

**MESSENGER AT MERCURY: A MID-TERM REPORT**

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After almost five years in development and more than six and a half years in cruise toward its destination, NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft finally entered orbit about Mercury on 18 March 2011, initiating a one-year, focused investigation of the innermost planet. Operating from a highly eccentric orbit designed to keep the spacecraft safe and to facilitate the required observations, MESSENGER is using its payload of seven instruments and the spacecraft's radio-frequency telecommunications system to characterize the planet's interior, surface, atmosphere, and magnetosphere. The demands of the many measurements needed to meet the program objectives, coupled with the constraints associated with spacecraft safety and the orbital geometry, led to the adoption of an automated science-planning tool to optimize science data collection. The tool was used to design the entire year of observations prior to orbit insertion and has the capability of regenerating the plan quickly in response to anomalies in flight (e.g., spacecraft safe-mode demotions) or on the ground (e.g., missed Deep Space Network tracks). Because one Earth year spans two Mercury solar days, there are two opportunities in the course of MESSENGER's science data-collection campaign to observe any specific location on the planet with a given viewing geometry. To take advantage of this schedule, the science plan was divided into two parts. During the first solar day, priority was given to producing global map products. The second day will be used to focus on specific targets and to recover observations missed during the first half of the year. Also, complementary observations can be made in the second day that, when paired with results from the first day, form a stereo map. Although only midway through the orbital operations phase of the mission, MESSENGER had, at the end of the first Mercury solar day, already viewed the entire surface of the planet once and produced global monochrome and multispectral maps. The spacecraft's orbit has completed two local-time rotations and three rotations in longitude, allowing spatial characterization of the planet's magnetic field, development of an elevation model from northern hemisphere altimetry, and global abundance estimates for major elements. After more than 350 orbits, more than 80 gigabits of compressed data have been collected, including more than 50,000 images. Calibrated data from the first two months in orbit have been delivered to NASA's Planetary Data System for dissemination to the science community.

## I. INTRODUCTION

The MErcury Surface, Space ENvironment, GEOchemistry, and Ranging (MESSENGER) mission<sup>1</sup> was selected by NASA in 1999 to become the seventh in its Discovery Program of innovative, cost-effective, and highly focused investigations of the solar system. MESSENGER is designed to study the characteristics and environment of Mercury from orbit. Specifically, the scientific objectives of the mission are to characterize the chemical composition of Mercury's surface, Mercury's geologic history, the nature of Mercury's magnetic field, the size and state of Mercury's core, the volatile inventory at Mercury's poles, and the nature of Mercury's exosphere and magnetosphere over a nominal orbital mission of one Earth year.

MESSENGER launched on 3 August 2004 from the Cape Canaveral Air Force Station in Florida on a Delta II 7925-H, the largest launch vehicle available to Discovery Program missions. Principal Investigator Sean C. Solomon of the Department of Terrestrial Magnetism at the Carnegie Institution of Washington leads the MESSENGER project. The spacecraft was designed and developed at The Johns Hopkins University Applied Physics Laboratory, which manages the project and conducts the mission and science operations<sup>2</sup>.

### Science Payload Selection

MESSENGER carries a science payload of seven instruments and a radio science (RS) experiment<sup>3</sup>, all designed to be low in mass and able to withstand the extreme environment near the Sun. The science payload was selected to achieve the following mission measurement objectives:

- Map the elemental and mineralogical composition of Mercury's surface,
- Image globally 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, and
- Characterize the exosphere neutral atoms and accelerated magnetosphere ions.

The seven instruments, depicted in Fig. 1, are the Mercury Dual Imaging System (MDIS)<sup>4</sup>, with wide-angle and narrow-angle cameras for imaging Mercury's surface; the Gamma-Ray and Neutron Spectrometer (GRNS)<sup>5</sup> and the X-Ray Spectrometer (XRS)<sup>6</sup> for remote geochemical mapping; the Magnetometer (MAG)<sup>7</sup> to measure the planetary magnetic field; the Mercury Laser Altimeter (MLA)<sup>8</sup> to measure the surface topography and planetary shape; the Mercury

Atmospheric and Surface Composition Spectrometer (MASCS)<sup>9</sup>, 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)<sup>10</sup> to characterize the charged particle and plasma environment of Mercury.

The payload was carefully chosen so that each instrument addresses more than one of the primary mission objectives, and each objective is addressed by more than one element of the science payload. This dual complementarity provides for important crosschecks between sets of observations and ensures that mission science requirements can be met even in the event of problems with some of the payload elements.

### Cruise Trajectory Design

The greatest challenge to putting a spacecraft into orbit about Mercury is decreasing the spacecraft's velocity enough relative to the Sun to allow it to be captured by the gravity of the planet. During its cruise to orbit, MESSENGER circled the Sun 15 times and used the gravity of three planets to slow itself and align the plane of its orbit to that of Mercury. During its six-and-a-half-year cruise phase, the spacecraft successfully completed six planetary flybys (of Earth in August 2005; of Venus in October 2006 and June 2007; and of Mercury in January 2008, October 2008, and September 2009) plus a number of propulsive changes to the trajectory, including five deep-space maneuvers that used the large-velocity adjust rocket engine.

A notable adjustment to the concept of cruise-phase operations resulted from the realization, in late 2007, that the solar radiation pressure (SRP) on the spacecraft, which is substantial at such proximity to the Sun, could be used to alter the spacecraft trajectory. As other missions have done in the past, MESSENGER used SRP to manage spacecraft momentum passively by tilting the angles of the solar panels and the spacecraft body. Beginning with the approach to the first Mercury encounter in January 2008, however, such adjustments were designed to influence the trajectory as well as to manage system momentum<sup>11</sup>. In the three and a half years that these "solar-sailing" techniques were used, 10 trajectory-correction maneuvers were deemed unnecessary, and the accuracy of all three Mercury flybys was exceptional.

