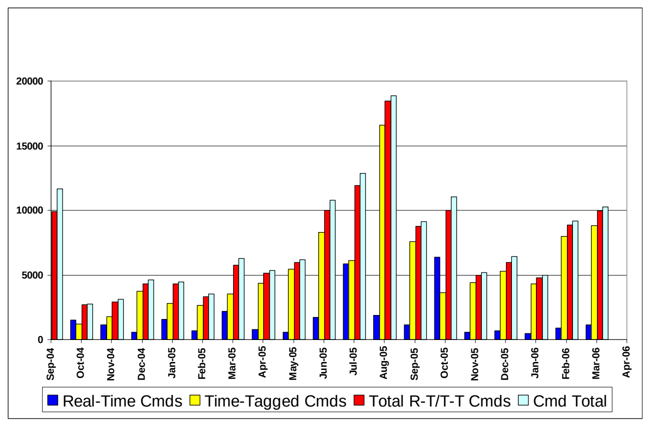

Figure 2. MESSENGER flight operations command history

1.2. Spacecraft Overview

The MESSENGER spacecraft was developed by The Johns Hopkins University Applied Physics Laboratory (APL) from January 2000 to August 2004 [4]. The spacecraft design was driven by strict mass requirements associated with a Delta 7925H launch and the harsh environment when orbiting Mercury. The 1100-kg spacecraft was 54% propellant at launch and can produce over 720 W of power in Mercury orbit. Key features (Figure 3) include a ceramic-cloth sunshade that effectively eliminates most of the solar input even in Mercury orbit, a dual-mode propulsion system providing more than 2300 m/s velocity change (ΔV) capability, two specially designed 2.6 m^2-solar panels that contain 2/3 mirrors and only 1/3 cells for thermal management, and instrument accommodation for a significant payload of seven instruments with a mass of nearly 47 kg and up to 97 W of power for operation.

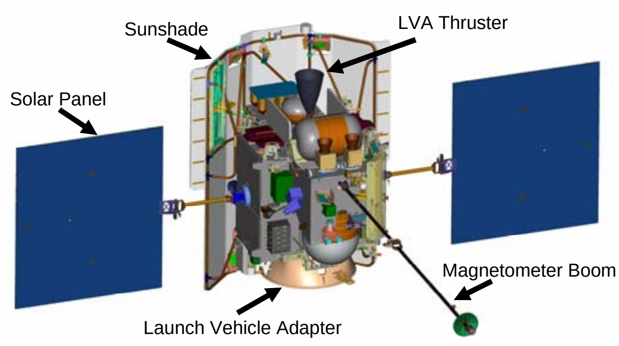

Figure 3. The MESSENGER spacecraft

1.3. Science Goals

The science goals of the MESSENGER mission [3] are based upon knowledge gained during the brief Mariner 10 flybys of Mercury in 1974 and 1975, as well as limited Earth-based observations. Mercury is a planet of extremes with both similarities to and significant differences from the other terrestrial planets. Mercury has the highest uncompressed density, i.e., corrected for self-compression, of any planet and the highest diurnal variation in temperature.

Since 1965, Mercury has been known to be in a 3:2 spin-orbit resonance, the only solar system body with such a dynamical property. On the basis of Mariner 10 images, Mercury's internal geological history ended earliest among the terrestrial planets, yet the planet has a global magnetic field and is the smallest planet with an Earth-like magnetosphere.

