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The MESSENGER mission to Mercury: Development history and early mission status

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This review of the status of the MESSENGER mission is dedicated to Larry E. Mosher, the lead engineer for the MESSENGER propulsion system. After seeing MESSENGER from concept through development and launch, Mr. Mosher passed away on 19 March 2005. Without his innovation and dedication, MESSENGER would not now be on its way to Mercury.

Abstract

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, launched 3 August 2004, will be the first spacecraft to orbit the planet Mercury. Mercury holds answers to several critical questions regarding the formation and evolution of the terrestrial planets. The MESSENGER mission will fly by Mercury in 2008 and 2009 and will orbit Mercury for one Earth year beginning in March 2011. The >14 kW m^{-2} solar thermal input and the large velocity change required to reach Mercury orbit make this a very challenging mission from thermal and mass perspectives. MESSENGER overcomes these challenges with innovative applications of existing technologies and materials. Seven miniaturized instruments, along with the spacecraft telecommunications system, satisfy all scientific objectives of the mission. The Mercury flybys are preceded by gravity assists at the Earth (2005) and at Venus (2006 and 2007). This paper offers an overview of mission history and objectives, spacecraft and payload, current status, and data acquisition plans.

Keywords: MESSENGER; Mercury; Planetary science

1. Introduction

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is underway to the innermost of the terrestrial planets, enigmatic Mercury. Understanding Mercury will provide new insights into the formation and evolution of our solar system and planetary systems around other solar-mass stars. MESSENGER is a competitively selected NASA Discovery mission (7th in that program line) directed by the Principal Investigator, Sean C. Solomon, of the Carnegie Institution of Washington (CIW). The spacecraft and mission have been designed, manufactured, and implemented by a consortium headed by CIW and The Johns Hopkins University Applied Physics Laboratory (APL) that also includes 22 science-team Co-Investigators and their institutions. Begun in January 2000 and launched 3 August 2004, MESSENGER is en route to fly by and then orbit Mercury, taking up the scientific investigation where Mariner 10 left off 30 years ago.

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2. Background

2.1. Early concept: dual mercury orbiters

Following the successful first reconnaissance of Mercury by Mariner 10, the need for, and problems in implementing, a Mercury orbiter were soon realized (Stern and Vilas, 1988). One key, enabling concept for near-term Mercury exploration was the work of Yen (1985, 1989) in reducing the required on-board propulsion requirements by using multiple Venus and Mercury flybys prior to orbit insertion.

A NASA-sponsored Science Working Team (Belcher et al., 1991) studied a Mercury orbital mission in the late 1980s. The team proposed two spacecraft launched with a Titan IV Centaur and using multiple gravity assists to reach Mercury in ~4 years for a one-year orbital mission. The two identical spacecraft would be injected into 12-h orbits with periapses of 200 km, one over the north pole and one over the equator, and would have their orbital-plane inclinations separated by about 60° for the first two Mercury years and then aligned for the second two. This approach provided for an initial concentration on magnetospheric science objectives followed by a switch to planetary surface science. The eleven instruments of the strawman payload, with an aggregate mass of ~100 kg and using ~100 W, would return between ~17 and 64 kilobits per second (kbps) of information. Each spacecraft would have ~1000 kg of mass (dry) and carry ~1600 kg of propellant (monomethyl hydrazine, MMH, and nitrogen tetroxide, NTO).

2.2. Discovery Program concepts

NASA's planetary Discovery Program was initiated with a workshop sponsored by the San Juan Capistrano Institute on 16–20 November 1992. Seven Mercury mission concepts were presented at the workshop (two more had been submitted but were withdrawn prior to the workshop). Of the 73 concepts discussed at the workshop, 11 were selected for funded study (NASA Press Release 93-02-11B, 11 February 1993). Of the latter, two were Mercury missions, one a multiple flyby mission and one an orbiter.