### Spacecraft Design

The design of the MESSENGER spacecraft<sup>12</sup> (Fig. 2) was driven largely by the requirement to minimize mass and by the harsh Mercury environment. The largest launch vehicle available to the Discovery Program was the Delta II 7925-H, which could inject ~1,100 kg into

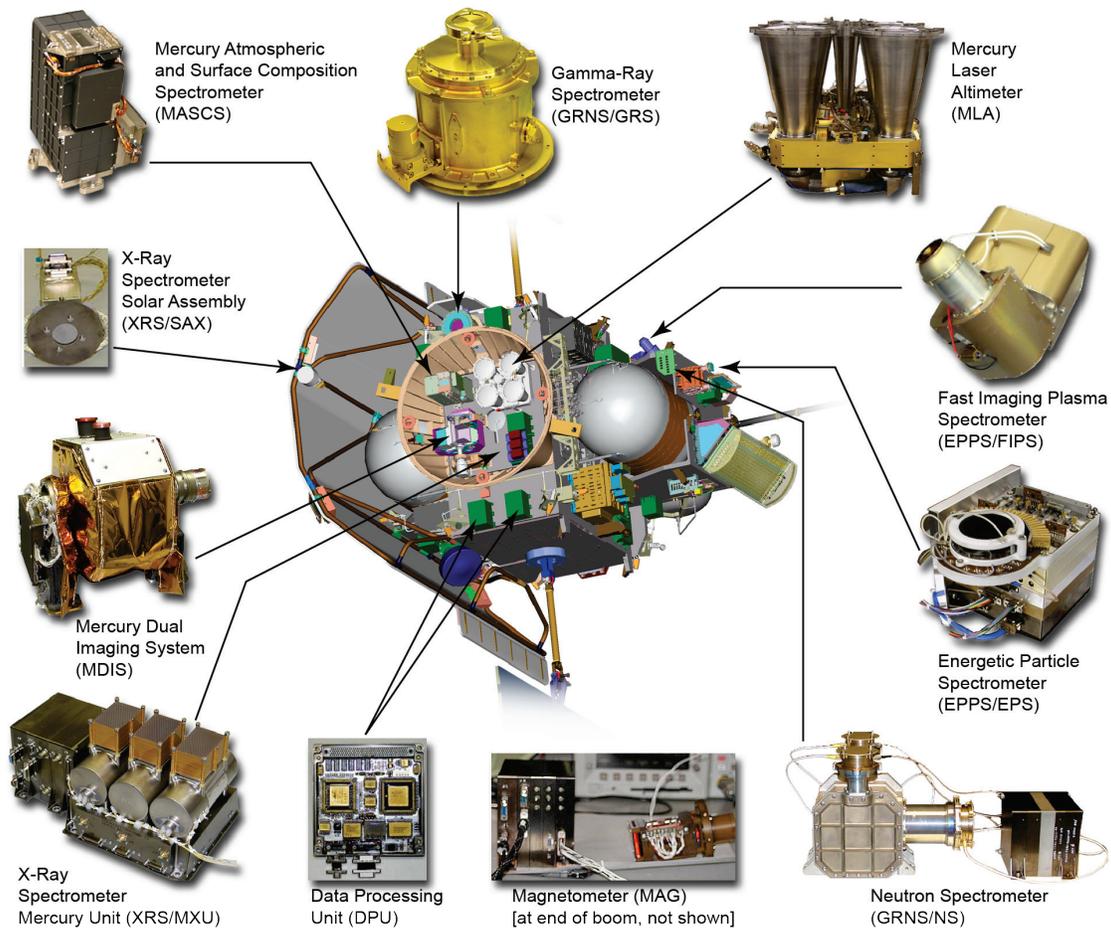


Fig. 1: All MESSENGER science instruments except MDIS are hard-mounted to the spacecraft.

the required interplanetary trajectory. Because more than half of that total launch mass was needed for the propellant required to achieve the mission design, only 500 kg remained for the total spacecraft dry mass.

A large number of mass-reduction measures were used in the development of the spacecraft. To avoid a cumbersome gimbaled antenna and the challenges associated with testing and operating it at high temperatures, an electronically steerable phased-array antenna system was developed. Used one at a time, each of two high-gain antennas—one on the spacecraft’s Sun-facing side and one aft—can be steered about one axis while the spacecraft body rolls about a second axis to point the antenna toward Earth at any point in the mission.

Mass was also conserved by limiting the number of components that articulate, and with the lone exception of MDIS, which has a one-degree-of-freedom gimbal, all science instruments are hard-mounted to the spacecraft. As a result, in addition to the spacecraft needing to be turned in order to downlink data, its attitude must also be changed to direct the instruments at their targets when making pointed observations.

The approach taken to protect the spacecraft from the intense insolation in the vicinity of Mercury was to harbor all systems behind a single sunshade that always points toward the Sun. This approach simplified the

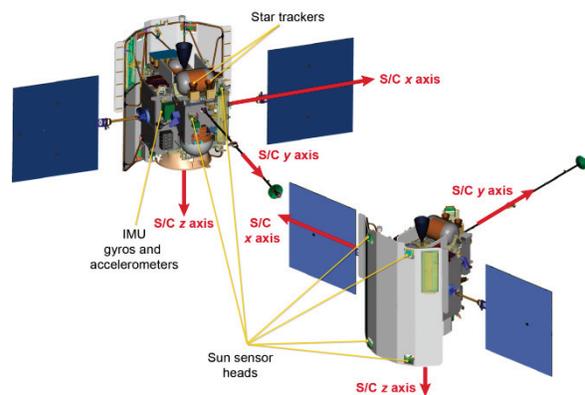


Fig. 2: A Sun-facing protective sunshade dominates the MESSENGER spacecraft design. IMU, inertial measurement unit; S/C, spacecraft.

design of the subsystems, which could be built using conventional electronics, but added a substantial constraint to the operation of the spacecraft. During its orbit about Mercury, MESSENGER must maintain its sunshade directed at the Sun within approximately  $\pm 10^\circ$ . Additionally, to protect the science payload from the solar radiation reflected from the planet, while the sunshade faces the Sun, portions of the instrument deck must be protected from direct exposure to the sunlit planet surface.

