



MESSENGER Mission Overview

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ABSTRACT

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission was proposed to NASA in 1998 as the next step in the robotic exploration of Mercury, following the Mariner 10 flybys in the 1970s. Six science questions framed the mission, guiding the designs of the trajectory, payload, and spacecraft. The mission design used a combination of maneuvers and planetary flybys to slow the spacecraft over a 6.6-year period in order to achieve an orbit about Mercury that would facilitate the specific measurements to be made over the course of a single Earth year. An instrument suite was chosen to provide the necessary data with measurement redundancy to guard against hardware failure during the long mission. An innovative ceramic-cloth sunshade—along with a robust fault-management system—afforded the spacecraft protection from the harsh environment as close as 0.3 AU from the Sun and allowed the use of traditional electronics, which operated at approximately room temperature. The development of a lightweight, electronically steerable phased-array antenna also proved to be enabling for the mission communications. The cadence of maneuvers and flybys during the long cruise phase proved to be demanding for the mission operations team, which remained at least as busy throughout the orbital phase of the primary mission and the two extended missions that followed. Automated science planning facilitated the collection of orders of magnitude more data than originally anticipated, all of which were delivered to the Planetary Data System on schedule.

INTRODUCTION

As of the mid-1990s, the Mariner 10 spacecraft remained the only mission to have explored Mercury. Two decades earlier, it had made three flybys of the innermost planet, and although that mission was successful, it was able to observe less than half the planet, and many important questions remained unanswered. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission promised to address

those questions as well as others derived from ground observations, and in so doing to fill a long-standing gap in the general understanding of terrestrial planets.

The articles in this issue, which focus largely on the execution of the mission, can be understood best with some context on how the mission was formulated and developed. The design of the trajectory, instruments, and spacecraft followed from the key science questions that

Table 1. The key science questions that drove the design of MESSENGER's primary mission

Guiding Question	Science Objective	Measurement Objectives (Instruments)
What planetary formational processes led to the high ratio of metal to silicate in Mercury?	Map the elemental and mineralogical composition of Mercury's surface	<ul style="list-style-type: none"> • Surface elemental abundances (GRNS and XRS) • Spectral measurements of surface [MASCS (VIRS)]
What is the geological history of Mercury?	Globally image the surface at a resolution of hundreds of meters or better	<ul style="list-style-type: none"> • Global imaging in color (MDIS wide-angle camera) • Targeted high-resolution imaging (MDIS narrow-angle camera) • Global stereo imaging (MDIS) • Spectral measurements of geological units [MASCS (VIRS)] • Northern hemisphere topography (MLA)
What are the nature and origin of Mercury's magnetic field?	Determine the structure of the planet's magnetic field	<ul style="list-style-type: none"> • Mapping of the internal field (MAG) • Magnetospheric structure (MAG, EPPS)
What are the structure and state of Mercury's core?	Measure the libration amplitude and gravitational field structure	<ul style="list-style-type: none"> • Gravity field, global topography, obliquity, libration amplitude (MLA, RS)
What are the radar-reflective materials at Mercury's poles?	Determine the composition of the radar-reflective materials at Mercury's poles	<ul style="list-style-type: none"> • Composition of polar deposits (GRNS) • Polar exosphere [MASCS (UVVS)] • Polar ionized species (EPPS) • Altimetry of polar craters (MLA)
What are the important volatile species and their sources and sinks on and near Mercury?	Characterize exosphere neutrals and accelerated magnetosphere ions	<ul style="list-style-type: none"> • Neutral species in exosphere [MASCS (UVVS)] • Ionized species in magnetosphere (EPPS) • Solar wind pickup ions (EPPS) • Elemental abundances of surface sources (GRNS, XRS)

framed the mission. Subsequent sets of questions guided the concept of operations through MESSENGER's two extended missions.

The best reference for the mission's science results is *Mercury: The View After MESSENGER*, to be published by Cambridge University Press. For more information on the mission design, spacecraft, and instruments, please see the dedicated articles in *Space Science Reviews*, Volume 131, 2007.

SCIENCE GOALS AND OBJECTIVES

The MESSENGER mission was designed to address six key science questions, the answers to which bear not only on the nature of the planet Mercury, but also more generally on the origin and comparative evolution of the terrestrial planets as a class. These questions, which guided the selection of the science payload and mission design, are shown in Table 1. The associated science and measurement objectives are also presented, along with the instruments required to achieve them.