In response to the first formal request for mission proposals in the Discovery Program NASA received twenty-eight proposals, including one for each of the two funded Mercury studies, in October 1994. In the selection of 28 February 1995 (NASA Press Release 95–19), Lunar Prospector was selected for flight; Comet Nucleus Tour (CONTOUR), Suess-Urey (later renamed Genesis), and Stardust were downselected for further study. On 22 November 1995, Stardust was selected for flight from among these (NASA Press Release 95209).

3. MESSENGER overview

3.1. History of the MESSENGER concept

The MESSENGER mission was conceived in March 1996, prompted in part by news that the next opportunity to propose to the Discovery Program would be announced soon. MESSENGER, a mission to launch a spacecraft with seven miniaturized instruments and use gravity assists to reach Mercury orbit, was first proposed to NASA on 16 December 1996 in response to NASA AO-96-OSS-02. The Phase 1 (initial) proposal, with a launch in September 2002 to reach Mercury orbit in February 2007, was selected for a Feasibility Study (along with Aladdin, Venus Environmental Satellite, and resubmissions of CONTOUR and Genesis). The MESSENGER Feasibility Study submitted to NASA on 11 August 1997 identified backup launch windows, including one similar to that currently begin flown by the MESSENGER spacecraft. MESSENGER was not selected for flight at that time, however (Genesis and CONTOUR were instead selected as Discovery missions 5 and 6, respectively).

The MESSSENGER mission was reproposed at the next opportunity on 26 June 1998 in response to NASA AO 98-OSS-04. Two new Co-Investigators (Co-Is) were added and one was dropped (bringing their number to 20). The gamma-ray spectrometer was supplemented with a neutron-spectrometer sensor to become the Gamma-ray and Neutron Spectrometer (GRNS), and the Energetic Particle Spectrometer (EPS) was supplemented with the Fast Imaging Plasma Spectrometer (FIPS) sensor to become the Energetic Particle and Plasma Spectrometer (EPPS). This proposal was accepted for further study (by means of a "Concept Study" rather than a "Feasibility Study") as were INSIDE Jupiter, Deep Impact, Aladdin (also reproposed), and Venus Sounder for Planetary Exploration. The MESSENGER Concept Study, submitted on 23 March 1999, identified a prime launch opportunity in March 2004 as well as a backup opportunity in early August 2004. Following a site visit by the Discovery review panel on 29 April 1999, MESSENGER was selected for flight as Discovery mission 7 on 7 July 1999 (and Deep Impact as mission 8). The MESSENGER project formally started on 1 January 2000.

The payload suite remains that proposed in 1998. The Principal Investigator (PI) and Co-Is from the 1998 proposal have all been retained, but two additional Co-Is were added (with NASA concurrence) during the development phase of the mission.

3.2. Scientific objectives

Determining the composition of Mercury, with its anomalously high ratio of metal to silicate, will provide a unique window on the processes by which planetesimals in the primitive solar nebula accreted to form planetary embryos and planets. Documenting Mercury's global geological history will elucidate the role of terrestrial planet size as a governor of magmatic and tectonic history. Characterizing Mercury's magnetic field and the size and state of Mercury's core will advance our understanding of the energetics and lifetimes of magnetic dynamos in solar system bodies. Determining the volatile species in Mercury's polar deposits, exosphere, and magnetosphere will provide insight into volatile inventories, sources, and sinks in the inner solar system. During the flybys of Mercury, regions unexplored by Mariner 10 will be seen for the first time, and new data will be gathered on Mercury's exosphere, magnetosphere, and surface composition. During the orbital phase of the mission, one Earth year in duration, MESSENGER will complete global mapping and the detailed characterization of the exosphere, magnetosphere, surface, and interior. These scientific objectives remain unchanged from the original Concept Study (Solomon et al., 2001; Solomon, 2003).