The three Mariner 10 flybys occurred synchronously near Mercury aphelion, so only ~45% of the planet surface was imaged. The exosphere was discovered by viewing hydrogen, helium, and oxygen in emission. Two of the flybys discovered and subsequently confirmed the internal magnetic field and the time-variable magnetosphere. Significant geological features included the Caloris Basin (Figure 4), the largest (~1300-km diameter) known impact basin on the planet and presumed to have formed during the early heavy bombardment of the inner solar system. At first glance Mercury's surface appears similar to the Moon, but there are distinctive differences. On the basis of Mariner 10 images, Mercury's surface has been divided into four major units: heavily cratered terrain, intercrater plains, lineated terrain (antipodal to Caloris), and smooth plains. The other prominent geological features are the lobate scarps, thought to record an early global contraction of the planet. Viewing the unseen half of the planet is key to understanding Mercury's formation and early evolution.
Subsequent to the Mariner 10 mission, Earth-based observations have added sodium, potassium, and calcium to the species known in Mercury's exosphere. Sodium (readily detected because of strong resonance lines in sunlight) is known to be variable in its abundance, though the sources of this variability are not fully understood. Perhaps most intriguing has been the discovery by Earth-based radar of Mercury's polar deposits. The radar backscatter and polarization properties of these deposits are well matched by water ice localized to the permanently shadowed floors of polar craters.

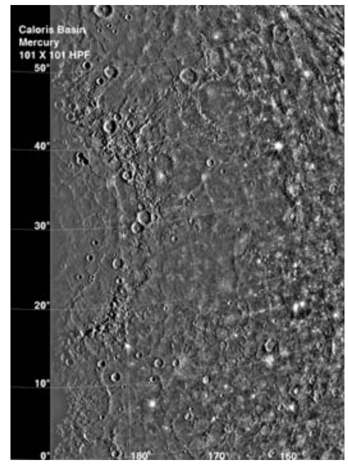

Figure 4. Mariner 10 mosaic of the eastern portion of the Caloris Basin, the largest known impact basin on Mercury. The western half of the basin will be imaged at high resolution for the first time by MESSENGER.

These tantalizing observations, combined with current thinking about the terrestrial planets and early solar-system history, led to the formulation of the broad questions that will be addressed by the MESSENGER mission: What is the origin of Mercury's high density? What are the composition and structure of its crust? What is the nature of its core? What is Mercury's tectonic history, and has its surface been shaped by volcanism? What are the characteristics of the exosphere and miniature magnetosphere? What is the nature of the mysterious polar deposits? These questions have been mapped to a set of mission objectives, which are in turn mapped to measurement objectives. These measurement objectives were used to determine, and optimize, the scientific instrumentation included as the payload on this mass-constrained mission.

1.4. Payload Overview

The MESSENGER payload is a robust collection of instruments selected to meet the key science objectives of the mission [5]. The instruments (Figure 5), including the Mercury Dual Imaging System (MDIS), Mercury Atmospheric and Surface Composition Spectrometer (MASCS), Mercury Laser Altimeter (MLA), Magnetometer (MAG), X-Ray Spectrometer (XRS), Gamma-Ray and Neutron Spectrometer (GRNS), and Energetic Particle and Plasma Spectrometer (EPPS), together with the telecommunications subsystem (for radio science) will make the first measurements in Mercury orbit, complementing measurements made during the three

MESSENEGER Mercury flybys, and will answer all of the questions that have framed the mission [3].

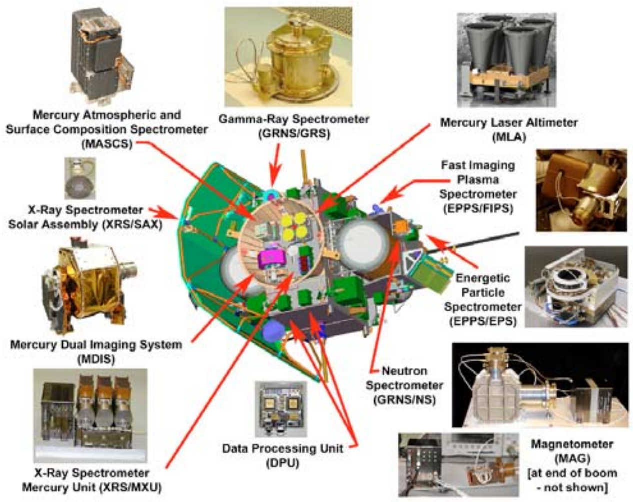

Figure 5. The MESSENGER payload

2. Critical Events

Flight critical events (CEs) for MESSENGER include the deep-space maneuvers (DSMs) required for significant modifications to the heliocentric trajectory, the planetary flybys that provide gravitational trajectory changes and unique science-gathering opportunities, and the orbit-correction maneuvers needed every three months to lower Mercury orbit periapsis altitude. Table 1 summarizes the CEs with the expected dates for the mission.

