

# MESSENGER - A Highly Constrained Mission to the Innermost Planet

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*Abstract*—MERcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) is a NASA Discovery Program mission to the Sun's closest neighbor. Launched on August 3, 2004, the spacecraft must fly in a cruise trajectory for almost seven years, circling the Sun 15 times and traveling approximately five billion miles before finally achieving orbit around Mercury [3]<sup>1,2</sup>.

With six planetary gravitational assists, five large velocity adjustments with its bi-propellant engine, and potentially dozens of smaller maneuvers distributed in between, the cruise phase of the mission is a challenge to the program's scientists, engineers, and planners alike. Flying by Earth once, Venus twice, and Mercury itself three times prior to orbit insertion requires continual re-optimization. Each Mercury flyby is at 200 km from the surface, requiring traditional radiometric, Delta Differential One-Way Ranging, and optical techniques for precision navigation.

In order for the spacecraft to operate safely while in orbit around Mercury, at 0.30 to 0.45 AU from the Sun, an innovative sunshade was developed and mounted on its sunward side. However, this constrains the spacecraft attitude to within a 20°x24° operating zone. Science observations, propulsive maneuvers, and all Earth communications must be accomplished in this small Sun Keep-In zone.

Launched on a Delta II 7925-H, the spacecraft mass was 54% propellant at liftoff; and throughout the development phase, remaining within the mass budget was a challenge, demanding smart trades in order to meet the mission goals.

Though flush with power while in Mercury orbit, the spacecraft also had to be designed to survive at a distance of 1 AU from the Sun for the first year of cruise. While each of the two solar array panels spans an area of 2.6 m<sup>2</sup>, only one third of this area is covered with solar cells, allowing

much of the incident energy from the Sun to be reflected by the remaining area, covered by optical solar reflectors, to reduce operating temperatures in Mercury orbit [2].

Finally, a phased-array antenna of unique design was developed to return the desired volume of science data from distances of up to 1.45 AU during Mercury orbital operations. This avoided using a typical, gimbaled high-gain antenna requiring its own large sunshade.

This paper will discuss the unique design of the spacecraft and the rapid pace of the cruise phase of the mission.

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## 1. INTRODUCTION

Sending a spacecraft to Mercury has unique challenges that stem largely from the planet's proximity to the Sun. There are some benefits to flying so close to the Sun. One benefit is the abundant solar flux available for onboard power generation. Keeping solar arrays within operating temperatures, however, can, in turn, be challenging. Another benefit is Mercury's proximity to Earth. The relatively short distance makes two-way-light-time communications fairly short in duration compared with missions to the outer planets. However, Mercury's 88-day orbit around the Sun results in multiple solar conjunctions, cutting off communication entirely. Further, though the distance from Earth to Mercury never exceeds 1.5 AU, maneuvering a spacecraft to catch up to Mercury and enter orbit - so close to the Sun's gravity well - must occur over many orbits around the Sun and requires a large change in velocity ( $\Delta V$ ).

<sup>1</sup> 1-4244-1488-1/08/\$25.00 ©2008 IEEE.

<sup>2</sup> IEEEAC paper #1250, Version 10, updated January 27, 2008

The final design of the MESSENGER spacecraft was the result of many trades to balance the thermal and mass requirements of the mission. The current trajectory from Earth to Mercury was driven by the launch date and the available propellant, resulting in multiple planetary gravitational assists and several large maneuvers. This rapid pace of critical operations during the cruise phase of the mission must be balanced by a robust but efficient planning and execution process in addition to constant vigilance by the small team that operates this complex spacecraft through its complex mission [2].

This paper describes the spacecraft and the mission at the system level, providing critical details of the subsystems and operations through the cruise phase, a 6.6-year journey to Mercury. The intended result is a description of some of the challenges faced by this Discovery-class mission. This paper serves to illustrate the intensity of operations through the cruise phase. Mercury Orbit Insertion (MOI) will not occur until March 2011, but the mission has already been, and will continue to be, both challenging and rewarding

## 2. SPACECRAFT OVERVIEW

The MESSENGER spacecraft was designed and built at the Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, Maryland. Launched on August 3, 2004, from the Kennedy Space Center on a Delta II 7925-H, the spacecraft launch mass was 1107 kg [1]. The spacecraft is fully redundant and cross-strapped, providing a high level of both robustness and flexibility. The spacecraft layout and system functional block diagram are shown in Figure 1 and Figure 2 [1], respectively.

The MESSENGER sunshade, perhaps the spacecraft's most easily recognizable feature, enabled the use of typical spaceflight-qualified hardware. The bulk of the spacecraft electronics, structure, instrumentation, and propulsion system reside in the shadow of this shade. The bulk of the spacecraft runs at or below room temperature. Only the few units mounted on the sunward side of the shade, the solar arrays and the Magnetometer boom, are exposed to direct sunlight.

*Processors* — The spacecraft is, from a functional point of view, centered on the Integrated Electronics Module (IEM).