3.3. Spacecraft

The spacecraft is dominated by the sunshade, solar arrays, and propellant tanks that are located inside the structure (Wiley et al., 2003). Two views of the spacecraft are shown in Fig. 1; the payload attach fitting (PAF) is at the bottom and the large velocity adjust (LVA) rocket motor is at the top. Within ~0.8 astronomical units (AU) of the Sun, the sunshade must point to within ~10° of the direction to the Sun to maintain spacecraft subsystem temperatures within acceptable bounds.

The spacecraft uses ordinary space electronics, has minimal moving parts, and has extensive redundancy and cross strapping to enhance its robustness. Major innovations include its ceramic-cloth sunshade, an integrated lightweight structure, a high-performance propulsion system, and a solar array incorporating optical solar reflectors to prevent overheating. Details of the design approach and system performance estimates during early phases of the program are given elsewhere (Santo et al., 2001, 2002).

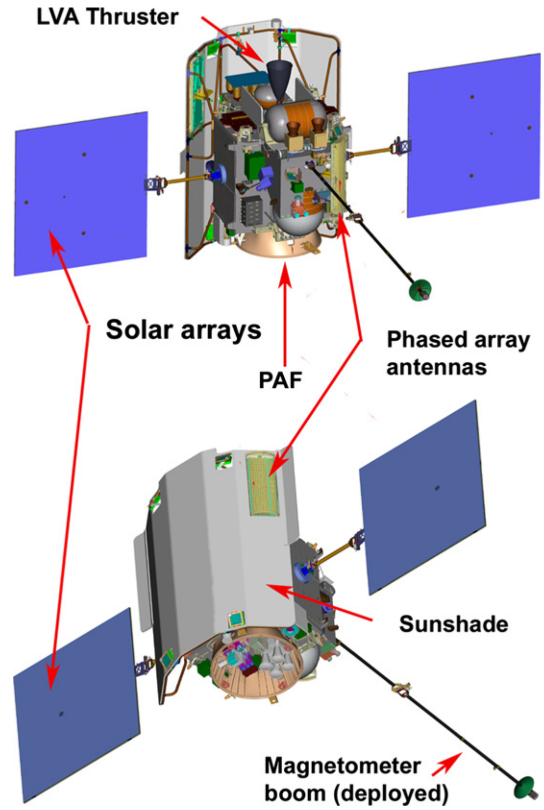

Fig. 1. Schematic of the MESSENGER spacecraft showing the "back" (top) and "front" (bottom).

3.4. Payload

The MESSENGER payload was tailored to meet mass constraints while responding to the science objectives. Masses and nominal power consumptions for the instruments are given in Table 1; their placement on the spacecraft is shown in Fig. 2.

Table 1
MESSENGER payload instruments

Instrument	Abbreviation	Mass (kg)	Nominal power (W)
Mercury Dual Imaging System	MDIS	7.9	Included with DPU power
Gamma-Ray and Neutron Spectrometer	GRNS	13.1	28.0
X-Ray Spectrometer	XRS	3.4	6.8
Magnetometer (including boom)	MAG	4.4	4.4
Mercury Atmospheric and Surface Composition Spectrometer	MASCS	3.1	6.7
Mercury Laser Altimeter	MLA	7.4	25.0 orbit average
Energetic Particle and Plasma Spectrometer	EPPS	3.1	8.8
Data Processing Units (2)	DPU	3.1	16.3 with MDIS on
Magnetic shielding, purge system, payload harness	MISC	1.5	No associated power
Total		47.0	96.0