Before MESSENGER's successful completion of its primary mission, on the basis of propellant and power usage projections, it was proposed to continue operating the spacecraft for an additional year, which would permit a substantial advance

in our understanding of Mercury beyond what would have been achieved at the end of the primary mission. Several overarching themes for this first MESSENGER extended mission ensured that the second year of orbital operations would not simply be a continuation of those of the primary mission. The new themes included operation during a period of greater solar activity, greater focus on observations at low spacecraft altitudes, and more variety of targeted observations. The extended mission enabled close-in observations of Mercury near a maximum in the solar cycle. The lower average altitude was accomplished by decreasing the nominal 12-h orbital period of the primary mission to 8 h by lowering the apoapsis of the orbit. The greater variety of instruments making targeted observations was enabled by the fact that the global mapping objectives of the primary mission had been accomplished. The six new, more-focused questions that framed the first extended mission are shown in Table 2.

Similarly, before the completion of this first extended mission, given the healthy state of the spacecraft and instru-

Table 2. A new set of six science questions guided MESSENGER's first extended mission

No.	First Extended Mission (XM1) Science Questions
XM1-Q1	What are the sources of Mercury's surface volatiles?
XM1-Q2	How late into Mercury's history did volcanism persist?
XM1-Q3	How did Mercury's long-wavelength topography change with time?
XM1-Q4	What is the origin of localized regions of enhanced exospheric density on Mercury?
XM1-Q5	How does the solar cycle affect Mercury's exosphere and volatile transport?
XM1-Q6	What is the origin of Mercury's energetic electrons?

ment payload and the ample amount of power margin and usable propellant remaining, a second extended mission proposal was prepared, this one for an additional 2 years of orbital operations. The seven guiding questions for the second extended mission (Table 3) followed from discoveries made during the first, or anticipated special aspects of either the timing of the observations or the geometry of MESSENGER's orbit during its final 2 years in orbit.

Through the natural evolution of MESSENGER's orbit in response to the gravitational attraction of the Sun, together with an optimized set of orbit-correction maneuvers (OCMs) conducted with MESSENGER's remaining propellant, the spacecraft orbit during its final year featured a unique low-altitude campaign, which is described by O'Shaughnessy et al. in this issue. Observations continued at extraordinarily low altitudes until the spacecraft finally impacted the planet in April 2015. These low-altitude measurements are unmatched by any mission at Mercury, either in the past or planned for the future.

SCIENCE PAYLOAD

MESSENGER carried a low-mass science payload of seven instruments and a radio science (RS) experiment. The science payload was selected to achieve the following mission measurement objectives:

- Map the elemental and mineralogical composition of Mercury's surface
- Globally image the surface at a resolution of hundreds of meters or better
- Determine the structure of the planet's magnetic field
- Measure the libration amplitude and gravitational field structure
- Determine the composition of the radar-reflective materials at Mercury's poles

Table 3. The goals of the second extended mission were captured in seven science questions

No.	Second Extended Mission (XM2) Science Questions
XM2-Q1	What active and recent processes have affected Mercury's surface?
XM2-Q2	How has the state of stress in Mercury's crust evolved over time?
XM2-Q3	How have the compositions of volcanic materials on Mercury evolved over time?
XM2-Q4	What are the characteristics of volatile emplacement and sequestration in Mercury's north-polar region?
XM2-Q5	What are the consequences of precipitating ions and electrons at Mercury?
XM2-Q6	How do Mercury's exosphere and magnetosphere respond to both extreme and stable solar wind conditions during solar maximum and the declining phase of the solar cycle?
XM2-Q7	What novel insights into Mercury's thermal and crustal evolution can be obtained with high-resolution measurements from low altitudes?

- Characterize the exospheric neutral atoms and accelerated magnetospheric ions

The seven instruments, depicted in Fig. 1, are the Mercury Dual Imaging System (MDIS), with wide-angle and narrow-angle cameras for imaging Mercury's surface; the Gamma-Ray and Neutron Spectrometer (GRNS) and the X-Ray Spectrometer (XRS) for remote geochemical mapping; the Magnetometer (MAG) to measure the planetary magnetic field; the Mercury Laser Altimeter (MLA) to measure the surface topography and planetary shape; the Mercury Atmospheric