Table 1. MESSENGER flight critical events

Critical Event	Date
Earth flyby	August 2, 2005
DSM-1	December 12, 2005
Venus flyby 1	October 24, 2006
Venus flyby 2	June 6, 2007
DSM-2	October 22, 2007
Mercury flyby 1	January 14, 2008
DSM-3	March 17, 2008
Mercury flyby 2	October 6, 2008
DSM-4	December 6, 2008
Mercury flyby 3	September 29, 2009
DSM-5	November 29, 2009
MOI	March 18-20, 2011
Periapsis lower 1	June 15-16, 2011
Periapsis lower 2	September 9-10, 2011
Periapsis lower 3	December 5-6, 2011

The CE process utilized on MESSENGER has been developed by APL over the course of several planetary missions. Created on the Near-Earth Asteroid Rendezvous (NEAR-Shoemaker) mission, the process focuses around safe and effective command sequencing surrounded by significant review and testing [6]. With a dozen CEs, MESSENGER is in a very challenging mission and will continuously test and refine the process as successful execution of the mission is dependent on it. The CE process requires six steps that produce key articles for review and testing (Figure 6).

Step 1: Team brainstorming for issues and event-specific difficulties. The action list formed allows key challenges to be addressed early in the process.
Step 2: Preliminary event design that incorporates the science and instrument teams for planetary flybys. A preliminary design review (PDR) is held (guided by documented process and standardized checklist) to discuss the event timeline, spacecraft configuration (including fault-protection-autonomy considerations), contingency-test cases, and verification methods for all event goals.
Step 3: Sequence generation using tested and configured reusable building blocks. Flight constraints and resource modeling are developed in Seqgen and SeqAdapt with iterations as needed to create a flight-worthy sequence.
Step 4: High-fidelity simulations (nominal and contingency cases) using the spacecraft hardware simulator.
Step 5: Critical design review (CDR) held (again guided by documented process and standardized checklist) to review simulation results and close all issues. The flight sequence walk-through occurs at the completion.
Step 6: Real-time processes for event execution and monitoring. Spacecraft contact is required for all CEs.

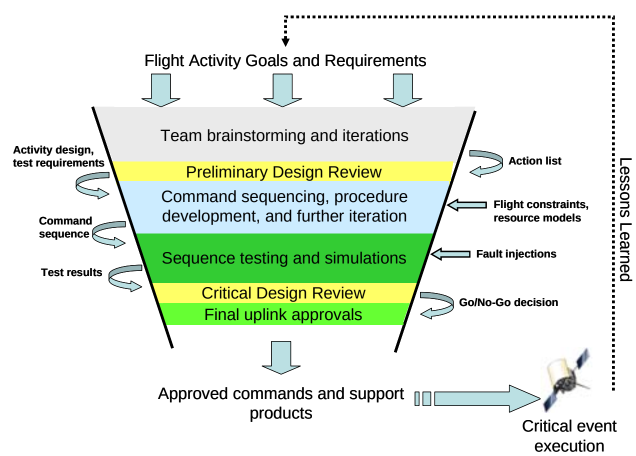

Figure 6. The critical-event management process

The CE management process provides the means for the team to be prepared for any eventuality during an event. Contingency planning and recovery options are part of the focus during the process and are essential in developing an effective, rapid response in the event of an anomaly. For example, DSM contingency plans provide re-optimized trajectory options through MOI for both the nominal flight path and a backup flight path using additional Mercury flybys.