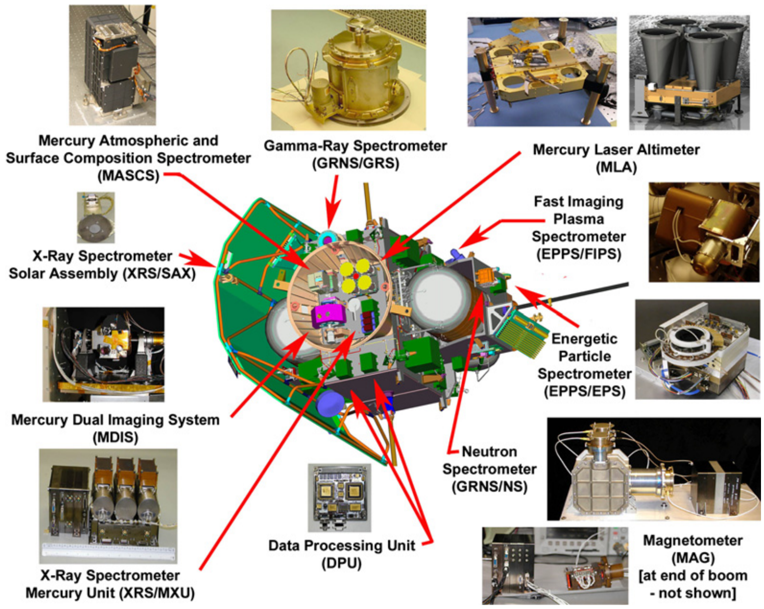

Fig. 2. MESSENGER spacecraft and locations of its payload instruments.

The initial approach to the payload implementation was described by Gold et al. (2001). Significant changes were made to the designs of the GRNS instrument and the Mercury Dual Imaging System (MDIS) prior to implementation. Originally based upon a passive scintillator approach, the design for GRNS was modified to use an actively cooled, high-purity germanium (HPGe) detector because of the poorer than expected signal-to-noise ratio returned by a similar gamma-ray instrument on the Near Earth Asteroid Rendezvous (NEAR)-Shoemaker mission (Goldsten et al., 1997). The original MDIS concept was modified to enable optical navigation images to be taken during the Mercury flybys and prior to the Mercury Orbit Insertion (MOI) maneuver. The instrument, as implemented, includes wide-angle and narrow-angle cameras and a scan platform to provide an additional degree of freedom in pointing. Other payload instruments include an integrated ultraviolet, visible, and infrared spectrometer that is sensitive enough to detect atmospheric emissions and robust enough to map mineralogical absorption features on the sun-lit surface; an X-ray spectrometer that complements GRNS for remote geochemical mapping; a vector magnetometer; a laser altimeter to determine the topography of surface features and whether Mercury has a fluid core; and an energetic particle and plasma spectrometer to characterize ionized species in the magnetosphere. Gold et al. (2003) provide some details for the updated payload as integrated into the spacecraft. The payload was fully calibrated before launch, and an additional series of calibration measurements are planned during the 6.5-year cruise to Mercury.

4. MESSENGER development

4.1. Design and development

Following the start of the program in January 2000, MESSENGER held a joint System Requirements Review/Conceptual Design Review (22 and 23 May 2000), Confirmation Assessment Review (21 May 2001), Preliminary Design Review (22–24 May 2001), and NASA Confirmation Review (2 June 2001) before beginning Phase C/D (critical design and development) on 1 July 2001. There were 33 formal external independent reviews with ~100 reviewers at the subsystem and system level. In addition, there were both preliminary and critical design reviews for all instruments, including special reviews that resulted in the revised GRNS approach beginning with an implementation meeting on 7 July 2001. In all, there were 29 formal instrument reviews that covered both hardware and software and involved 226 reviewers in all.

The MESSENGER Critical Design Review (CDR) was held on 19–22 March 2002. At that point the approach for both the spacecraft and instruments was firm, the planned launch targeted an optimized March 2004 window (Yen, 2001; McAdams et al., 2002), and backup launches in May 2004 and July to August 2004 were identified. The overall spacecraft concept and all subsystems were designed (e.g., Ercol and Santo, 1999; Ercol et al., 2000; Persons et al., 2000; Wallis and Cheng, 2001; Vaughan et al., 2001; Dakermanji et al., 2002; Krupiarz et al., 2002; Nhan et al., 2002; Conde et al., 2002; Le et al., 2002; Ling et al., 2002; Moore, 2002; O'Shaughnessy and Vaughan, 2003; Krupiarz, 2003; Stilwell et al., 2003; Stratton et al., 2003; Hauck and Finnigan, 2003; Heiligman et al., 2003).