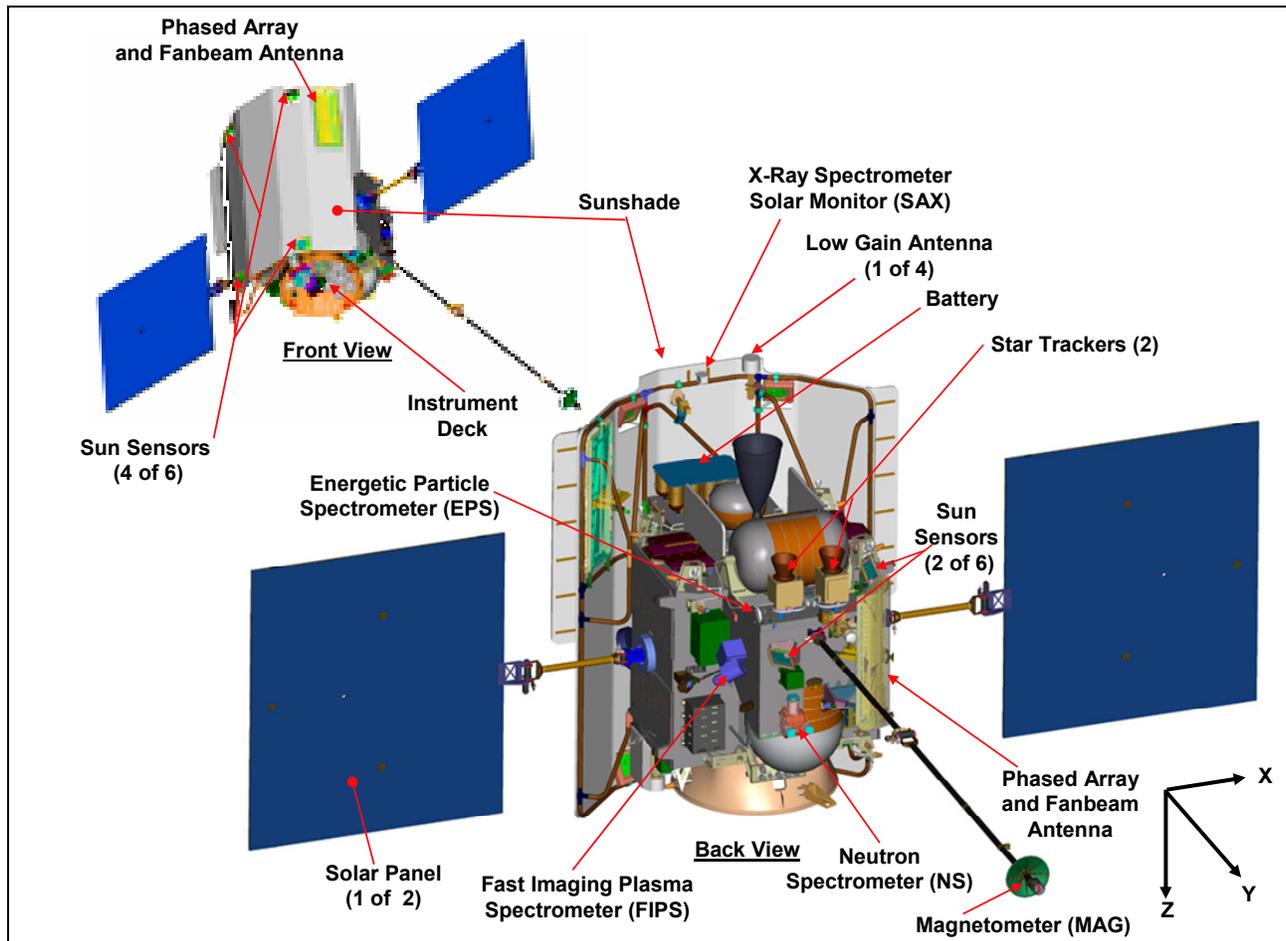


Figure 1 - MESSENGER Spacecraft Layout

Figure 3 shows a functional block diagram for the IEM. This unit contains two RAD6000 processors [1]. The first, the Main Processor (MP), runs custom-written C code that performs most of the major functions on the spacecraft. The second processor, operating as a MIL-STD 1553 Bus Monitor (BM), performs independent fault detection and protection functions for the spacecraft. Many of the functions described in the list below are expanded upon in the subsystem descriptions that follow.

The MP performs the following functions [1]:

- Processes ground commands, both real-time and sequenced
- Routes commands to subsystem and payload units
- Downlinks all telemetry, some generated within the MP and some received from other units via CCSDS (Consultative Committee for Space Data Systems) protocol
- Processes inertial, Sun-based, and star-based sensor data to determine spacecraft attitude
- Processes onboard ephemerides for the spacecraft, Earth, and the “target planet” (Earth or Venus or Mercury)
- Controls spacecraft attitude, using reaction wheels during most operations, and using thrusters during propulsive events
- Executes all propulsive maneuvers through closed-loop

- control, using accelerometer-based  $\Delta V$  accumulation and gyro-based attitude monitoring
- Monitors power subsystem output and determines optimal operating state of solar arrays
- Monitors battery state of charge and determines proper recharge rates
- Controls the MIL-STD 1553 data bus
- Runs a DOS-like file system for onboard data storage and manages the Solid-State Recorder (SSR) where the file system is resident
- Manages the onboard file playback, utilizing the CCSDS File Delivery Protocol (CFDP)
- Compresses images before downlink to the Earth
- Controls propellant tank temperatures through closed-loop temperature monitoring and heater commanding

Each IEM has an MP, but the system will allow only one IEM to be the Bus Controller (BC) and the Command and Data Handling (C&DH) unit at a time, forcing the redundant processor into a 1553 Remote Terminal (RT) mode. Typically, the redundant MP is powered only for periodic updates to non-volatile memory space.