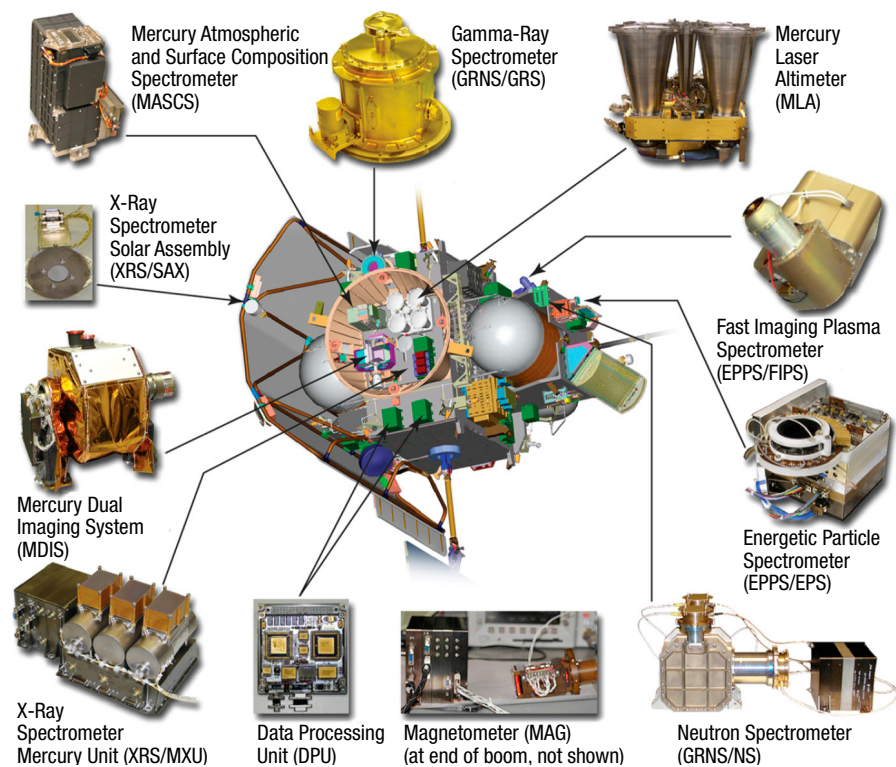


Figure 1. The placement of the MESSENGER science payload elements on the spacecraft facilitated measurements of the planet while the instruments operated behind the sunshade.

and Surface Composition Spectrometer (MASCS), combining an Ultraviolet and Visible Spectrometer (UVVS) with a Visible and Infrared Spectrograph (VIRS) to make high-resolution spectral measurements of the surface and to survey the structure and composition of Mercury's tenuous neutral exosphere; and an Energetic Particle and Plasma Spectrometer (EPPS) to characterize the charged particle and plasma environment of Mercury.

Table 4. Key parameters of the science payload elements

Instrument	Mass ^a (kg)	Power ^b (W)
MDIS	8.0	7.6
GRNS	13.1	22.5
XRS	3.4	6.9
MAG	4.4	4.2
MLA	7.4	16.4
MASCS	3.1	6.7
EPPS	3.1	7.8
Data processing units	3.1	12.3
Miscellaneous ^c	1.7	
Total	47.3	84.4

^aMass includes mounting hardware and captive thermal control components. The mass for MDIS includes the calibration target. The MAG mass includes the boom.

^bNominal average power consumption per orbit; actual values varied with instrument operational mode and spacecraft position in orbit.

^cPower includes purge system, payload harnesses, and magnetic shielding for the spacecraft reaction wheels.

The payload was carefully chosen so that each instrument addressed more than one of the primary mission objectives, and each objective was addressed by more than one element of the science payload. This dual complementarity provided for important cross-checks between sets of observations and ensured that mission science requirements could be met even in the event of problems with some of the payload elements. Although the instruments were of necessity single-string in design, the data processing unit that controlled them was fully redundant. This redundancy was not ultimately needed, and the payload as a whole remained healthy throughout the mission. Table 4 summarizes the key parameters of the payload.

With the exception of an early failure in one of the subsystems of the Energetic Particle Spectrometer (EPS) in the EPPS instrument, and the expected failure of the Gamma-Ray Spectrometer (GRS) cryocooler in the extended mission, the entire payload performed superbly throughout the primary mission year, plus three additional years of extended orbital operations.

Although the loss of the EPS time-of-flight subsystem reduced its capability, the sensor was able to make definitive measurements of the energetic particle population around Mercury. In particular, it confirmed that the population is primarily energetic electrons rather than energetic ions, as reported by Mariner 10, and was also able to characterize the distribution of these particles and contribute to the conclusion that the electrons are accelerated in the near-tail region of Mercury's magnetosphere and injected onto closed magnetic field lines on the planet's nightside.

Table 5. The mission science objectives mapped into the design of the MESSENGER orbit

Mission Objectives	Mission Design Requirements (Instrument)	Mission Design Features
Globally image surface at 250-m resolution	Provide 2 Mercury solar days at two geometries for stereo image of entire surface; near-polar orbit for full coverage (MDIS)	Orbital phase of 1 Earth year (13 days longer than 2 Mercury solar days) with periapsis altitude controlled to 200–505 km; 82.5°-inclination initial orbit
Determine the structure of Mercury's magnetic field	Minimize periapsis altitude; maximize altitude-range coverage (MAG)	Mercury orbit periapsis altitude from 200 to 505 km; apoapsis altitude near 15,200 km; orbit period from 11.76 to 12.07 h
Simplify orbital mission operations to minimize cost and complexity	Choose orbit with period of 8, 12, or 24 h	
Map the elemental and mineralogical composition of Mercury's surface	Maximize time at low altitudes (GRNS, XRS)	
Measure the libration amplitude and gravitational field structure	Minimize orbital-phase thrusting events (RS, MLA) Orbit inclination of 82.5°; latitude of periapsis near 60° N (MLA, RS)	Initial orbital inclination of 82.5°; periapsis latitude drifts from 60° N to 74° N; primarily passive momentum management; first orbit-correction ΔV after 89 days and then one orbit-correction ΔV every 44 days for the next 6 months
Determine the composition of radar-reflective materials at Mercury's poles	Orbit inclination of 82.5°; latitude of periapsis maintained near 60° N (GRNS, MLA, MASCS, EPPS)	
Characterize exosphere neutrals and accelerated magnetosphere ions	Wide altitude range coverage; visibility of atmosphere at all lighting conditions	Extensive coverage of magnetosphere; orbit cuts bow shock, magnetopause, and upstream solar wind