4.2. Integration and test

Integration and Test (I&T) began with the delivery of the integrated structure and propulsion system to APL on 3 February 2003. The MESSENGER web site (http://messenger.jhuapl.edu/) links to various time-lapse videos (http://messenger.jhuapl.edu/webcam/daily-movies.html) including a movie of the entire spacecraft integration filmed at one frame every 15 min from 31 March 2003 to 30 January 2004, when the spacecraft was sealed within the thermal vacuum chamber at Goddard Space Flight Center for thermal vacuum testing.

During the summer of 2003, integration of various subsystems was falling behind schedule. Manufacturing issues with the inertial measurement unit had led to its identification as the pacing risk item. Common manufacturing problems were identified with the electromagnetic interference filters on most of the payload instruments, leading to remanufacture of electronics boards. MESSENGER uses multiple-layer electronics boards to reduce mass, and several flight boards from subsystems across the spacecraft were found to exhibit delaminations that could cause critical failures. The MESSENGER Program management concluded that the prudent action was to remanufacture and replace all of the suspect boards, rather than risk the mission. As schedule slips continued, the project reluctantly endorsed a launch delay from March 2004 to May 2004 launch window to NASA management on 28 August 2003. The endorsement was accepted but led to further erosion of financial reserves that had been expended in dealing with the manufacturing problems. All flight items exhibiting possible problems were replaced.

4.3. Functional testing

Functional testing of the spacecraft was more complicated, with more test cases, than usual because of the large amount of cross-strapping between the various subsystems. The autonomy system testing complexity also increased as a result of both the cross-strapping and the large number of onboard autonomy rules. This complex implementation of autonomy was driven by an exhaustive study of mission-threatening scenarios that could cause a failure in the pointing of the sunshade toward the Sun while MESSENGER is inside Venus's orbit and, especially, while it is in orbit about Mercury. Because the round-trip light time from the Earth to the spacecraft can be as great as ~30 min, the spacecraft must be autonomous in regaining control of its attitude in any fault situation to prevent catastrophic mission loss. As designed, MESSENGER will regain control of its attitude in ~15 min. This is within the ~30-min limit after which irreversible thermal damage would begin to affect the spacecraft under worst-case conditions.

Following the completion of thermal vacuum testing at Goddard Space Flight Center, MESSENGER was shipped to the Astrotech Space Operations facility in Florida, where testing continued to be run from the Missions Operations Center at APL (Fig. 3(a)).

Because of a desire for further testing and to ensure that a later slip could be accommodated, on 24 March 2004 NASA directed the MESSENGER project to delay the launch window for a second time, from May 2004 until early August 2004. This allowed additional testing to proceed and removed possible conflicts with other launches (if the planned launch had remained in May, NASA could not guarantee availability of the launch site in August if new problems developed later in the program). This August launch opportunity had been the backup window in the original proposal for this Discovery selection. At that time, implementation of this window required an Earth flyby one year after launch followed by two flybys of Venus and two of Mercury prior to orbit insertion in September 2009. The previous March and May 2004 windows had allowed for a larger launch mass, however, and the additional mass had in fact been used to simplify further the (still complex) MESSENGER spacecraft. Those mass additions precluded orbit insertion after only two Mercury flybys with the August launch. By adding a third flyby of the planet in September 2009 and delaying Mercury orbit insertion to March 2011, the mass margin was increased to an acceptable level at the expense of a longer cruise time and an orbit that would heat the spacecraft to higher, but still acceptable, temperatures.