The IEM also houses the 8-Gbit SSR, a spacecraft interface card that performs critical command decoding, the uplink receipt and downlink framing hardware, and a secondary power converter board [1]. The SSR and interface card

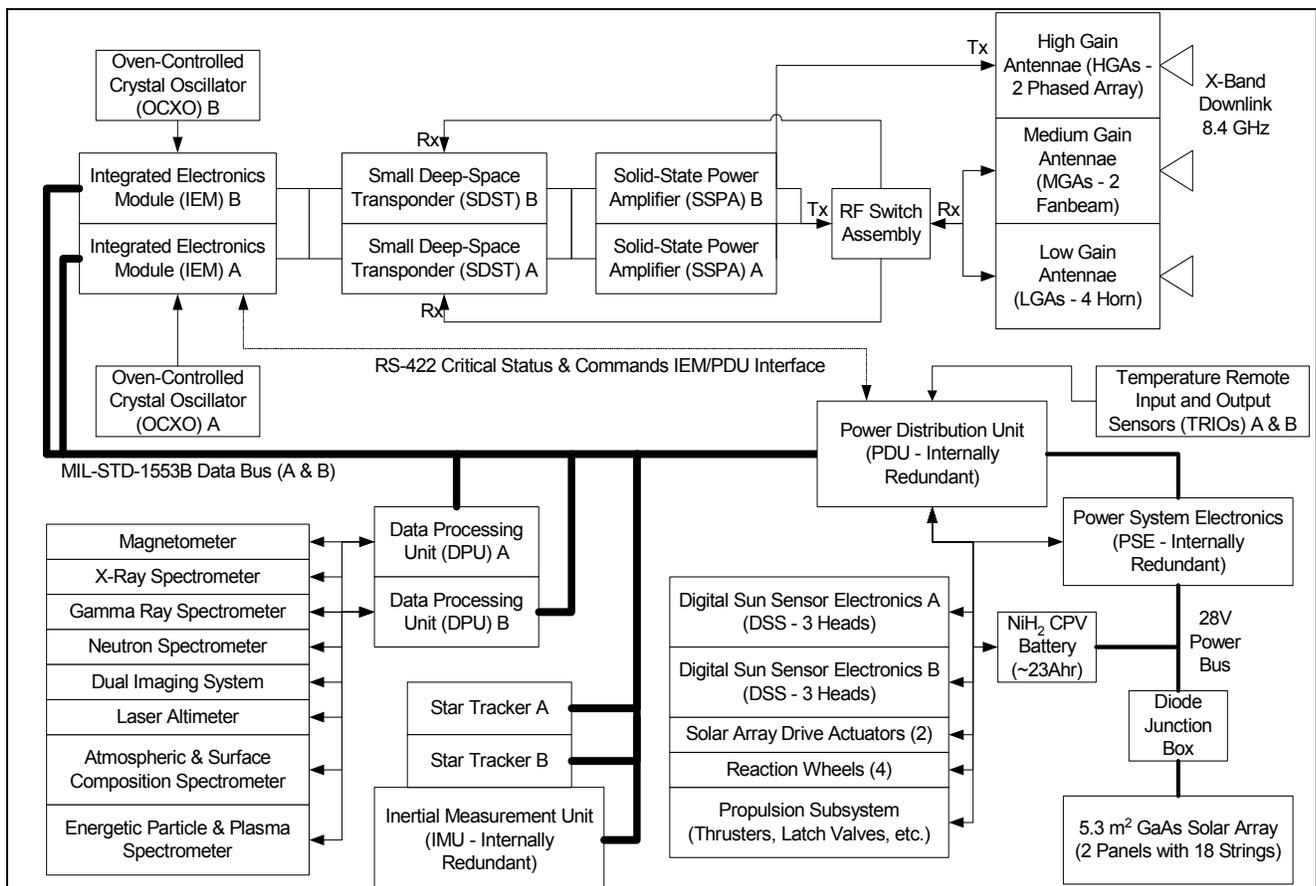


Figure 2 - MESSENGER System Functional Block Diagram

communicate with the MP via an internal Peripheral Component Interconnect (PCI) bus.

The IEM has a companion unit, the Oven-Controlled Crystal Oscillator (OCXO), which is used to provide precision onboard timing [1].

The second processor in the IEM, the Fault Protection Processor (FPP), monitors the MP and most other units on the spacecraft for health and safety. The FPP has the authority to switch to redundant units, including the redundant Main Processor. The FPP software runs a Reverse Polish Notation (RPN) rule evaluation engine. Two hundred and seventeen autonomy rules are evaluated at 1 Hz to determine if a limit has been violated or a state has changed from healthy to unhealthy. If an error persists for a pre-programmed duration, the rule will trip and execute a series of relative time commands to address the issue.

The rules monitor telemetry from all subsystems but take only a handful of different actions. The system is deliberately designed to either: a) switch to a redundant unit, b) enter one of two demoted modes, or c) power down the faulted unit.

The two demoted modes are fairly similar in overall spacecraft configuration, with the critical distinction being that Safe Hold (SH) Mode retains coarse ephemeral knowledge of the spacecraft and Earth positions and can, therefore, point the high-gain phased-array downlink antenna in Earth's direction. Furthermore, this mode simply pauses the currently executing stored command load and retains the commanded instrument power state, providing quicker recovery of the instrument observation schedule.

Earth Acquisition (EA) Mode does not retain any knowledge of the Earth's position with respect to the spacecraft body. EA Mode instead sweeps one of the two medium-gain fanbeam antennas through space by rotating around the Sun-line.

*Guidance and Control* — Guidance and Control (G&C) of the spacecraft is achieved through software running in the Main Processor. This software depends on attitude data provided by one of two co-bore-sighted, redundant Autonomous Star Trackers (ASTs) from Galileo Avionica in Florence, Italy. Nominally, only one AST is powered at any time with the second held as a cold spare. The G&C software depends upon a Northrop-Grumman Scalable Space Inertial Reference Unit (S-SIRU) for body rate and linear acceleration information. A suite of Adcole Digital Sun Sensors (DSSs) provide Sun-position knowledge [1].

The G&C algorithms execute at up to 50 Hz to determine current attitude and make decisions on which actuators to use to achieve the commanded attitude. The commanded attitude can be one of several options, including inertial right ascension and declination pointing, Sun-relative pointing, target-body relative pointing, or target-body surface pointing (i.e., specific latitude or longitude). The latter pointing modes are supported by onboard time, ephemeris, and rotating body models, parameterized for targets such as Earth, Venus, or Mercury [1]. This highly flexible pointing scheme allows the spacecraft to achieve the global mapping and other science goals of the mission.