## II. ORBITAL-PHASE DESIGN

All aspects of the orbital phase were designed to minimize risk and optimize the capability of the spacecraft to collect the science data required to achieve the mission's objectives.

### Orbit Design

The MESSENGER orbit about Mercury<sup>13</sup> was chosen as a compromise between science viewing opportunities and spacecraft engineering constraints. The impact on mission operations activities was also a

consideration. The nominal orbit is highly eccentric ( $200 \times 15,200$  km), with a period of 12 hours, an initial inclination of  $82.5^\circ$ , and an initial periapsis latitude of  $60^\circ$  N. The geometry of MESSENGER's orbit is shown in Fig. 3, and the links between measurement objectives and the orbit characteristics are summarized in Table 1.

### Orbit Corrections

MESSENGER's orbit is subject to a number of perturbations, including those due to solar gravity, variations in Mercury's gravity, solar radiation pressure, and thermal radiation pressure from Mercury. These perturbations cause the periapsis altitude to increase, the periapsis latitude to drift northward, the orbit inclination to increase, and the right ascension of the ascending node to decrease during the one-year orbital operations phase. To maintain orbital parameters within desired ranges for optimal science observations, five orbit-correction maneuvers (OCMs) are scheduled throughout the year of orbital operations. These maneuvers occur approximately once every 44 days, or half of a Mercury year, beginning 90 days after orbit insertion. The first,

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

Table 1: The MESSENGER orbit characteristics derived from the mission objectives.

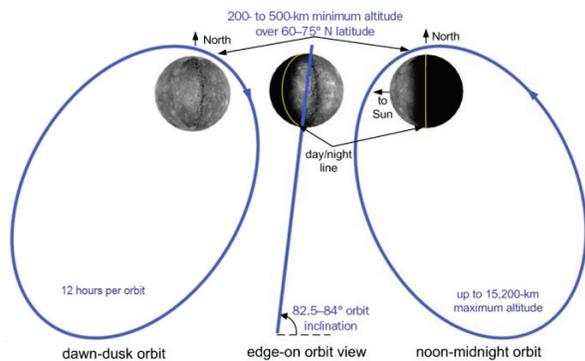


Fig. 3: MESSENGER's highly eccentric orbit is shown in its dawn-dusk and noon-midnight configurations.

third, and fifth OCMs are executed when the spacecraft is at apoapsis and are designed to reset the periapsis altitude to 200 km. Because each periapsis-altitude reduction also decreases the orbit period, the second and fourth OCMs are required to increase that period back to 12 hours. These smaller maneuvers are performed when the spacecraft is at periapsis. The schedule of OCMs follows.

OCM-1 reset periapsis altitude	16 June 2011
OCM-2 reset orbit period	26 July 2011
OCM-3 reset periapsis altitude	7 September 2011
OCM-4 reset orbit period	24 October 2011
OCM-5 reset periapsis altitude	5 December 2011

#### Seasons and Geometry

During the one Earth year of orbital operations, Mercury will make four revolutions around the Sun. Four Mercury years are required for measuring the planetary libration, and the planet's 3:2 spin resonance means that MESSENGER's orbital phase extends for two Mercury solar days. This duration allows for global surveying during the first six months followed by stereo coverage, concentrated observations of targets of interest, and repeat coverage as required. A one-Earth-year orbital phase also improves the accuracy of surface composition measurements.

Within a single Mercury year, MESSENGER experiences four seasons. When the spacecraft crosses Mercury's equatorial plane closest to the planet's day/night terminator, it is said to be in a dawn-dusk orbit. This orientation occurs twice, near Mercury's perihelion and again near its aphelion.

The noon-midnight orbit configurations occur when the spacecraft crosses Mercury's equatorial plane closest to local solar times of noon and midnight. When MESSENGER's periapsis is on the dayside of the planet, it is in the "hot-planet" season.

The different orbit and spacecraft configurations are shown in Fig. 4.

By the end of the year of orbital operations, the MESSENGER orbit will have evolved such that the

inclination will be  $84.0^\circ$ , the right ascension of ascending node will be  $345.8^\circ$ , and the sub-spacecraft periapsis latitude will have risen to  $73.5^\circ$  N. Propagation of the nominal end-of-mission state leads to an estimated Mercury impact in late 2014. Any estimate of end-of-mission orbit and Mercury surface impact, of course, will vary in accordance with updates in the accuracy of Mercury's gravity field and the accuracy of future maneuver performance.

### III. SCIENCE OPERATIONS APPROACH

The demands of the many measurements needed to meet the mission objectives, coupled with the constraints associated with spacecraft safety and orbital geometry, led to the adoption of an automated science-planning tool to optimize science data collection. The tool, called SciBox<sup>14</sup>, was used prior to orbit insertion to define the entire year of observations as a single, integrated "baseline" plan. SciBox has the capability of regenerating the observation plan quickly in response to anomalies in flight, such as spacecraft safe-mode demotions, or on the ground, such as missed Deep Space Network (DSN) ground contacts.

The actual implementation of the baseline observation plan during the orbital phase uses a parallel approach that allows validation of the spacecraft command sequences for near-term observations at the same time that plans for future observations are refined.

#### Science Observation Plan Development

The baseline observation plan includes command sequences that control all science-related payload and spacecraft activities throughout the orbital phase. In addition to instrument commanding, these sequences include guidance and control (G&C) and radio frequency (RF) telecommunication system commands required to point the spacecraft properly during the observations and to transmit the data to Earth ground stations. Solid-state recorder volume and spacecraft power state are modelled and monitored, and associated constraints are factored into the plan.