4.4. Shipment to the launch site and launch

Following the Mission Readiness Review (MRR) on 24 June 2004 and the Mission Readiness Briefing to the NASA Associate Administrator for Space Science on 8 July, MESSENGER was fueled, mated to the Delta II third stage (Fig. 3(b)), and encapsulated in the shroud (Fig. 3(c)). On 21 July, the assembly was moved to Pad 17-B of the Cape Canaveral Air Force Station (CCAFS) (Fig. 3(d)).

The Flight Readiness Review (FRR) and Launch Readiness Review (LRR) were conducted on 29 and 31 July, respectively, for the opening of the launch window in the early morning hours of 2 August. The tower was rolled back at ~5:00 PM on 1 August, and the terminal countdown began at 11:16 PM Eastern Daylight Time (EDT) for a launch on 2 August at 2:16:11 AM EDT. With thunderstorms in the vicinity of the launch pad as the 12-second launch window neared, the countdown was halted and the launch rescheduled for the next window that would open ~24 h later.

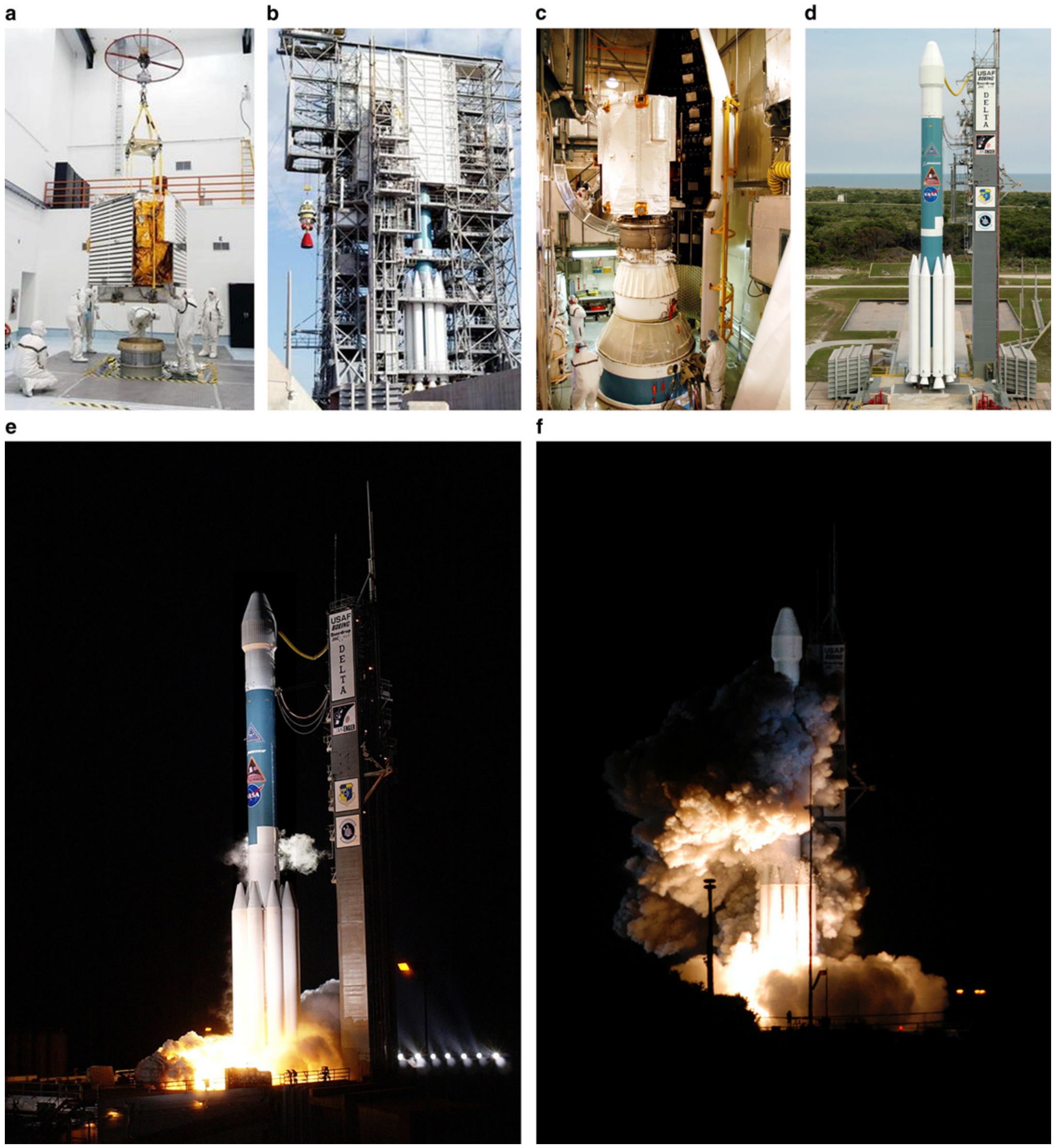

Fig. 3. Views of the MESSENGER spacecraft and launch vehicle from final testing through launch on 3 August 2004. (a) Spacecraft being lowered onto spin table (6 July 2004); (b) Delta II second stage being lifted up the mobile service tower (6 July 2004); (c) encapsulation of MESSENGER in shroud; (d) vehicle stack at Pad 17B (1 August 2004); (e) ignition; and (f) liftoff! (3 August 2004).

During the late evening on 2 August, there were again thunderstorms in the area. The count was continued into the early morning of 3 August and a break in the weather pattern occurred, yielding a "go" for the "range". MESSENGER was successfully launched at 02:15:56.537 EDT (Figs. 3(e) and (f)).

Staging and engine restart were successful, as was solar array deployment.

4.5. Current status

To date MESSSENGER has successfully responded to over ~25,000 commands. One safe-hold event, soon after launch, was resolved within hours and traced to slightly off-parameter settings in the autonomy system that have now been corrected. The autonomy system functioned as designed and the spacecraft was never in danger.