Early in the first year of extended operations, the GRS cryocooler failed after 9500 h of trouble-free operation, which was 1500 h longer than its expected lifetime. Although the GRS could no longer measure gamma rays, the instrument was repurposed through a software revision and continued to make meaningful contributions to the science campaign. Specifically, the GRS's anti-coincidence shield offered neutron measurements that were complementary to those of the Neutron Spectrometer (NS), and because of its location on a different deck of the spacecraft than the NS, the measurements were subject to smaller variability. The effect was to improve substantially MESSENGER's ability to characterize neutron populations about Mercury. In addition, the software reconfiguration enabled an improvement of two orders of magnitude in the temporal resolution of energetic electron events compared to what had been possible with the NS alone.

All full-mission-success criteria for the primary mission were met before the end of that first year in orbit about Mercury, and the criteria for both extended missions were similarly met earlier than required.

MISSION DESIGN

After a 6.6-year journey through the inner solar system in a heliocentric orbit, the MESSENGER spacecraft executed a 15-min maneuver and became the first spacecraft to orbit Mercury. The orbit achieved had been designed carefully to facilitate science collection while maintaining the health of the spacecraft, and MESSENGER remained in a similar orbit for the entire 1-year primary mission. During the first extended mission, the orbit was adjusted to decrease the orbital period from 12 to 8 h, thereby increasing the amount of data collected at lower altitudes. After 3 years in this orbit, a low-altitude campaign was conducted just before the end of operations. Trajectory planning and execution are discussed in the article by McAdams et al. in this issue.

Orbital Trajectory Design

The MESSENGER orbit design was influenced by a combination of constraints, requirements, and scientific objectives. The spacecraft's battery capacity dictated that time in solar

eclipse last no longer than 65 min. This constraint, combined with an objective to avoid complex mission-operations scheduling, led to the choice of 60°N subspacecraft periapsis latitude and a 12-h orbital period for the initial orbit. Results of design-phase thermal analysis helped determine that the right ascension of the ascending node must lie between 169° and 354°. This requirement effectively placed the spacecraft orbit periapsis near the day/night terminator or on Mercury's nightside when Mercury was closest to the Sun. Several science objectives, including determining the geometry of Mercury's internal magnetic field, mapping the elemental and mineralogical composition of Mercury's surface, and globally imaging Mercury's surface at a ≥ 250 -m resolution, led to an orbit design that maintained periapsis altitudes between 200 and 505 km for the first 3 of the 4 years in orbit. The mapping of the various primary mission objectives into the initial science orbit design is shown in Table 5.

Heliocentric Trajectory

After MESSENGER's successful launch from Cape Canaveral, Florida, on 3 August 2004, the first phase of its innovative trajectory was a 6.6-year interplanetary cruise that included six planetary flybys—one of Earth, two of Venus, and three of Mercury—as well as 17 maneuvers. This heliocentric trajectory is shown in Fig. 2 along with the flyby dates, locations, and closest-approach altitudes. Each flyby brought the spacecraft's heliocentric