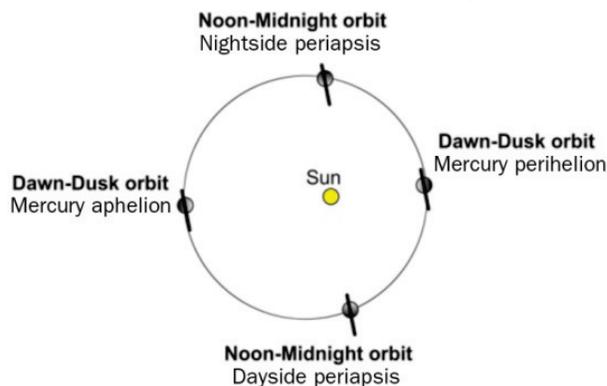


Fig. 4: MESSENGER's orbit configuration is shown for the four seasons of a Mercury year.

The many science observation campaigns that are required to achieve the MESSENGER measurement objectives can be categorized broadly into six types, as detailed in Table 2. In addition to this diverse set of observations, which range from surface mapping to exosphere scans, the observation plan includes a variety of instrument calibration activities and accommodates orbit events such as eclipses as well as spacecraft activities such as OCMs.

Because one Earth year spans two Mercury solar days, there are two opportunities in the course of MESSENGER's science data-collection campaign to observe any specific location on the planet with a given viewing geometry. The observation plan takes advantage of this natural division of the orbital phase by giving priority in the first solar day to producing monochrome and multispectral global map products. The second day will be used to focus on specific targets and to recover observations missed during the first half of the year. Also, complementary observations made during the second day, when paired with results from the first day, will form a global stereoscopic map.

The orchestration of this wide variety of science observations was made more challenging by the strict constraints on pointing imposed to maintain the safety of the spacecraft in proximity to the Sun. Because the majority of the observations require adjustment of the

spacecraft attitude, authority over the G&C system became the driver for prioritizing the measurements.

Typically, although one instrument controls the spacecraft pointing, many others will take valuable measurements at the same time. As an example, while MLA controls the attitude (when the spacecraft is within 1500 km of the surface), the Gamma-Ray Spectrometer (GRS), Neutron Spectrometer (NS), XRS, VIRS, and MDIS take "ride-along" observations of the surface while MAG and EPPS continue to measure the magnetosphere and energetic particle environment.

The end result is a conflict-free schedule for the entire orbital phase that contains approximately 80,000 carefully placed images, more than 4 million spectra, and more than 360 DSN contacts.

#### The Science Operations Process

The science planning process relies on the ability of SciBox to regenerate the observation plan quickly when given modified input. Although the baseline science plan laid out the entire year of observations, the weekly command loads must be finalized with the most up-to-date information before being validated and then sent to the spacecraft. Every week, SciBox replans the remainder of the mission using the latest orbit prediction and an updated DSN-station schedule. A new set of commands is then generated for the following week. The

<b>Observation</b>	<b>Measurement Requirements and Relevant Instrument/Investigation</b>
Global surface mapping	<ul style="list-style-type: none"> <li>• Monochrome imaging, <math>\geq 90\%</math> coverage, <math>\leq 250</math>-m average resolution for morphology: MDIS</li> <li>• Multispectral imaging, <math>\geq 90\%</math> coverage, <math>\leq 2</math> km per pixel average resolution for mineralogy: MDIS</li> <li>• Stereoscopic imaging, <math>\geq 80\%</math> coverage for global topography: MDIS</li> <li>• Elemental abundance determination: GRNS, XRS, NS</li> <li>• High-resolution spectral measurements of geological units for mineralogy: VIRS</li> <li>•</li> </ul>
Northern hemisphere and polar region observations	<ul style="list-style-type: none"> <li>• Northern hemisphere topography, obliquity, and libration amplitude measurements: MLA</li> <li>• Composition of polar deposits: GRNS</li> <li>• Polar ionized species measurement for volatile identification: EPPS</li> <li>• Polar exosphere measurement for volatile identification: UVVS</li> <li>•</li> </ul>
Magnetosphere observations	<ul style="list-style-type: none"> <li>• Mapping magnetic field to characterize the internally generated field: MAG</li> <li>• Determining magnetospheric structure, plasma pressure distributions, dynamics: MAG, EPPS</li> <li>• Solar wind pick-up ions to understand volatiles: EPPS</li> <li>•</li> </ul>
Exosphere survey	<ul style="list-style-type: none"> <li>• Neutral species in exosphere to understand volatiles: UVVS</li> <li>•</li> </ul>
Region-of-interest targeting	<ul style="list-style-type: none"> <li>• High-resolution and stereo imaging, spectroscopy of key regions: MDIS, VIRS, UVVS</li> <li>• Photometric measurements to determine surface texture, process color images: MDIS</li> <li>•</li> </ul>
Radio science measurements	<ul style="list-style-type: none"> <li>• Gravity field determination to characterize internal structure (in combination with topography and libration): RS</li> </ul>

Table 2: The MESSENGER measurement objectives are grouped into six observation campaigns.

new plan also factors in the success or failure of past commands and makes any necessary adjustments. If a global-map observation is missed for any reason in the first solar day, SciBox can reschedule it for an appropriate time in the second solar day. Along with the command generation, mission-monitoring products are regenerated to track progress toward mission-long science measurement objectives.

#### IV. OBSERVATORY PERFORMANCE IN ORBIT

At 00:45:15 UTC on 18 March 2011 MESSENGER's rocket engine fired for 15 minutes, slowing the spacecraft and allowing it to be captured by the gravity of Mercury. After a short commissioning period, in which it was verified that all subsystems and instruments were functioning nominally, the science data-collection phase began on 4 April. The spacecraft has performed continuously and nominally for the past six months and is expected to continue to do so.