MESSENGER has made several trajectory correction maneuvers to date, and the trajectory for the mission has been optimized, now that the spacecraft launch parameters are known (McAdams et al., 2005). The spacecraft is fully commissioned, and all instruments have been fully checked out except for the Energetic Particle and Plasma Spectrometer (EPPS), which will have its first high-voltage turn-on in space in April 2005.

Planning is currently underway for the first MESSENGER gravity assist, a flyby of Earth on 2 August 2005, followed by the first deep space maneuver (and use of the bipropellant propulsion system) in December. That maneuver will line up the trajectory for the first Venus gravity assist on 24 October 2006.

Basic mission implementation plans remain unchanged from those discussed by Solomon et al. (2001); dates have changed to accommodate the new arrival date (now 18 March 2011 versus 6 April 2009, which corresponded to the original March 2004 launch date). MESSENGER will collect data from Mercury orbit for one Earth year. The MESSENGER Project as currently planned will cease spacecraft operations in March 2012, and one more year will be spent on final analysis and archiving of the data.

5. International interactions

MESSENGER has no non-U.S. Co-Is; however, since selection, the MESSENGER Science Team and Project have sustained productive and mutually beneficial dialogues with members of the science team on BepiColombo, approved as a Cornerstone mission by the European Space Agency in October 2000. The first meeting between representatives of the two teams was held in September 1999 at APL. Meetings have been held since then on a regular basis (McNutt et al., 2004), the most recent being at the 35th COSPAR meeting in Paris in July 2004. With MESSENGER launched and BepiColombo designs and plans maturing, the opportunities for continuing synergies using the capabilities of both missions also continue to mature.

Acknowledgments

“The MESSENGER Team” includes hundreds of scientists, engineers, designers, technicians, support personnel, subcontractors, and managers too numerous to enumerate. We also acknowledge the assistance of NASA personnel and others who gave of their time to help review the program and enable MESSENGER to be on its way to Mercury.

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