MESSENGER: An Extreme Systems Engineering Challenge

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Although each deep-space mission is unique in design and accomplishment, all spacecraft carry payloads and need subsystems to provide command and data-handling capability, propulsion, structural support, thermal protection, guidance and control, power, and telecommunications. Add flight software to operate the craft and fault protection to maintain health and safety when the craft is far from home, and one has the generic in-flight components of a deep-space mission. Whereas the coordination of these various elements in all cases clearly demands a systems approach, the technical and budgetary constraints imposed on the MESSENGER mission (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) and the distant and extreme environment in which it is meant to operate posed a special challenge for the systems engineering team at the Johns Hopkins University Applied Physics Laboratory.

The MESSENGER mission was the seventh selected in NASA's Discovery Program of relatively low-cost missions. The mission's goal is to answer a number of guiding science questions about the nature of Mercury by becoming the first spacecraft to orbit the innermost planet. None of the challenges facing the designers of this mission could be addressed without considering the other challenges, and an extraordinary amount of interplay and a large number of trades among discipline areas were necessary to develop a viable concept. JHU/APL led the development, integration, and testing of the spacecraft and provided five of the seven scientific instruments.

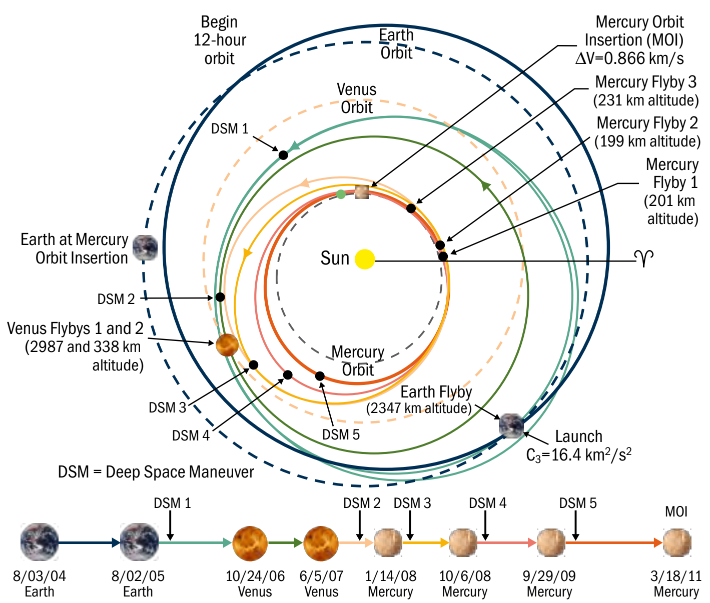

Figure 1. The MESSENGER mission design requires six planetary flybys and five deep-space maneuvers (DSMs) before the spacecraft can be inserted into orbit about Mercury.

MESSENGER Challenges

The primary requirement was to use a launch vehicle no larger than a Delta-II 7925-H, which can lift a maximum of 1,100 kg into an interplanetary trajectory. The amount of mass available for the spacecraft and its payload depended on the quantity of propellant required to reach, capture, and maintain the craft in an acceptable orbit. Although Mercury is not remote from Earth by planetary standards, it is rather difficult to orbit because of the sizable velocity change needed to lower the vehicle's speed relative to Mercury to allow it to enter orbit about the planet. In order to minimize the use of propellant, mission planners determined that by utilizing gravity assists from six planetary flybys and by conducting five deep-space maneuvers, the spacecraft could be poised to enter orbit in a little more than six and a half years from launch (figure 1).

The long duration of this cruise period mandated that critical subsystems be made redundant to lower the risk of single-point failures. The MESSENGER command and data-handling system, for example, employs redundant integrated electronics modules, each with a main processor and a fault-protection processor that monitors the main processor and most other units on the spacecraft for health and safety. To answer the six guiding science questions, mission planners chose a suite of seven instruments such that each question is addressed by more than one instrument, and each instrument addresses more than one question.

The amount of propellant required to accomplish the MESSENGER mission design was approximately 600 kg, which left slightly more than 500 kg for the spacecraft. With mass clearly the primary driver of the subsystem designs, innovation was required to accomplish subsystem tasks.

The propulsion system was integrated into a graphite-cyanate ester structure, which was carefully designed to transfer loads in such a way that the composite panels could be thin relative to their size. The MESSENGER mechanical team and subcontractors collaboratively developed custom-made, lightweight, 0.5 to 1.0 mm thick titanium tanks and embedded them into the structure; they also embedded the 17 variously sized thrusters that were required to accomplish the numerous trajectory-correction maneuvers. A large velocity-adjust engine was used for the deep-space maneuvers.