The G&C system uses four Reaction Wheel Assemblies (RWAs) from Teledix in Heidelberg, Germany, to maintain the commanded attitude for most operations. During

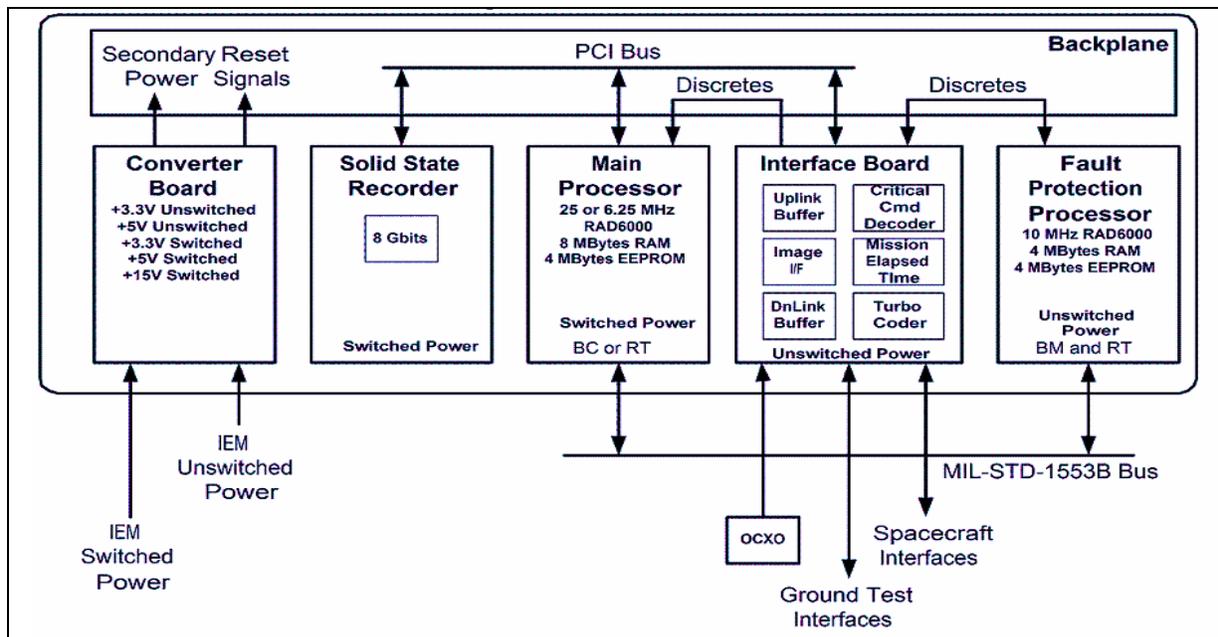


Figure 3 - Integrated Electronics Module (IEM)

propulsive maneuvers, the G&C system relies on thrusters for attitude control and allows the wheels to spin down. During certain maneuvers, the wheels may be deliberately driven to a pre-determined state for momentum management.

The G&C software also controls the Solar Array Drive Assemblies (SADAs), maintaining the solar arrays at the proper angle to the Sun. Further, the G&C system provides two points of information to the payload, though it does not perform closed-loop control of these units. G&C provides angle information to the Mercury Dual Imaging System (MDIS) instrument and target-planet range and slant-angle information to the Mercury Laser Altimeter (MLA) instrument. Finally, the G&C software provides ephemeris-based commands to the communications system by which the phased-array beam is steered to Earth for high-rate downlink.

*Propulsion* — MESSENGER’s propulsion system, shown in Figure 4, has seventeen thrusters and five tanks and is fully integrated into the spacecraft structure. There are twelve 4.4-N monopropellant thrusters situated around the spacecraft’s center of mass. Figure 4 shows various components of the propulsion system. There are four 22-N monopropellant thrusters, which are co-aligned with the 667-N, Large Velocity Adjust (LVA) engine. There are two main fuel tanks, each containing approximately 180 kg of hydrazine (N<sub>2</sub>H<sub>4</sub>) at launch, one oxidizer tank containing approximately 231 kg of nitrogen tetroxide (N<sub>2</sub>O<sub>4</sub>) at launch, a refillable auxiliary fuel tank with a maximum

capacity of approximately 10 kg of hydrazine, and a titanium-lined composite over-wrapped helium pressurant tank [1]. The system provides approximately 2300-m/s ΔV for the mission [2].

The G&C software performs all command and control functions during propulsive maneuvers. The system can operate in three different modes:

**Mode 1:** The auxiliary tank is used in a blow-down mode to supply the 4.4-N monopropellant thrusters for small ΔV maneuvers and for system momentum unloading.

**Mode 2:** The main fuel tanks are used to supply the four 22-N thrusters for large ΔV maneuvers. During Mode 2 maneuvers, the 4.4-N thrusters are used to augment attitude control in conjunction with off-pulsing of the 22-N thrusters.

**Mode 3:** The main fuel tanks and the oxidizer tank are used to supply bi-propellant reactants to the 667-N engine for large velocity adjustments. During Mode 3 maneuvers, the 22-N thrusters are used for attitude control, with the 4.4-N thrusters providing rotation control around the thrust axis.