##### Observatory Commissioning

The Mercury orbit insertion maneuver<sup>15</sup> executed precisely as planned, safely delivering the spacecraft into an orbit with a 206.77-km periapsis altitude, a 12.07-hour orbit period, a 59.98°N sub-spacecraft periapsis latitude, a 350.17° right ascension of the ascending node, and an 82.52° initial orbit inclination. As indicated in Table 3, all parameters of MESSENGER's initial orbit were within design specifications.

The first two weeks in orbit were dedicated to confirming the proper functioning of the subsystems and to verifying that they were ready to support the orbital operations phase. During this period, the performance of the propulsion system was analyzed, and the propellant budget was updated accordingly. The attitude control system was calibrated, validating the star tracker field-of-view keep-out region as well as the alignment of the inertial measurement units. Whereas throughout the cruise phase system momentum was managed primarily in a passive manner with adjustments to the orientation of the solar panels and spacecraft body, the constant changes to spacecraft attitude in the orbital phase require routine propulsive momentum desaturation. These adjustments began in the commissioning period and have been executed approximately weekly without issue since.

When MESSENGER entered orbit, the periapsis of its orbit was on the nightside of Mercury, and the spacecraft experienced short eclipses as it passed through the planet's shadow once each orbit. The battery, which had been called upon to provide spacecraft power only occasionally throughout the cruise phase, had its first test during the first orbit after orbit insertion, and it performed as expected.

The solar arrays, now operating almost constantly at temperatures experienced only briefly during the Mercury flybys, also performed nominally. To minimize the temperature of the arrays, adjustments were made to tilt them as far away from the Sun-line as possible while still providing the requisite power to the spacecraft.

Although the MESSENGER thermal design had been validated in environmental tests prior to launch and through a number of close perihelion passes during the cruise phase<sup>16</sup>, only in orbit could the effectiveness of the design be thoroughly qualified. In three cases, there was substantial discrepancy between thermal models and the orbital flight temperatures. The digital Sun sensor (DSS) and the Solar Assembly for X-Rays (SAX) sensor of the XRS instrument, both of which are mounted on the sunshade, experienced peak temperatures in excess of predicted operational limits but below unit qualification levels. A combination of power cycling and spacecraft off-pointing during the hottest portion of the orbits has mitigated the thermal risk. The DSS temperature has remained below its qualification value and continues to perform nominally despite its elevated temperature. The same mitigations have helped the SAX to continue operating, and its temperature was further lowered by running its thermal electric cooler at higher power to draw more heat from the sensor.

The MASCS instrument in general runs 10–15°C hotter than originally predicted, but the elevated temperatures pose no risk to the hardware, and the instrument continues to be fully functional. The major impact of the higher operating temperature is on the VIRS sensor, which experiences increased thermal background and degraded signal-to-noise ratio when its detector temperature exceeds 35°C. The majority of the spectra collected by VIRS are unaffected, and it has been making valid science measurements since the beginning of the science campaign.

	Semi-Major Axis (km)	Orbit Eccentricity	Orbit Inclination (°)	Right Ascension of Ascending Node	Argument of Periapsis (°)	Time, UTC (hh:mm:ss)
Targeted	10135.120	0.740	82.50	350.17	119.13	12:47:56.0
Achieved	10175.39	0.740	82.52	350.17	119.16	12:52:19.9
Deviation	40.27	0.00038	0.0219	-0.0039	0.034	263.9 s

Table 3: The performance of the Mercury orbit insertion maneuver was within specifications.

### Spacecraft In-Orbit Performance

The activities during the commissioning period confirmed the good health of the observatory in its new environment, but not until an entire Mercury year had passed had the spacecraft encountered the full variety of conditions it must survive during the orbital phase.

The timing and duration of a number of key orbital events during MESSENGER's first Mercury year are depicted in Fig. 5. Green data points indicate occultations, during which Mercury passed between MESSENGER and Earth, causing communication blackout periods lasting as long as 45 minutes per orbit. During eclipses (blue data points), MESSENGER passed through the shadow of the planet and the onboard battery, rather than the solar arrays, provided power to the spacecraft. MESSENGER began its orbital phase with its orbit periapsis on the nightside of Mercury and experienced eclipses that were relatively short, lasting no longer than 32 minutes per orbit.

Later in the Mercury year, MESSENGER entered the hot-planet season when its periapsis moved to the dayside of the planet. This season posed the most stressful conditions yet for the spacecraft, which experienced both its hottest and its coldest temperatures. To address these challenges, adjustments were planned to the operation of the thermal and power systems.

From 13 May through 10 June, the solar arrays were turned away from the Sun for approximately 25 minutes of each orbit (see purple data points in Fig. 5) to protect them from extreme temperatures. In addition, from 24 May through 3 June, the spacecraft experienced relatively long eclipses, which lasted as long as 62 minutes.

To lessen the load on the battery, which supplied power during solar-array off-pointing and eclipses, many of the science instruments were turned off for the portion

of each orbit in which these events occurred. NS was turned off for the long-eclipse period, and MLA was also inoperable during that time. With the exception of these instruments and GRS, which remained powered on throughout the hot-planet season, all other instruments were power cycled each orbit.

Another adjustment made to protect the observatory in the hot-planet season was to tilt the spacecraft about its  $y$ -axis (Fig. 2) through periapsis passes to prevent reflected solar radiation from overheating components of the front phased-array antenna assembly.

Data collected throughout MESSENGER's first Mercury year were used to refine spacecraft thermal models and to define plans for the second hot-planet season. The temperature of the spacecraft adaptor ring is representative of the environment of the instrument deck of the spacecraft, and a plot of that temperature versus time (Fig. 6) shows great repeatability in the second Mercury year. The jagged profile of the temperature at the beginning of the first year is a result of commissioning activities in which the spacecraft pointing was not representative of the science phase. Note that the temperatures during the second hot-planet season (denoted by red triangles) are decidedly lower than those at the same point in the first year. This difference is largely the result of the progression of the orbit toward higher periapsis latitudes.