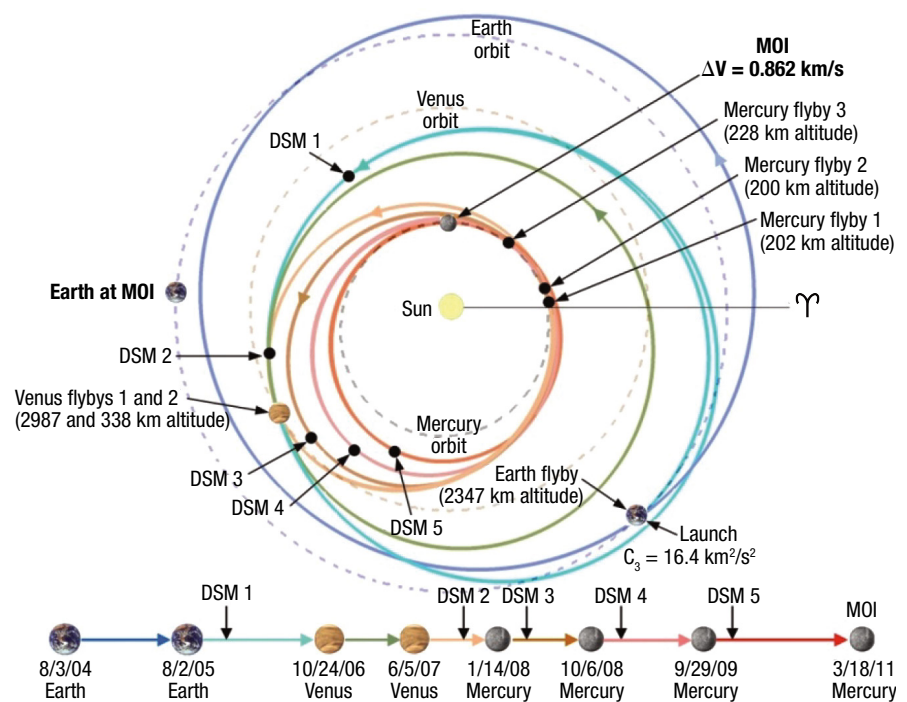


Figure 2. MESSENGER's heliocentric trajectory and deep-space maneuver (DSM) locations as seen from above the north ecliptic pole. A timeline at the bottom indicates the relative timing of planetary flybys and DSMs.

Table 6. Orbit changes resulting from MESSENGER's planetary flybys

Event	Equivalent ΔV (km/s) ^a	Longitude of Perihelion (°)	Longitude to Goal (°)	Orbit Inclination (°)	Inclination to Goal (°)	Perihelion Distance (AU)	Distance to Goal (AU)	Aphelion Distance (AU)	Distance to Goal (AU)
Launch	–	205	128	6.3	0.7	0.923	0.615	1.077	0.610
Earth flyby	5.9963	132	55	2.5	4.5	0.603	0.295	1.015	0.548
Venus flyby 1	5.5225	104	27	8.2	1.2	0.547	0.239	0.900	0.433
Venus flyby 2	6.9378	47	30	6.8	0.2	0.332	0.024	0.745	0.278
Mercury flyby 1	2.3040	56	21	6.9	0.1	0.313	0.005	0.700	0.233
Mercury flyby 2	2.4526	68	9	7.0	0.0	0.302	0.006	0.630	0.163
Mercury flyby 3	2.8361	81	4	7.0	0.0	0.303	0.005	0.567	0.100
Orbit about Mercury (goal)	0.8617 (MOI)	77	–	7.0	–	0.308	–	0.467	–

^aValues apply to the spacecraft's orbit after completion of the listed event.

orbit closer to that of Mercury and lowered the spacecraft's speed relative to Mercury, thereby decreasing the amount of spacecraft-originated velocity change (ΔV) required to insert the probe into the planned initial science orbit around Mercury. Table 6 lists the effect of each planetary flyby on key orbital parameters.

Early in the cruise phase, for trajectory-correction maneuvers (TCMs) >0.85 AU from the Sun, the sunshade was pointed away from the Sun so that sunlight could help warm fuel tanks and lessen the demand for power from the solar panels. For TCMs <0.85 AU from the Sun, when solar power was plentiful, all maneuvers were performed with the spacecraft sunshade center-panel normal direction within 12° of Sun pointing in order to protect the spacecraft bus from direct sunlight exposure.

Five of the 17 maneuvers during the interplanetary cruise phase were major course corrections or deep-space maneuvers (DSMs), which imparted a total of 1040 m/s in ΔV and targeted subsequent planetary flybys and insertion into orbit about Mercury. The remaining TCMs totaled 58 m/s and consisted of small course corrections that substantially reduced targeting errors on approach to a planetary flyby. After December 2007, these small TCMs were no longer required because of the use of MESSENGER's solar-panel tilt and sunshade orientation as solar sail controls. This novel approach, described by Gold et al. in this issue, resulted in precise targeting of the second and third Mercury flybys and Mercury orbit insertion (MOI), as well as propellant savings that enabled a final 6-week mission exten-

sion. The interplanetary cruise phase ended with MOI on 18 March 2011 (UTC).

Orbit about Mercury

A maneuver on 18 March 2011 at 00:45:15 UTC marked the beginning of the mission's orbital phase. Lasting ~ 15 min and imparting a ΔV of 862 m/s, the MOI maneuver slowed the spacecraft's Mercury-relative velocity by using variable-direction thrust with the thrust vector remaining nearly opposite to the instantaneous spacecraft velocity vector throughout the maneuver. MOI safely delivered the spacecraft into an orbit with a 207-km periapsis altitude, 12.07-h orbital period, 82.5° inclination, and 60.0° N sub-spacecraft periapsis latitude.