Propulsive maneuvers are executed closed-loop, with the G&C software monitoring the cumulative ΔV reported by the accelerometers and terminating the burn once the target ΔV is achieved. Numerous checks are automatically

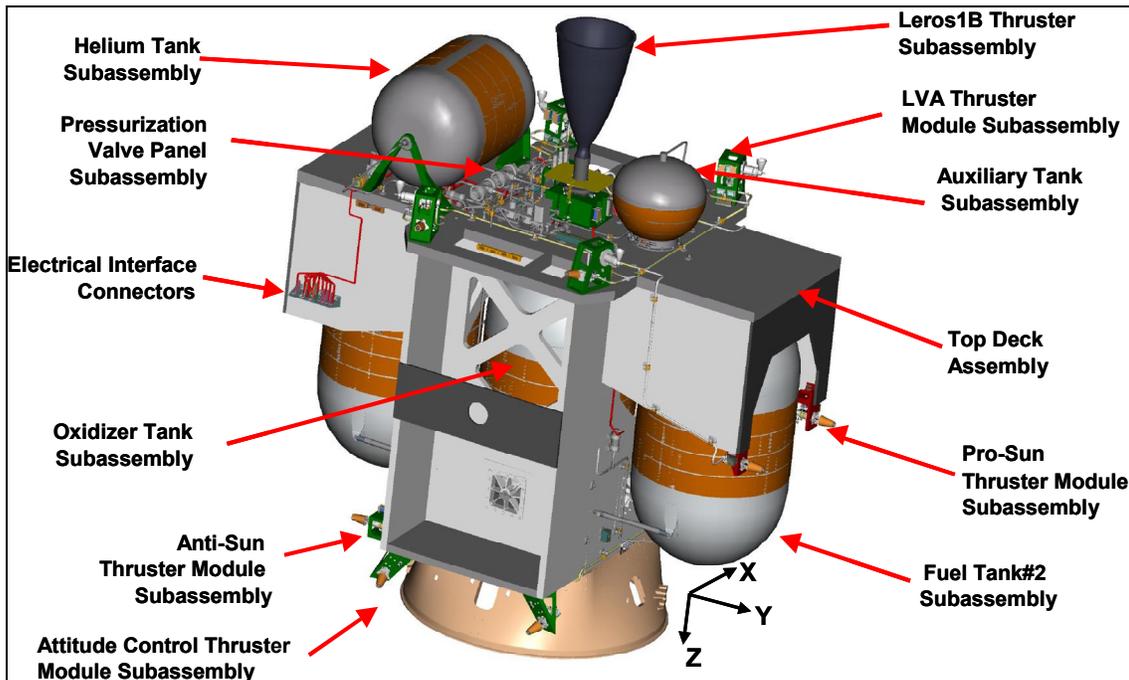
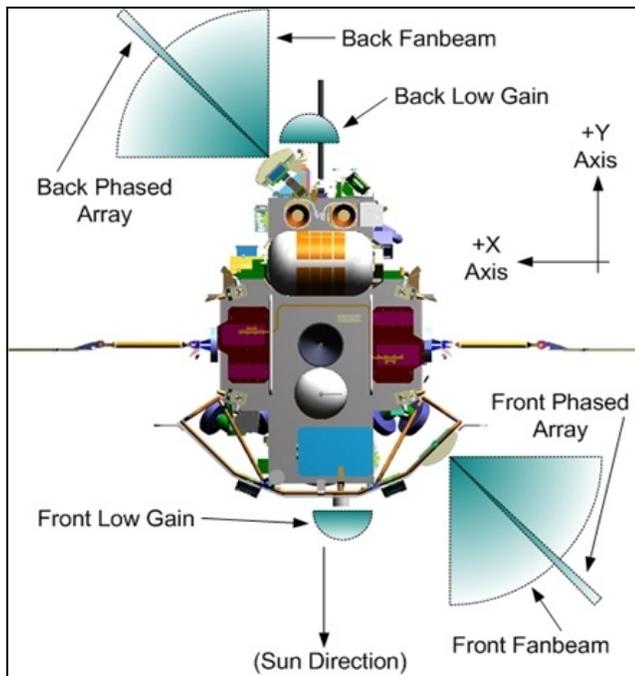


Figure 4 – Propulsion System Components

performed on various propulsion system parameters continuously during each burn to ensure safe execution.

*Communications* — The X-band Radio Frequency (RF) telecommunications system on MESSENGER is a fully redundant, cross-strapped system. There are two custom-built Solid-State Power Amplifiers (SSPAs), two General-Dynamics Small Deep Space Transponders (SDSTs), redundant switch assemblies, four hemispherical Low-Gain Antennas (LGAs), two fanbeam medium-gain antennas, and two phased-array High-Gain Antennas (HGAs). Figure 5 shows the antennas and their fields of view looking down on the spacecraft from above the LVA motor. Note that the



**Figure 5 – Antenna Fields of View**

field of view for the forward low-gain antenna, with a bore-sight along the  $-Z$  axis of the vehicle, and the aft low-gain antenna, with a bore-sight along the  $+Z$  axis of the vehicle, are not shown.

The SSPAs and all antennas were designed and manufactured at APL specifically for the MESSENGER spacecraft [1]. The HGA design was a mission-enabling technology. Early design trades considered how to keep a traditional dish at operational temperatures over the wide range of Sun-probe-Earth angles that are seen through the mission. Requiring, perhaps, its own sunshade and a large boom with multiple gimbals, this design was discarded. In order both to simplify the mechanical design and survive the intense thermal environment, a unique phased-array antenna was designed for MESSENGER. There are two phased arrays, one on the sunward side of the spacecraft, mounted on the sunshade, and the other on the opposite side of the spacecraft. These antennas, used one at a time, can be electronically steered around one axis, and the spacecraft

body rolled about a second axis, to achieve Earth-pointing at any point in the mission. Capable of operating at its design point while exposed to the equivalent of 11 Suns, this design is critical to MESSENGER's ability to achieve mission success [1].

The low- and medium-gain antennas are used for low-rate downlink and for all uplink, providing virtually  $4\pi$ -steradian coverage. This suite of antennas ensures uplink with the spacecraft regardless of vehicle attitude. Furthermore, these antennas ensure downlink in demoted states, even when the spacecraft no longer has knowledge of Earth direction.