2.1 Earth Flyby

While the first Mercury flyby is still some years in the future, earlier flybys of the Earth and Venus are useful both for exercising the instruments, as well as providing for science of opportunity. The first CE after launch, the Earth flyby in August 2005, was highly successful [7]. This flyby provided a valuable calibration opportunity for the payload and tested out the CE preparation process in a complete manner. It was a joint operation by the entire MESSENGER team including all instrument teams.

Synthesized color images of the Earth in August 2005 (Figure 7) have been used to confirm the operation of the imager. Similarly, comparison of the Earth's magnetic field measurements against very accurate models has confirmed the magnetometer operation. Scans of the geocorona in Lyman-alpha radiation, observations of a magnetic cloud and its particle signature, and the use of the onboard altimeter in a laser-ranging measurement to Earth [8] were also used to check out the payload. The following CE, DSM-1, required only the engineering team.

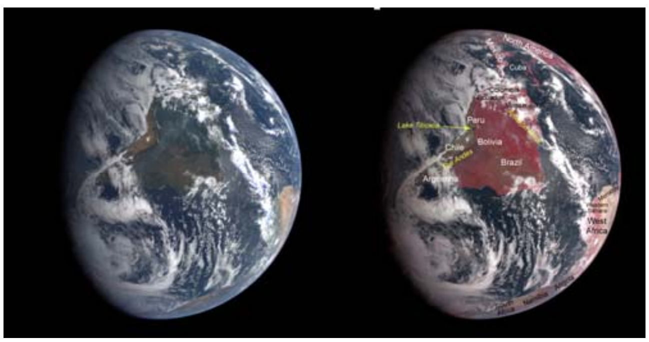

Figure 7. Visible (l) and infrared (r) synthesized color images of the Earth from the MESSENGER flyby

2.2 Deep Space Maneuver 1

The first engineering-only CE was DSM-1 on December 12, 2005. This maneuver is also referred to as Trajectory Correction Maneuver (TCM) 9, since it was the ninth planned maneuver for the mission. The 316 m/s maneuver successfully performed at 0.6 AU from the Sun allowed the spacecraft to target Venus for flyby ten months later [9]. DSM-1 required the first use of the bi-propellant system including the large velocity adjust (LVA) Leros-1b 667-N thruster. Figure 8 depicts the spacecraft orientation during DSM-1. Arrows show the directions of the Earth and Sun, the spacecraft velocity with respect to the Sun, and the course-correction ΔV.