Throughout the 4.1 years orbiting Mercury, MESSENGER's trajectory was perturbed by several forces, of which solar gravity and Mercury's small gravitational oblateness, J_2 , were the dominant factors.

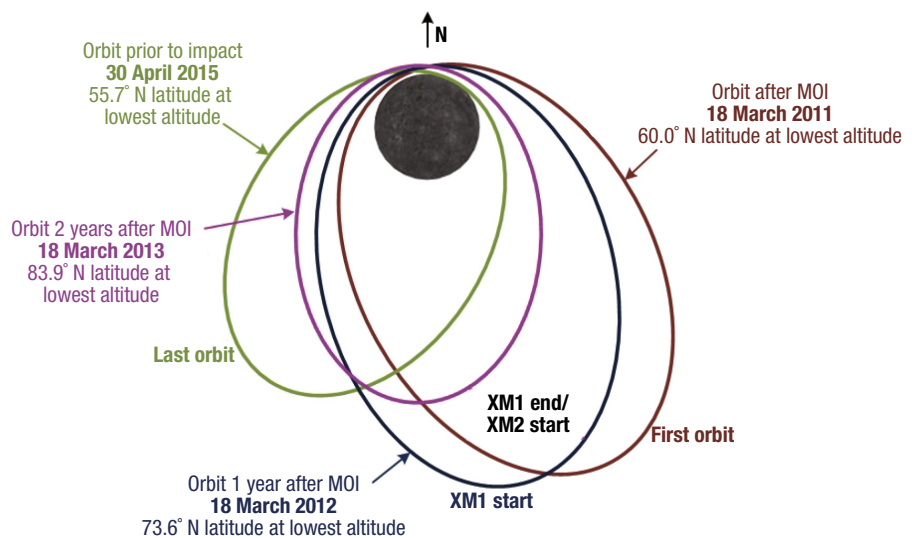


Figure 3. MESSENGER's changing orbit about Mercury.

Figure 3 shows MESSENGER's orbit at key times during the mission.

During its first year in orbit, MESSENGER performed six OCMs, counteracting the influence of a variety of trajectory perturbations—including those attributable to solar gravity, solar radiation pressure, planetary radiation pressure, and variations in Mercury's gravity field—to maintain the desired periapsis altitude range of 200–500 km without altering the 12-h period substantially. Beginning 89 days after MOI, the first five OCMs were executed approximately every 44 days, either to return the spacecraft's periapsis altitude to 200 km or to adjust the orbital period to an average of 12 h. The sixth OCM, conducted 88 days after OCM-5, lowered periapsis altitude to 200 km.

Shortly after the start of MESSENGER's second year in orbit about Mercury (i.e., early in the first extended mission), on 16 April and 20 April 2012, respectively, OCM-7 and OCM-8 reduced the spacecraft's orbital period from 11.6 to 8 h. This period reduction was split between two OCMs to minimize risk and deplete remaining accessible oxidizer. Because of the rotation of the orbital line of apsides through its northernmost Mercury latitude of 84.1°N ~12 days before the 18 March 2013 start of the second extended mission, solar gravity perturbed the orbit in such a way that no OCMs were required to maintain the desired periapsis altitude until MESSENGER's fourth and final year in orbit, or 1 year into the second extended mission.

During the mission's final year, the MESSENGER team performed four OCMs (OCM-9 to OCM-12) that enabled a low-periapsis-altitude campaign consisting of orbits with periapsis altitudes between 15 and 200 km. OCM-9 to OCM-11 each targeted times before the next OCM when periapsis altitude settled with little variation over many orbits to ~25 km above the closest terrain feature beneath the spacecraft. OCM-12 targeted an extended period when periapsis altitude settled with little variation over many orbits to ~15 km above Mercury's terrain. During the mission's final 44 days, MESSENGER performed seven OCMs (OCM-13 to -15, -15A, -16 to -18) as part of a low-periapsis-altitude hover campaign (see O'Shaughnessy et al., this issue) to maintain unprecedented minimum

altitudes from 5 to 35 km above Mercury's terrain before the spacecraft's inevitable final descent and impact onto Mercury's surface on 30 April 2015.

SPACECRAFT

The MESSENGER spacecraft design was driven by three critical mission challenges:

1. Achieving orbit about Mercury
2. Surviving in the harsh environment at Mercury
3. Returning all collected science data to Earth

The intricate trajectory design outlined in the Mission Design section required a lightweight vehicle with a substantial amount of propellant to provide the necessary propulsive ΔV . To save mass, a composite structure was chosen over a less expensive and simpler conventional aluminum design. A ceramic-cloth sunshade eliminated the need for a heavy, complex, active cooling system. MESSENGER also used a novel high-gain antenna design that obviated the need for a relatively costly and heavy gimbaled parabolic dish. Instruments were optimized for mass, resulting in a total payload mass of <50 kg. Lightweight, custom-designed titanium propellant tanks allowed for storage of nearly 600 kg of liquid propellant. In fact, careful optimization of the vehicle design resulted in the liquid propellant outweighing the remainder of the vehicle by >90 kg. This propellant, coupled with a bipropellant main engine and 16 additional monopropellant thrusters, allowed the