Another change implemented for the second Mercury year as a result of the performance during the first resulted in increased science data collection. The power margin realized during the first long-eclipse period was sufficient to reduce the amount of instrument power cycling, and in the second Mercury year, the MAG and NS remained powered throughout the long-eclipse season, along with GRS.

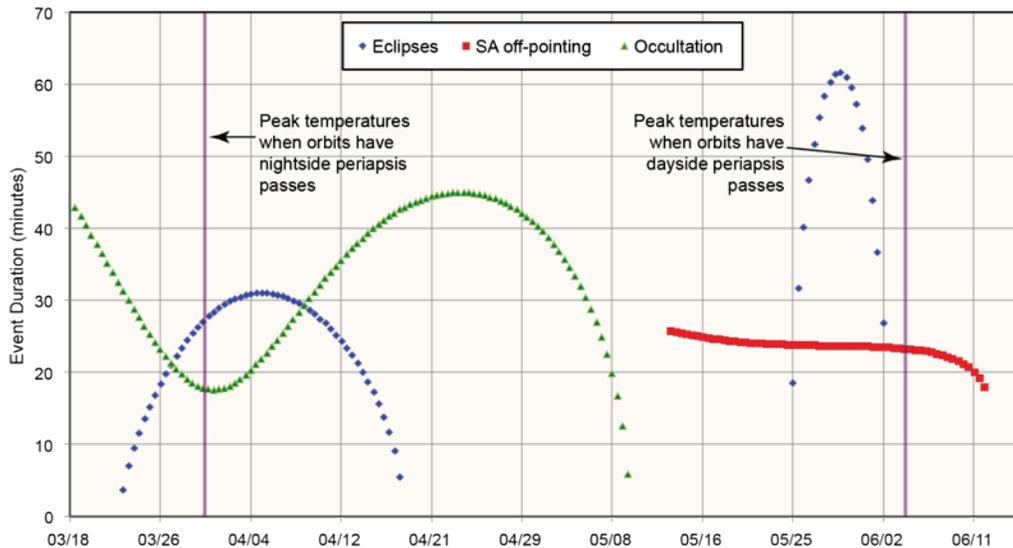


Fig. 5: The timing and duration of key orbital events during MESSENGER's first Mercury year. SA, solar array.

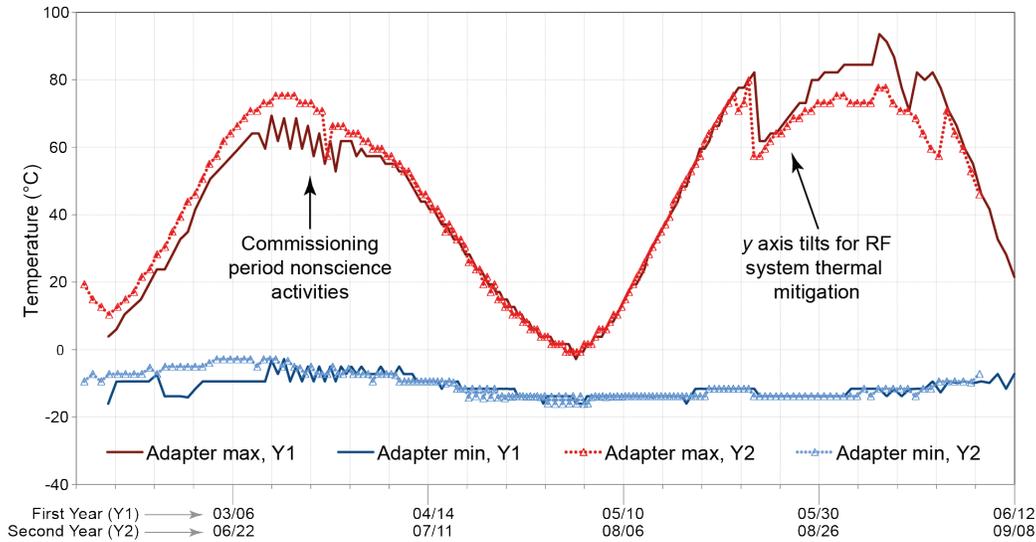


Fig. 6: The instrument deck temperature is shown for the first two Mercury years. Lower temperatures in the second hot-planet season are the result of progression of the orbit to higher periaispis latitude.

Three OCMs were executed during MESSENGER's first solar day. On 16 June 2011, OCM-1 successfully lowered the periaispis altitude from 505 to 200 km and in so doing reduced the orbital period to 11.8 hours. OCM-2, on 26 July 2011, reset that period to 12.0 hours, primarily to simplify scheduling of mission operations activities and the scheduling of DSN tracks. On 7 September, OCM-3 successfully lowered the periaispis altitude once again to 200 km.

The execution of routine mission operations activities has closely followed the plans set in place prior to orbit insertion. Propulsive momentum desaturations, instrument memory checks, ephemeris uploads, and other tasks have continued on a weekly basis, and unattended passes are used during most weekends, when no commanding is planned. Also, the profile of DSN support has deviated little from the original plan.

#### Instrument Performance in Orbit

Except for the relatively short periods of time in which elements of the payload were turned off as part of thermal and power management strategies, MESSENGER's seven science instruments functioned nominally throughout the first solar day and have been collecting valid science data continuously since the beginning of the formal science campaign on 4 April 2011. The spacecraft RF telecommunications system has also performed well, facilitating all planned radio science measurements.

In early June 2011, the observatory faced its first exposure to severe solar weather when a coronal mass ejection (CME) passed directly by the spacecraft. The probe proved to be very resilient and survived the storm without damage. Currents associated with high count

rates in GRS, NS, and XRS caused internal autonomy responses in all three sensors, reducing their operating voltages. A number of MDIS images and MASCS spectra became noisy because of radiation effects, but analysis showed that there were no single-event effects in any spacecraft system or instrument, and the entire science payload was operating nominally within a day of the event. The reaction of the spacecraft to this CME offered confidence that MESSENGER will weather similar such events in the future, as solar activity increases.