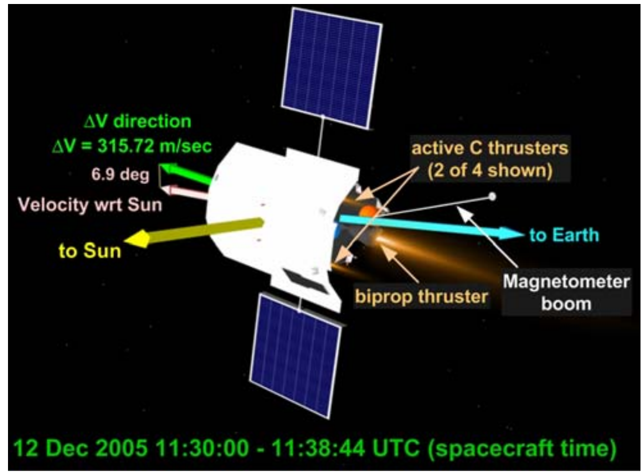

Figure 8. Spacecraft orientation during DSM-1

The CE process uncovered several issues during the incremental development of the maneuver. During initial planning, it was realized that the on-board fault protection system would have to be customized for the event. Due to the time-critical nature of the maneuver, the rule-based autonomy engine that monitors spacecraft health and safety was temporarily suspended for the duration of the maneuver for all cases except the most serious of faults. A backup maneuver was planned for a week later as mitigation in the unlikely event that the baseline maneuver did not execute. The PDR was held on October 6, 2005. Six action items resulted. All were minor; two recommended increasing the scope of the contingency simulations; three recommended further investigation and review of the fault protection strategy and contingency plan; and one recommended the creation of a "first-use" item list and clarification of the risk associated with each. PDR actions were completed as were mission simulations in preparation for the CDR. The CDR was held on November 29, 2005. No formal action items resulted, but the recommendation to revisit the fault protection strategy was taken and addressed. The customization of the fault protection autonomy system was very challenging, but when effectively employed, helped ensure a robust activity. The CE process produced a successful event (Table 2). The maneuver was very accurate and well within required limits [10].

Table 2. DSM-1 performance summary

Planned magnitude	315.72 m/s
Actual magnitude from navigation reconstruction	315.63 m/s
% Error (< 0.34% requirement)	-0.027%
Pointing error (< 0.344° requirement)	0.026°
Propellant usage	106 kg

Lessons learned from DSM-1 are automatically incorporated into the CE process for future events either explicitly or through new constraints, sequence modifications, or spacecraft changes (including software uploads). For DSM-1, there were eight software change requests that will be uploaded to the spacecraft in 2007 in preparation for DSM-2.

2.3 Venus Flyby 1

The first Venus flyby, on October 24, 2006, increases the orbit inclination and reduces the orbit period [2]. This non-propulsive flyby is at a high altitude (>3000 km), lowering mission risk. However, two additional complexities, a prolonged solar conjunction affecting communications and an approximately one-hour eclipse compound the operation and make it a CE for the mission (Figure 9) and preclude the ability to perform science measurements safely. Operation of the payload will be conducted at the lower altitude, second Venus flyby in June 2007. That flyby will be similar in scope to the flyby of the Earth in 2005 and will be used to accomplish instrument calibrations, rehearse for the first Mercury flyby, and acquire science of opportunity at Venus itself.

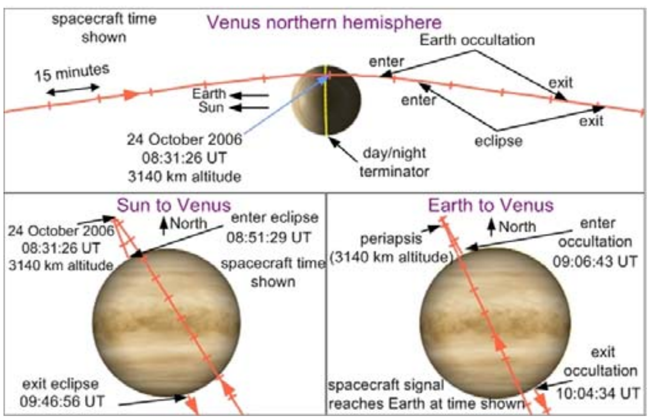

Figure 9. Venus flyby 1 trajectory details

As the spacecraft approaches Venus, it will enter a superior solar conjunction. Effectively, the Sun is in between the Earth and the spacecraft. Experience from the NEAR mission shows that communication inside of a 3° Sun-Earth-Spacecraft angle is possible, but can be difficult. Inside of 2° can result in dropped packets and inside of 1.5° communications will be severely compromised, and the mission plans to monitor only beacon tones in this area (Figure 10). MESSSENGER has daily 4-hour tracks planned through the Deep Space Network (DSN) outside of 1.5° to allow spacecraft health and safety monitoring and radio science calibrations. The 57-minute eclipse following the Venus flyby produces the coldest temperatures that the solar arrays will experience during the mission (-130°C).

Initial planning has identified a set of on-board autonomy rules that will alter the spacecraft state as it approaches eclipse for power management. Load shedding is performed prior to eclipse entry and then nominal spacecraft state (including transmitter turn on) is returned once the battery achieves full charge following the eclipse. Also, two weeks prior to the flyby, the spacecraft will be thermally conditioned by boost heating as many areas as possible, allowing heater power to be minimized during the eclipse.