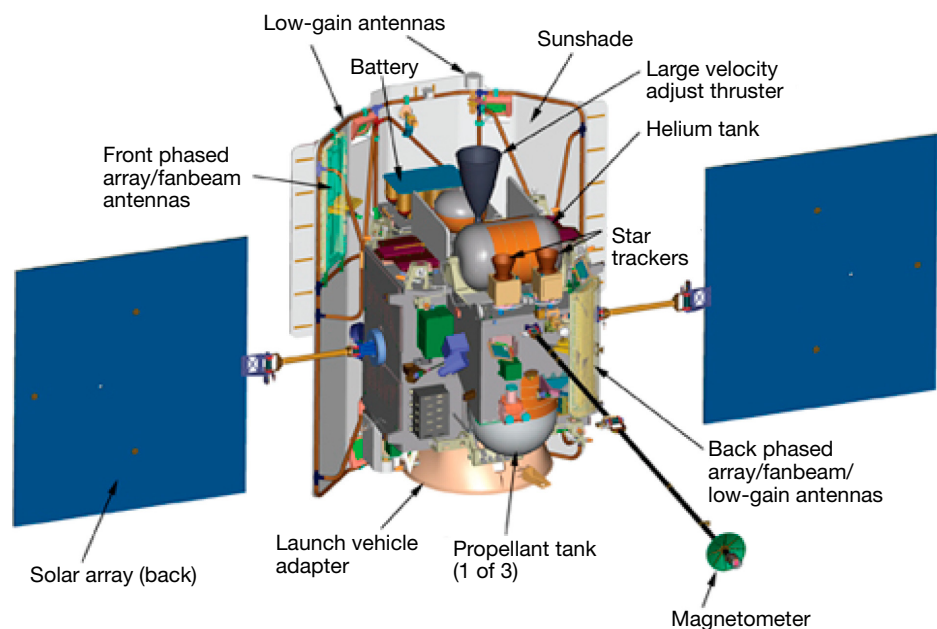


Figure 4. This rear view of the spacecraft shows the elements harbored behind the ceramic-cloth sunshade.

spacecraft to complete the necessary 2 km/s of ΔV to achieve and operate from Mercury orbit. Figure 4 shows the placement of the primary spacecraft components.

The primary challenge to operating safely in the Mercury environment was dealing with the extreme temperatures. The direct solar intensity at 0.3 AU is ~11 times that at Earth, and the heat reflected off the planet is 4 times the intensity felt at Earth. In response, the physical layout of the MESSENGER spacecraft was dominated by the large ceramic-cloth sunshade, which isolated the main spacecraft components and instruments from direct sunlight and high temperatures. The sunward side of the sunshade routinely experienced temperatures in excess of 300°C, while the elements harbored behind it operated at approximately room temperature. The latter conditions allowed the use of standard electronics, helping to reduce costs and increase reliability. The assembled sunshade is shown during testing at APL in Fig. 5.

The sunshade was effective at isolating the bulk of the vehicle from high temperatures, but not all components could remain in its shadow. Solar arrays rely on sunlight for power and, as such, required tolerance of high tem-



Figure 5. MESSENGER engineers at APL adjust the ceramic-fabric sunshade in preparation for the spacecraft vibration test.

peratures to ensure that sufficient power could be produced when in orbit about Mercury. To help manage temperatures, optical solar reflectors covered two-thirds of the solar-array surface, in order to reflect the bulk of the sunlight incident on the panels. The solar arrays were also mounted on articulated booms that allowed the solar panel normal to be rotated away from the Sun direction, to further reduce temperatures. This arrangement allowed the arrays to generate sufficient power by pointing directly at the Sun early in the mission, when the spacecraft was near Earth. Late in the mission, when the spacecraft was in orbit about Mercury, the arrays were routinely operated $>70^\circ$ from the Sun direction, simultaneously allowing sufficient electrical power production while managing temperatures.