*Power* — Parts of the power subsystem also faced the challenge of being exposed directly to the Sun. Specifically, the solar arrays were built with a 2:1 ratio of Optical Solar Reflectors (OSRs) to solar cells, significantly increasing the reflectance from the array compared with the absorption due to the gallium arsenide cells themselves [1]. The surface normal to each array panel is pointed directly to the Sun when the spacecraft-to-Sun distance is greater than 0.55 AU. The arrays are off pointed from the Sun line for solar distances below 0.55 AU to balance the power required for operations with the temperature of the arrays.

The power subsystem is a peak-power-tracking system that isolates the battery and spacecraft electronics from the variations in voltage (45-90 V) of the solar arrays. These variations are due to a combination of variable solar flux, panel operating temperature, and panel offset angle, all of which vary with solar distance. Further, the spacecraft, while in Mercury orbit, will go through eclipse seasons, with eclipses lasting up to an hour, resulting in battery discharges, as well as large drops in solar array temperature. A 22-cell, 23-A-hr  $NiH_2$  battery supports the spacecraft through these eclipses [1].

*Structure* — The MESSENGER structure is a set of thin composite panels that were integrally combined with the propulsion tanks. The design was mass-optimized to carry the launch loads of the system, given the tight mass constraints of the mission. The solar panel face sheets are, similarly, lightweight composite construction. The design of the solar panel was required to handle the large swings in temperature, on the order of  $250^{\circ}C$ , that they will see coming out of eclipse and back into the 11-Sun environment of Mercury orbit [1].

The sunshade support structure is welded titanium, chosen for its lightweight properties. This tubular frame was required to carry the launch loads of the sunward phased-array antenna assembly, four of the six Sun sensor heads, two low-gain antennas, and the X-Ray Spectrometer solar monitor.

*Thermal* — As previously mentioned, the spacecraft units, for the most part, operate around room temperature. In order to accomplish this under the 11-Sun intensity that the

spacecraft will experience while in Mercury orbit and at perihelion during the cruise phase, a custom built, lightweight ceramic cloth sunshade was positioned between the spacecraft and the Sun [2]. The size and shape of the shade dictates the 20°x24° Sun Keep-In (SKI) zone enforced by the G&C system. Overall, the system is a cold-biased design that requires heater power to maintain temperature in proper operating ranges. The large heaters on the propellant tanks in the core of the spacecraft provide most of this heat. These heaters are on almost all of the time, with the heat flux out from the tanks keeping most of the spacecraft warm without much additional unit-level heater power. As the spacecraft passed through its closest approach to the Sun (0.33 AU) on September 1, 2007, the heaters on the tank closest to the Sun shut down. The small amount of heat that passed through the sunshade was sufficient to allow that heater to shut down. As the spacecraft spends more time at such close distances to the Sun, similar effects are expected.

Direct solar energy is not the only intense thermal source that MESSENGER was designed to accommodate. Because of the planet's proximity to the Sun, the surface temperature of Mercury is as much as 400°C during the day. The combined effect of planetary albedo and thermal emission represents an additional thermal source into the spacecraft that varies during the Mercury solar day. The spacecraft is capable of handling these extreme thermal conditions. However, for the most intense combination of environments, the spacecraft must operate within tighter

attitude constraints. Specifically, during limited portions of the orbital mission, the G&C system is programmed to keep the -Z deck of the spacecraft from being illuminated by the hottest part of the planet's surface, the sub-solar point, referred to as the Hot Pole Keep-Out (HPKO) constraint, while also keeping the Sun within the previously discussed SKI zone.

### 3. SCIENCE INSTRUMENTATION

The MESSENGER payload is a suite of seven instrumentation packages. Figure 6 shows the layout of instruments with the instrument deck visible inside the launch vehicle attachment ring.

The MESSENGER instrument suite consists of:

- **The Mercury Dual Imaging System (MDIS)** includes a monochromatic Narrow Angle Camera and a Wide Angle Camera that has 11 filters. These cameras are mounted on a pivot to allow concurrent multiple bore-sight observations with other instruments.
- **The Mercury Atmospheric and Surface Composition Spectrometer (MASCS)** has a fixed bore-sight and is mounted on the planet-facing instrument deck. MASCS is actually two separate instruments in the same unit: an Ultraviolet and Visible