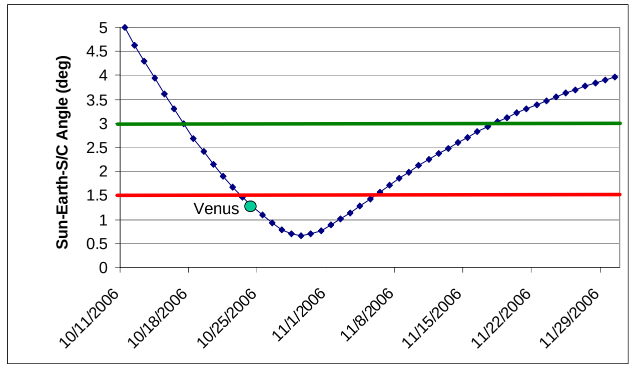

Figure 10. Venus flyby 1 timeline

The CE PDR will be held on July 20, 2006, followed by a CDR on September 14, 2006. These reviews will provide the necessary scrutiny to facilitate a safe and effective operation.

2.4 Venus Flyby 2

While no payload operations are planned for the first Venus flyby due to operational constraints, similar calibration and opportunity measurements are being planned for the second Venus flyby. Notable amongst these will be the first opportunity and attempt to use the onboard lidar to range to the Venus cloud deck and explore its structure. In addition, fields and particles measurements in the upstream solar wind will be obtained by MESSENGER for comparison against the magnetic field draping around the Venus ionosphere and its state as measured by the European Space Agency's Venus Express, now in orbit about that planet. This is a unique opportunity for viewing both the input solar wind parameters and Venus response. Finally, there has been some recent re-analysis of telescopic observations [11] suggesting that some information from Venus surface may be available in a spectroscopic window near 1 micron. MESSENGER will be flying over near Ovda Regio (Figure 11), an interesting region as identified in radar imaging from the Magellan mission to that planet, and will attempt to image this region.

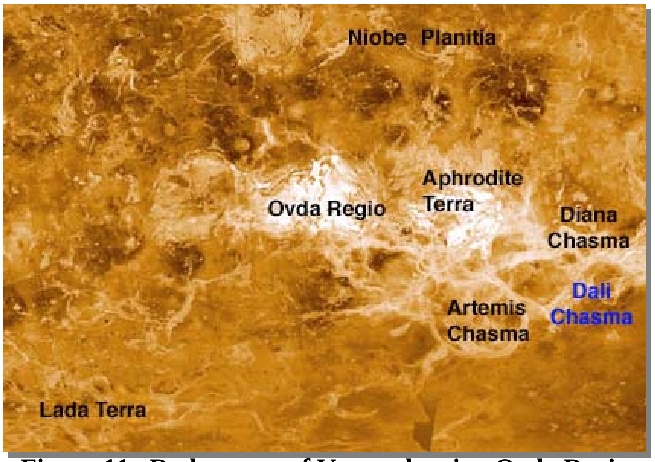

Figure 11. Radar-map of Venus showing Ovda Regio

3. Conclusion

The MESSENGER mission continues to be successful through the second year of operations. Part of this success is attributable to the APL-developed CE management process. The process provides established, repeatable products, developed incrementally, facilitating thorough, continuous review. This process will continue to be refined as the mission progresses through two Venus flybys, three Mercury flybys, and finally the first orbiting mission of Mercury.

4. Acknowledgments

"The MESSENGER Team" includes hundreds of engineers, scientists, technicians, support personnel, and managers. The current MESSENGER effort is supported by the NASA Discovery Program under contract NAS5-97271 at APL and NASW-00002 at the Carnegie Institution of Washington.

References

1. McNutt, R. L., Jr., Gold, R. E., Solomon, S. C., Leary, J. C., and Grant, D. G., MESSENGER: A Discovery mission to Mercury, *Proceedings of the 6th International Conference on Low-Cost Planetary Missions (ICLCPM),* 71-77, Kyoto, Japan, October 13-15, 2005.