The development of an effective sunshade was critical to surviving Mercury's harsh environment, but ensuring continued safe and uninterrupted operation of the spacecraft also required a well-thought-out fault-management approach. A simple yet robust strategy was developed to ensure vehicle safety in the face of onboard faults (e.g., environmental uncertainties and/or component failures). Faults were classified into three categories: recoverable, serious, or critical. Recoverable faults were addressed autonomously by the vehicle and allowed uninterrupted science data collection. Serious faults caused the vehicle to interrupt science operations by establishing a well-known high-bandwidth Earth communication configuration (termed safe-hold mode), thereby allowing a speedy fault diagnosis and recovery by ground operators. Critical faults posed a substantial threat to vehicle safety and were addressed by relying only on very robust onboard systems to ensure Sun-safety while the vehicle slowly attempted to reestablish a communication link to Earth, a mode termed Earth-acquisition mode. Recovery from safe-hold mode and Earth-acquisition mode required ground commands. This strategy allowed the spacecraft to protect itself by quickly establishing one of two well-known, reliable, and safe configurations. This self-preservation was essential to ensure vehicle survival because communication delays with Earth coupled with MESSENGER's proximity to the Sun could result in components overheating before ground operators were even aware of a problem. To minimize complexity, the more difficult and time-consuming fault diagnosis and recovery was left to ground operators. The MESSENGER fault-management design proved capable of maintaining vehicle safety throughout >10 years of flight operations.

In addition to achieving orbit about Mercury and operating there, mission success also required collecting and safely transmitting back to Earth the science data collected by the instruments. MESSENGER used X-band antennas, communicating through the Deep Space Network ground stations, and was controlled via the Mission Operations Center at APL. Onboard,

MESSENGER used a novel electronically steerable phased-array antenna for high-gain downlink to Earth. This antenna was repurposed from a military design, with upgrades made through APL independent research and development investment. The antenna had no moving parts and was capable of operation in the extreme temperature and radiation of direct sunlight (on the front of the vehicle sunshade). Engineers and operators also worked carefully to optimize the performance of the communications link. Special encoding on the downlink signal further improved the bandwidth of the system by 25%. A novel file-delivery protocol minimized the retransmission needs when communications were interrupted, greatly facilitating a high volume of returned data. Also, as MESSENGER traversed the sky (as seen from Earth), the communications link changed, but operators routinely adapted data transmission rates during contacts with the ground Deep Space Network stations to accommodate the changing link, thereby maximizing data return. This system design, the optimization performed by operators, and the longer-than-expected orbital mission resulted in >10 TB of science data returned to Earth, nearly 10 times the amount expected at launch.

OPERATIONS

The mission operations effort on MESSENGER began 2 years before the 2004 launch and continued without interruption for more than a decade afterward, ending with the spacecraft's 30 April 2015 impact into the planet. Unlike many other planetary missions, which can reduce operations while on the way to their target or even put the spacecraft into a hibernation mode, MESSENGER experienced an extraordinarily active cruise phase, with numerous TCMs, six planetary flybys, five DSMs, and an orbit-insertion maneuver, all of which required a substantial amount of planning and analysis. Once in orbit, the pace did not slow, with 18 OCMs spaced over the 4 years at Mercury. Calloway et al., in this issue, offer a detailed description of MESSENGER's orbital mission operations, and McAdams et al., also in this issue, address the maneuver planning and execution processes.

The extremely harsh and unforgiving environment at 0.3 AU from the Sun required close monitoring of the spacecraft's health, and this constraint restricted the amount of automation that could be applied to routine mission operations activities. On the other hand, automating the science planning effort was required, given that a 12-h orbit is tantamount to conducting two flybys per day. In addition to reducing the effort involved in preparing a command sequence, the SciBox science

planning software was able to develop an entire year of prioritized observations in a matter of hours. This capability was particularly helpful in deciding which orbit inclination angle to adopt and in assessing the effect of changing the orbital period from 12 to 8 h. See the article by Ensor et al., in this issue, for more about science planning.

As important as collecting the data were the validation and distribution of those data to the scientific community and the public. For the primary mission and for each extended mission, a detailed schedule of deliveries to the Planetary Data System was proposed and agreed upon with NASA. Because of the diversity of the data sets collected (in all >200 product types), six Planetary Data System nodes received data in a total of 16 deliveries. Deliveries during the cruise phase were timed to follow key mission events, such as planetary flybys, and the cadence changed to every 6 months beginning with the primary mission. A final delivery was made at the end of the project, in May 2017. More on the MESSENGER data archiving and distribution effort can be found in the summary by Ensor et al. in this issue.

CONCLUSIONS

More than most missions, MESSENGER represented the Discovery Program's charter to develop low-cost, innovative approaches to planetary exploration. It was an ambitious concept that ultimately exceeded all expectations and filled a serious gap in the understanding of the terrestrial planets. The design of the mission, spacecraft, and payload all proved effective in accomplishing the mission goals, but as the articles in this issue show, adjustments made during the cruise and orbital phases were essential for MESSENGER to achieve its full potential.



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Peter Bedini, a program manager in APL's Space Exploration Sector and a member of the Principal Professional Staff, was MESSENGER Project Manager from 2007 through the end of the first extended mission in 2013. He also managed the development of the CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) instrument on NASA's Mars Reconnaissance Orbiter and was Deputy Project Manager of the New Horizons mission to Pluto. At present, he is working on the Europa Lander mission study. His e-mail address is peter.bedini@jhuapl.edu.