### V. PROGRESS OF THE SCIENCE COLLECTION

The science-planning tools and processes have proven to be well designed for this mission. From the onset of orbital operations, SciBox has been able to regenerate the entire observation plan in approximately two hours, and validation of the weekly command sequences has been almost entirely error-free. The plan is now typically regenerated on a weekly basis, and advance science planning is done in parallel with the validation of the weekly command sequences.

#### Science Campaigns

Operations in the orbital phase have closely followed the general priorities laid out in the baseline observation plan, and progress has been made in all six of the science campaigns listed in Table 2.

As part of the global surface mapping campaign, MDIS has now imaged more than 91% of the planet's surface in monochrome with an average resolution of 160 m per pixel (Fig. 7). Multispectral coverage (Fig. 8) extends over 93% of the surface with an average

resolution of 1030 m per pixel. MDIS is also pursuing an imaging campaign to monitor the south polar region of Mercury. By imaging the region in differing illumination conditions throughout the first solar day, MDIS has been able to identify the location of permanently shadowed areas.

GRS, NS, and XRS have operated almost continuously during MESSENGER's first 350 orbits to establish the average surface abundance of major elements, and all three sensors continue to accumulate data to improve counting statistics and to reduce uncertainties in their measurements. VIRS has collected

a total of 900,000 spectra of the Mercury surface to date with a wide range of incidence, emission, and phase angles.

The study of the northern hemisphere combines MDIS images with topography measurements by MLA. Mercury has now rotated beneath MESSENGER's orbit three full times, and MLA has recorded surface profiles for the majority of the 350 orbits that constituted the first solar day (Fig. 9).

The MESSENGER spacecraft has now made approximately 700 crossings of Mercury's magnetopause and bow shock and 350 crossings of the

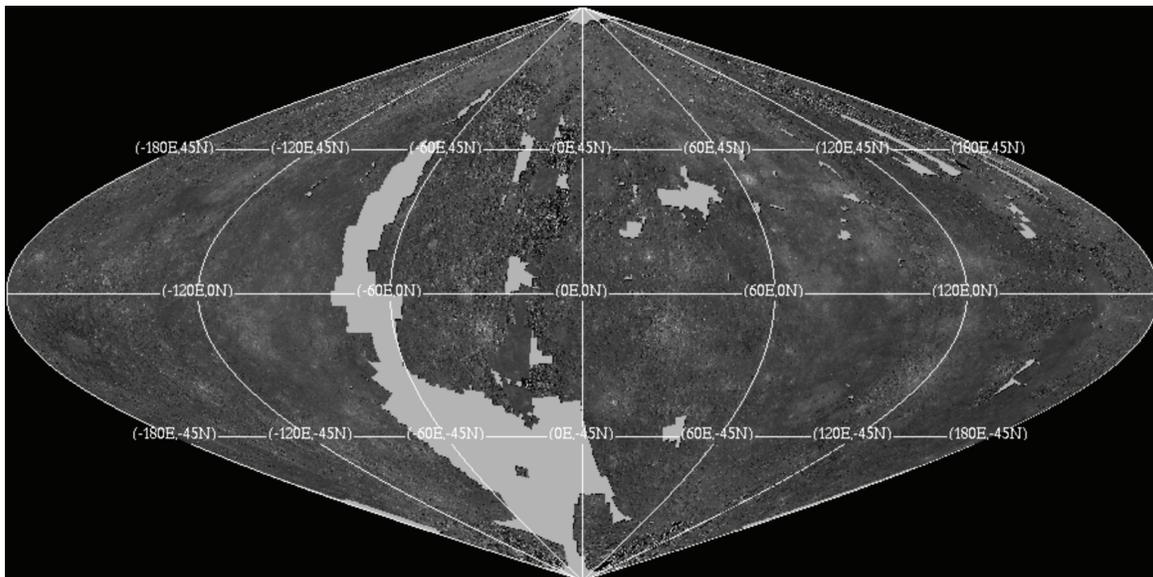


Fig. 7: MDIS has imaged more than 91% of Mercury's surface with an average resolution of 160 meters per pixel.

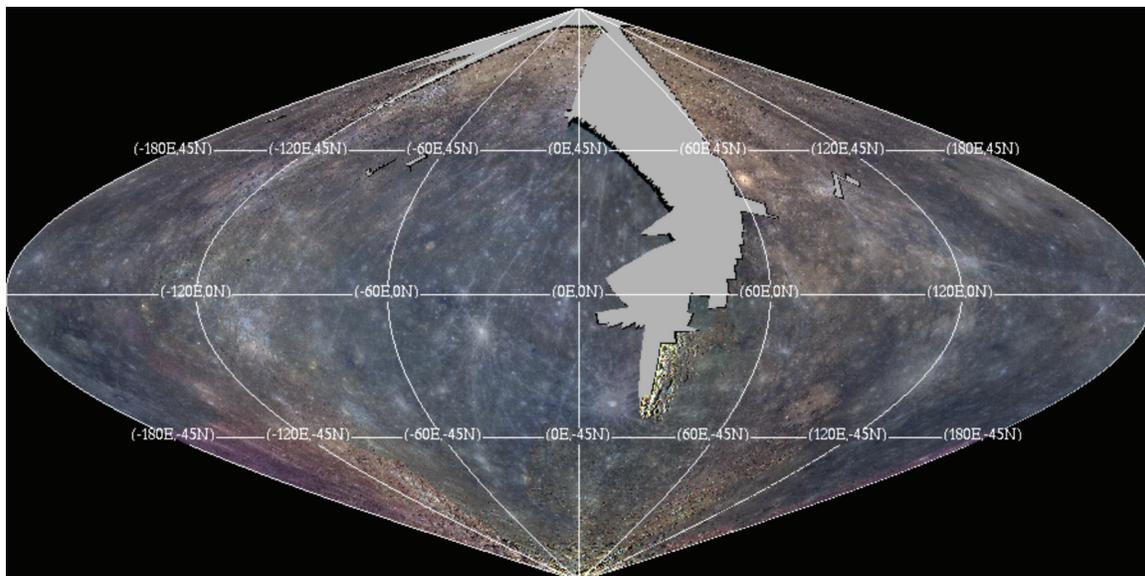


Fig. 8: The MDIS multispectral map extends over 93% of Mercury's surface and has an average resolution of 1030 meters per pixel.