Perhaps the biggest single subsystem challenge was to develop a lightweight thermal subsystem to protect the spacecraft from the extreme environment of Mercury. At about 0.3 AU from the Sun, the intensity of solar radiation is 11 times that experienced on Earth. In the Mercury orbit that meets the science requirements, the spacecraft will pass very close (approximately 200 km) to the surface of the planet, and at that distance, the reflected solar intensity is approximately four times that on Earth.

The solution to the thermal challenge was to harbor the spacecraft behind a sunshade that is pointed at the Sun at all times (figure 2). Incorporating the sunshade largely removed the thermal burden from the other subsystems, allowing the use of traditional components and designs, which saved both cost and mass. The lightweight sunshade is made of a ceramic cloth and traditional aluminized kapton sheets, supported by a framework of titanium tubes. Although it weighs only about 20 kg, it withstands temperatures in excess of 300°C and allows the subsystem and payload to remain at approximately room temperature. In addition, diode heat pipes were employed to separate some components from the spacecraft when it is close to the planet and to channel heat to the side of the vehicle that is not in view of the planet.

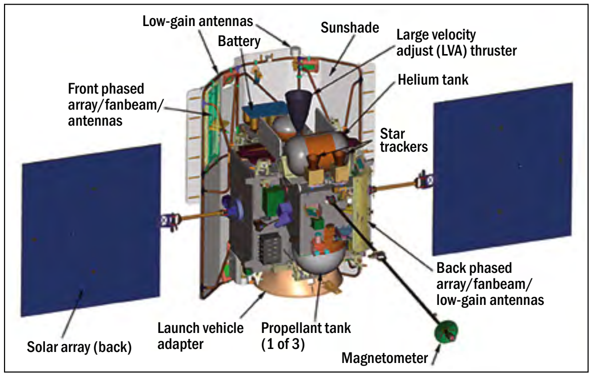

Figure 2. The MESSENGER spacecraft subsystems are compactly positioned behind the sunshade.

The power system must independently address the thermal challenge. Both 2.6 m^2 solar panels were designed to consist of two-thirds mirrors and one-third solar cells in order to reflect most of the heat and reduce the overall temperature of the arrays. In addition to withstanding the extremely high temperature of over 270°C, the arrays were developed to withstand rapid changes in temperature (to as low as -135°C) driven by solar-eclipse periods during planetary flybys and orbital operations. At solar distances less than 0.6 AU, the solar panels are tilted away from the Sun to lower temperatures further. The design incorporates a battery to supply power when the solar arrays are not illuminated.

The continued proper behavior of the propulsion, thermal, and power systems is largely the responsibility of the guidance-and-control system, which also monitors the many propulsive maneuvers by using a system of feedback accelerometers. This subsystem also affords attitude information to the science instruments to facilitate their pointed observations.

To avoid carrying the mass of a conventional gimbaled dish, and the complications of verifying such an assembly at extreme temperatures, telecommunications system designers incorporated innovative, electronically steerable phased-array antennas. Used one at a time, each of these high-gain antennas—one on the sunshade 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.

To minimize mass and complexity, the seven instruments of the science payload are controlled through a central data-processing unit, and all but the Mercury Dual Imaging System (MDIS) are fixed-mounted to the spacecraft. Limiting the number of gimbaled instruments to one simplified the mechanical design but increased the burden on the guidance-and-control system, which must change the spacecraft attitude to accommodate pointed observations.

Finally, because the spacecraft will exist in such a harsh environment, far enough from home to preclude real-time control, the autonomous fault-protection system needed to be robust enough to oversee the complex interactions among subsystems. This subsystem checks 217 autonomy rules every second to ensure the nominal behavior of the entire system. In the event of anomalous performance, the fault-protection system can place the spacecraft into either of two demoted states until mission controllers re-establish contact and address the situation.

So Far, So Good

MESSENGER has now completed all six planetary flybys, has successfully conducted its five large velocity-adjust deep-space maneuvers, and is on course to begin orbiting Mercury in March 2011. Although the prime mission has yet to begin, throughout the spacecraft's six-year journey since launch, the interplay among subsystems has been verified in a number of ways. During multiple passes within the orbit of the innermost planet, the thermal-protection system has demonstrated that it can keep the spacecraft at the desired temperature despite the harsh environment. On MESSENGER's second visit to Venus and for its three passes of Mercury, the science payload performed as expected, confirming the ability of the guidance-and-control system to manage all pointing requests by the instruments while keeping the sunshade pointed toward the Sun at all times. The data collected from the instruments and transferred to Earth through the phased-array antennas have yielded exciting new results that promise to be surpassed during the year of orbital operations.

The continuing flight success of the MESSENGER mission validates the ability to execute robotic scientific investigations in extreme operating environments and within programmatic constraints. By applying systems engineering at all levels within the project, APL maintained focus on the scientific objectives and technical challenges embodied in the first orbital mission to study the mysteries of the planet closest to the Sun.