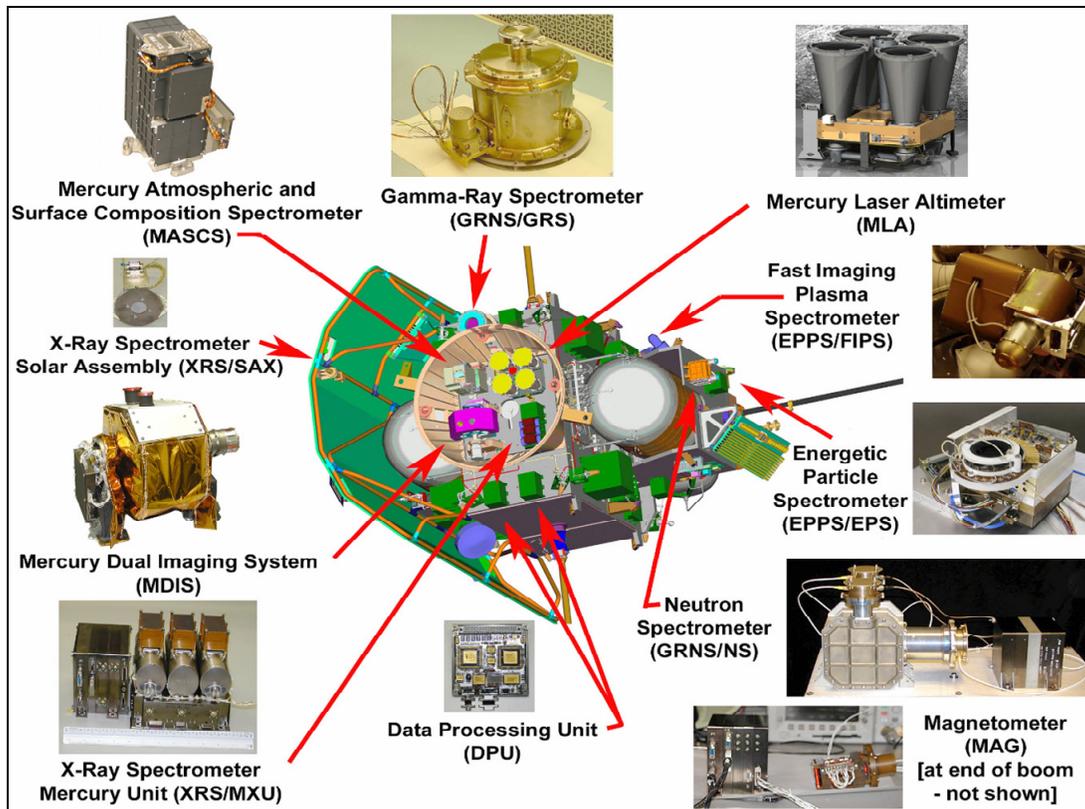


Figure 6 – MESSENGER Science Instrumentation

Spectrometer (UVVS) and a Visible and Infrared Spectrograph (VIRS).

- **The Mercury Laser Altimeter (MLA)** is a diode-pumped Nd:YAG laser range finder. Interestingly, this laser has been used to perform two-way optical communication over unprecedented distances with Earth-based lasers at NASA's Goddard Space Flight Center.
- **The Magnetometer (MAG)**, with triaxial fluxgate sensors, will be used to map the magnetic field of Mercury. Boom-mounted, the MAG will not be protected by the spacecraft's sunshade at certain attitudes and therefore has its own small sunshade.
- **The Energetic Particle and Plasma Spectrometer (EPPS)** contains an Energetic Particle Spectrometer (EPS) and a Fast Imaging Plasma Spectrometer (FIPS) to perform in-situ particle characterization.
- **The Gamma-Ray and Neutron Spectrometer (GRNS)** includes two detectors that share a common electronics unit and will detect gamma rays and neutrons from Mercury's surface.
- **The X-Ray Spectrometer (XRS)** has detectors mounted on the instrument deck and a supplemental detector on the sunshade to monitor the solar X-ray flux, which influences the X-ray fluorescence from Mercury's surface.

The MESSENGER payload is tied together at the Data Processing Unit (DPU), a remote terminal on the 1553 data bus. The DPU acts as a C&DH hub for all the scientific

instruments.

Another scientific measurement will be made via the variability of the RF downlink as the spacecraft moves through Mercury's gravity field. Further, downlink will be monitored for certain occultation events as Mercury passes between the spacecraft and Earth.

#### 4. CRUISE PHASE HIGHLIGHTS

During a cruise phase of 6.6 years, one might expect long periods of inactivity and virtual hibernation. However, this has not been the case for MESSENGER. Operations have been fast-paced and challenging and will continue to be so until Mercury Orbit Insertion in March 2011. Figure 7 [3] shows the spacecraft trajectory from the Earth to Mercury as well as a linear representation of the critical trajectory changes.

*The first year* – After launch on August 3, 2004, the spacecraft spent approximately one year orbiting the Sun at about 1 AU. This was not the original launch date; the original launch date, approximately five months earlier, would have allowed the spacecraft to start immediately toward the inner solar system. However, the August 2004 launch required this year-long “outer cruise,” sometimes beyond 1 AU from the Sun. Since the spacecraft is cold-biased, and the power available from the arrays at 1 AU represents a mission-minimum power generation, the spacecraft had to be “flipped,” with the sunshade pointed away from the Sun so that the spacecraft would be warmed by the Sun. The operations team had to choreograph carefully these 180° turns as the Sun distance increased and decreased. The final flip occurred in June 2006, almost two years after launch. After this final turn to a Sun-safe attitude, the spacecraft now operates at all times within the

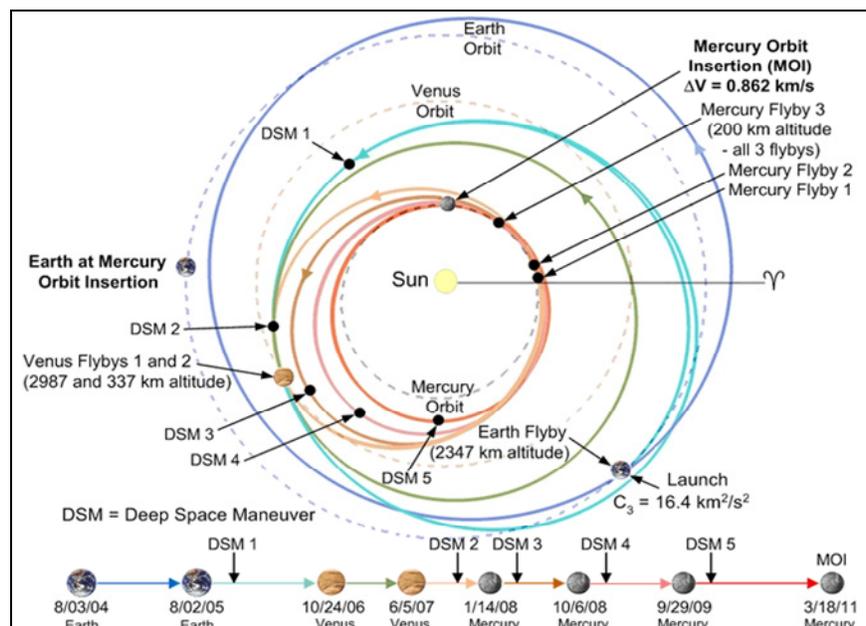


Figure 7 – MESSENGER Cruise Trajectory and Event Timeline

SKI boundaries.