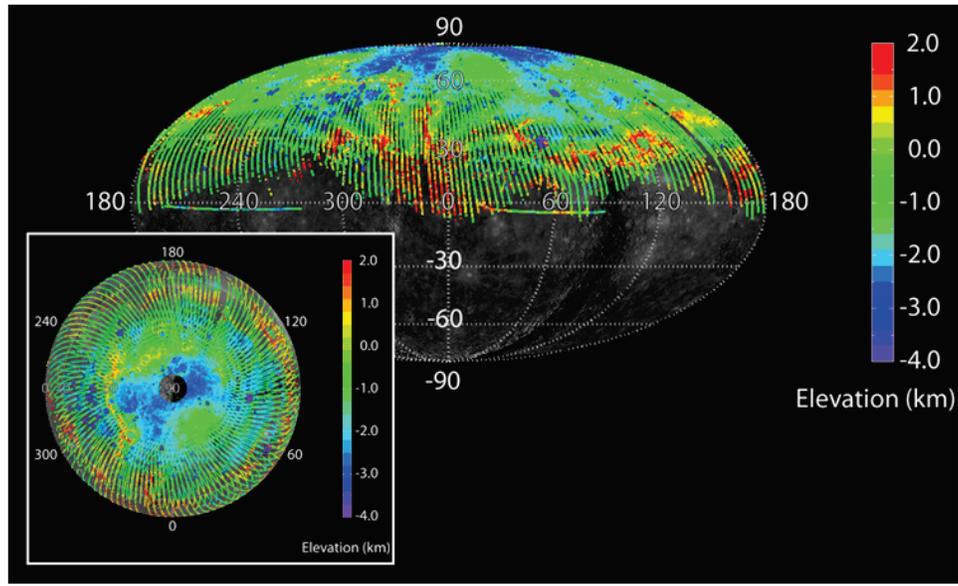


Fig. 9: MLA altimetry measurements cover the northern hemisphere. Elevations are shown relative to a sphere with a radius of 2440 km.

near-planet equatorial region, allowing MAG to define the geometry of the magnetic field and to locate the magnetospheric boundaries used to order the observations of both MAG and EPPS. In addition, the two local-time rotations that the spacecraft orbit has completed in the first solar day have provided the first maps of the plasma and energetic particle environment at Mercury.

The population of neutral species in the exosphere is being recorded by UVVS, which has already collected almost 1.5 million spectra. The spatial distribution of species such as sodium, calcium, magnesium, and hydrogen are being mapped. Although global surface maps were given priority in planning for the first solar day, a large number of targeted observations have already been made. MDIS has collected high-resolution images for more than 1300 distinct targets, UVVS has targeted the surface on approximately 400 occasions, and VIRS has collected spectra during more than 75 targeted observations.

Finally, the RF telecommunications system has operated continuously, allowing the radio science investigation to collect a large amount of range-rate data between the spacecraft and DSN ground stations. These data are used to derive a spherical harmonic expansion of Mercury's gravity field. The RS experiment has also successfully measured the ingress and egress times of approximately 150 occultations, helping to constrain the planetary radius at the location of the grazing path. To aid in the determination of Mercury's radius, MDIS has imaged the limb of the planet in the southern hemisphere to complement measurements made by MLA of the northern hemisphere.

#### Early Science Results

Only halfway through its primary science phase, and with most of its observation campaigns yet to be completed, MESSENGER has already uncovered compelling and surprising science results.

Orbital images have provided new evidence that flood volcanism has been widespread on Mercury<sup>17</sup> and offer the first close-up views of Mercury's "hollows," depressions in bright deposits within impact craters<sup>18</sup>. Also, the first direct measurements of the chemical composition of the planet's surface have now been taken; these measurements indicate that Mercury has an average composition different from that of the Moon and the other terrestrial planets<sup>19</sup>.

Magnetospheric measurements reveal that Mercury's magnetic dipole is offset northward from the geographic equator by 20% of Mercury's radius<sup>20</sup> and show indications that that polar regions are important sources of Mercury's ionized exosphere<sup>21</sup>.

Further, bursts of energetic electrons are seen at a range of latitudes and times of day, implying that efficient acceleration mechanisms operate within Mercury's magnetosphere on a regular basis and produce electrons with energies up to hundreds of keV on timescales of seconds<sup>22</sup>.

As MESSENGER continues to collect and analyze data according to its observation plan, steady progress is being made toward meeting its mission objectives.

#### Data Distribution

At the end of MESSENGER's first solar day, NASA's Planetary Data System (PDS) released to the public, for the first time, MESSENGER data collected

while in orbit about Mercury. With the delivery of those data to the PDS, MESSENGER has now delivered a total of 1.1 terabytes of data for release to the science community. Approximately 200 gigabytes of the most recently released data, including 18,000 images, are from the orbital phase.

Data delivered include formatted raw and calibrated data products, along with ancillary data. High-level data products are being generated and will be delivered to the PDS at the end of the mission.

## VI. CONCLUSION

More than 35 years after Mariner 10 completed its third and final flyby of Mercury, MESSENGER has taken the next step in the investigation of the innermost planet by conducting a systematic, global characterization from orbit. Mid-term through its primary science phase, the spacecraft and instruments are healthy and performing nominally, and the science observation plan has successfully coordinated the measurements required to meet all mission objectives. The science operations processes and data distribution effort are proceeding as planned, and all indications are that MESSENGER will fully meet all of its mission objectives.

## VII. ACKNOWLEDGEMENTS

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