2. McAdams, J. V., Dunham, D. W., Farquhar, R. W., Taylor, A. H., and Williams, B. G., Trajectory design and maneuver strategy for the MESSENGER mission to Mercury, *15th AAS/AIAA Space Flight Mechanics Conference*, Paper AAS 05-173, 21 pp., Copper Mountain, CO, January 23-27, 2005.

3. Solomon, S. C., McNutt, Jr., R. L., Gold, R. E., Acuña, M. H., Baker, D. N., Boynton, W. V., Chapman, C. R., Cheng, A. F., Gloeckler, G., Head, III, J. W., Krimigis, S. M., McClintock, W. E., Murchie, S. L., Peale, S. J., Phillips, R. J., Robinson, M. S., Slavin, J. A., Smith, D. E., Strom, R. G., Trombka, J. I., and Zuber, M. T., The MESSENGER mission to Mercury: Scientific objectives and implementation, *Planetary and Space Science, 49,* 1445-1465, 2001.

4. Santo, A. G., Leary, J. C., Peterson, M. R., Huebschman, R. K., Goss, M. E., McNutt, Jr., R. L., Gold, R. E., Farquhar, R. W., McAdams, J. V., Conde, R. F., Ercol, C. J., Jaskulek, S. E., Nelson, R. L., Northrop, B. A., Mosher, L. E., Vaughan, R. M., Artis, D. A., Bokulic, R. S., Moore, R. C., Dakermanji, G., Jenkins, J. E., Hartka, T. J., Persons, D. F., and Solomon, S. C., MESSENGER: The Discovery-class mission to orbit Mercury, *International Astronautical Congress, World Space Congress, American Institute of Aeronautics and Astronautics, Paper IAC-02-U.4.1.04,* 11 pp., Houston, TX, October 10-19, 2002.

5. Gold, R. E., McNutt, Jr., R. L., Solomon, S. C., and the MESSENGER Team, The MESSENGER science payload, *Proceedings of the 5th International Academy of Astronautics International Conference on Low-Cost Planetary Missions, Special Publication SP-542*, edited by R. A. Harris, pp. 399-405, European Space Agency, Noordwijk, The Netherlands, 2003.

6. Holdridge, M. E., Applying successful NEAR mission operations approaches and refining for CONTOUR mission operations, *Acta Astronautica*, 52, 343-352, 2003.

7. Solomon, S. C., McNutt, R. L., Jr., Domingue, D. L., Gold, R. E., and Leary, J. C., The MESSENGER mission to Mercury: Status after the first planetary flyby, *Eos Trans. AGU, 86(52), Fall Meet. Suppl*., Abstract P51A-0894, 2005.

8. Smith, D. E., Zuber, M. T., Sun, X., Neumann, G. A. , Cavanaugh, J. F. , McGarry, J. F., and Zagwodzki, T. W., Two-way laser link over interplanetary distance, *Science*, 311, 53, 2006.

9. Vaughan, R. M., Leary, J. C., Conde, R. F., Dakermanji, G., Ercol, C. J., Fielhauer, K. B., Grant, D. G., Hartka, T. J., Hill, T. A., Jaskulek, S. E., McAdams, J. V., Mirantes, M. A., Persons, D. F., and Srinivasan, D. K., Return to Mercury: The MESSENGER spacecraft and mission, *IEEE Aerospace Conference*, IEEEAC paper #1562, 15 pp., Big Sky, MT, March 4-11, 2006.

10. MESSENGER project website, mission design section (http://messenger.jhuapl.edu/the_mission/mission_design.html).

11. Hashimoto, G. L., and Sugita, S., On observing the compositional variability of the surface of Venus using nightside near-infrared thermal radiation, *J. Geophys. Res.,* 108, 5109, doi:10.1029/2003JE002082, 2003.