Also in the first year of cruise, the team performed the typical system-wide post-launch checkouts and instrument deployments (boom, covers) as well as the execution of five propulsive Trajectory Correction Maneuvers (TCMs).

The first year of cruise was punctuated by an Earth flyby on August 2, 2005, at an altitude of 2348 km, allowing the spacecraft to begin to head into the inner solar system. The team took advantage of the flyby to calibrate a number of instruments. Further, the spacecraft took enough images to create a full-color departure movie of Earth [3]. Figure 8 presents an image from this movie sequence [5].



**Figure 8 – Earth Image from MESSENGER**

*Earth to Venus* – In the 14-month period between the Earth flyby and the first Venus flyby the team executed five propulsive maneuvers and two propulsive momentum dumps. One of the maneuvers was the first use of the bi-propellant Large Velocity Adjust engine on December 12, 2005. While this Deep-Space Maneuver (DSM) 1 was critical to maintaining the cruise trajectory, this event also represented the verification of the bi-propellant propulsion system.

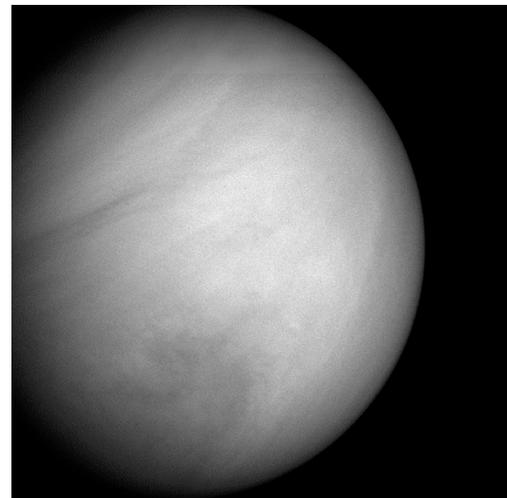
The first encounter with Venus on October 24, 2006, at an altitude of 2987 km was complicated by the near coincidence of several events. As a result of the flyby geometry, the spacecraft encountered the mission’s first eclipse of the Sun, at 56 minutes the longest of the mission prior to orbit insertion. The flyby and associated eclipse period occurred near entry into the first significant superior solar conjunction of the mission, 30 days in duration. Because of the conjunction period, the long eclipse, and the relatively high flyby altitude, it was determined early in mission planning that the instrument suite would not be active during this flyby event, thus alleviating some of the demands on the team. Nonetheless, the combination of the gravitational assist by Venus, the solar eclipse, and the solar

conjunction made preparations and operations through this period very demanding.

*Venus to Mercury* – In the next 15-month segment of the mission, the operations tempo was stepped up significantly, requiring the team to prepare for two planetary flybys with the full instrument suite operational, another DSM, the longest superior solar conjunction of the mission, and numerous potential TCMs.

Between the first and second Venus encounters, there were three propulsive maneuvers, including a small bi-propellant maneuver. The end result was an extremely accurate flyby for the second Venus encounter, at an altitude of 337 km. Between the second Venus encounter and the first Mercury encounter, there was only one major maneuver, a deterministic, large bi-propellant maneuver, DSM-2. The accuracy of the second Venus gravitational assist eliminated the need for any small corrective maneuvers between the encounter and DSM-2.

As intense as operations were leading up to and through the first Venus encounter, they did not, as noted, include any instrument operations. Only a few distant images of Venus were obtained many days before the encounter. The second Venus encounter (June 5, 2006) was a different matter. Through the winter and spring of 2006, the team developed both the process and the products for full operation of the payload in concert with the G&C system to take scientific measurements, including 614 images of the planet. This intensive planning effort yielded a highly successful encounter campaign, validating the MESSENGER team’s flyby planning process. Figure 9 shows an image of Venus taken during the second encounter sequence [5].



**Figure 9 – Venus Image from MESSENGER**

These processes were in turn used to plan for the first Mercury encounter, where the spacecraft obtained the first close-up images of Mercury since Mariner 10’s third Mercury flyby in 1975.

Between DSM-2 on October 17, 2007, and the first Mercury encounter on January 14, 2008, the mission experienced its longest superior solar conjunction, running from October 26 to December 12, 2007. The proximity of this DSM to the conjunction period and the uncertainty of operations within the conjunction made for potential uncertainties in the post-conjunction trajectory. To correct for these potential uncertainties, the team prepared five propulsive maneuver opportunities between December 19 and January 12 to re-target the 200-km flyby altitude at Mercury, while concurrently planning for the intensive science observation sequence during the encounter. In the end, only one of these maneuvers was needed.

*On to Mercury Orbit* – The cruise phase of the mission will continue at a somewhat slower but still demanding pace until the fall of 2009. After the first Mercury encounter, the team must plan for and execute:

- DSM-3 in March 2008
- The second Mercury encounter in October 2008
- DSM-4 in December 2008
- The third Mercury encounter in September 2009
- DSM-5 in November 2009

Interspersed among these large operations will be numerous smaller trajectory correction maneuvers and instrument calibration activities.

The time between DSM-5 in the fall of 2009 and Mercury Orbit Insertion in March 2011 is a reasonably long interval. However, in that time the team must adequately prepare for one of the largest  $\Delta V$  maneuvers of the mission, Mercury Orbit Insertion (MOI), and complete preparation and validation of the observation plans, tools, processes and procedures for the year-long Mercury orbital phase of the mission.

## 5. CONCLUSION

Flight operations of the MESSENGER spacecraft have, to date, been challenging and rewarding. With four successful planetary flybys as of January 2008 and two more to complete on the way to orbit insertion, the rapid pace of operations has tested the expertise of a small but skilled and dedicated team. Looking forward to the next three years of operations reveals a continuation of intense activity that will culminate with orbital insertion for a year-long science mission.

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## BIOGRAPHY

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