Spacecraft Packaging

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A spacecraft designed for an interplanetary mission is like any highly integrated system and adheres to the basic principle that "form follows function." The configuration of an interplanetary spacecraft is largely driven by its instruments and their fields of view, pointing, mass, and power and thermal requirements. This article looks at three recently launched APL spacecraft—New Horizons, MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging), and STEREO (Solar TErrestrial RElations Observatory)—in the context of their design constraints, how these constraints were met, what areas they had in common, and what areas were unique and why.

INTRODUCTION

The science payloads developed for interplanetary missions are assembled to answer a specific set of questions, such as (*i*) what are the physical and geological properties of the planets and (*ii*) how and under what conditions were the planets formed and evolved. These scientific measurements are made by using a variety of instruments, such as visible and infrared spectrometers, x-ray and gamma-ray spectrometers, magnetometers, interferometers, particle detectors, sampling devices, etc. The primary function of the spacecraft is to support these scientific instruments. The spacecraft provides the propulsion, attitude control, electric power, communications, thermal protection, and necessary support structure to ensure that the science payload is protected during launch and enables it to maintain the correct orbit and point in the proper direction. Finally, these interplanetary spacecraft are designed to operate for a specific lifetime over which they must operate and relay their data back to Earth.

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is the first spacecraft to orbit the planet Mercury (Fig. 1), and it has a science payload consisting of seven scientific instruments. Understanding Mercury and the forces that have formed it are fundamental to our understanding of the terrestrial planets and their evolution. (For additional information, refer to Ref. 1.) A key MESSENGER constraint is the intense heat of the planet

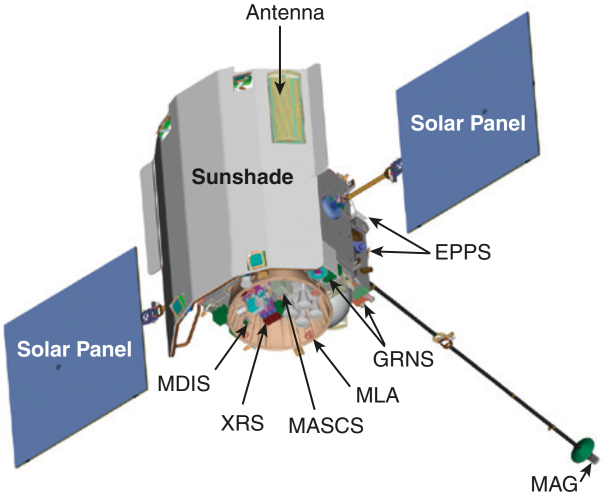

Figure 1. The MESSENGER spacecraft. EPPS, Energetic Particle and Plasma Spectrometer; GRNS, Gamma-Ray and Neutron Spectrometer; MAG, Magnetometer; MASCS, Mercury Atmospheric and Surface Composition Spectrometer; MDIS, Mercury Dual Imaging System; MLA, Mercury Laser Altimeter; XRS, X-Ray Spectrometer.

Mercury, which has a surface temperature of 450°C. This extreme temperature required that the spacecraft and the science payload be protected from the direct rays of the Sun. A fixed sunshade was attached to the Sun-pointing side of the spacecraft in order to keep its interior temperature near 25°C. Another key driver in the design of the MESSENGER spacecraft was the large amount of propellant required to perform its mission. The size and weight of the propulsion system dominated the available packaging volume and its overall launch weight. To achieve minimum weight and maximum strength, the spacecraft structure was designed using graphite epoxy composite materials.

The two Solar TErrestrial RElations Observatory (STEREO) spacecraft (Fig. 2) were designed for a 2-year mission. These two nearly identical spacecraft are used to provide the first ever 3-D "stereo" images of the Sun to study the nature of its coronal mass ejections. These powerful solar eruptions are a major source of the magnetic disruptions on Earth and a key component of space weather, which can greatly affect spacecraft operations, communications, and global climate. (For additional information, refer to Ref. 2.) Each spacecraft houses four primary instrument suites for a total of 16 scientific instruments. The science goals of these instruments placed severe electromagnetic compatibility (EMC) constraints on the spacecraft and its electronic enclosures. The two spacecraft were stacked one on top of the other for launch. This plus the need to have these spacecraft spun during launch required special consideration.

The New Horizons spacecraft (Fig. 3) was designed to obtain a firsthand look at Pluto–Charon, a binary planet, and then multiple Kuiper Belt objects. This spacecraft seeks to learn more about the surfaces, atmospheres, interiors, and space environments of Pluto, Charon, and Kuiper Belt objects. (For additional information, refer to Ref. 3.) The average temperature on Pluto is –220°C. For its 3-billion-mile journey to the outer solar system, this spacecraft required the use of a radioisotope thermoelectric generator (RTG) to generate the necessary electric power. The nature of this power source became a

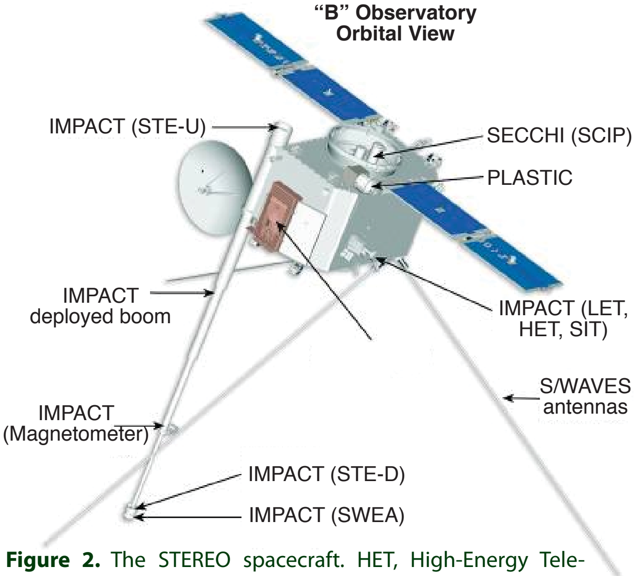

Figure 2. The STEREO spacecraft. HET, High-Energy Telescope; HI, Heliospheric Imager; IMPACT, In situ Measurements of PArticle and Coronal mass ejection Transients; LET, Low-Energy Telescope; PLASTIC, PLAsma and SupraThermal Ion Composition; S/WAVES, STEREO/WAVES; SCIP, Sun-Centered Imaging Package; SECCHI, Sun–Earth Connection Coronal and Heliospheric Investigation; SIT, Suprathermal Ion Telescope; STE-D, SupraThermal Electron-Downstream; STE-U, SupraThermal Electron-Upstream; SWEA, Solar Wind Electron Analyzer.

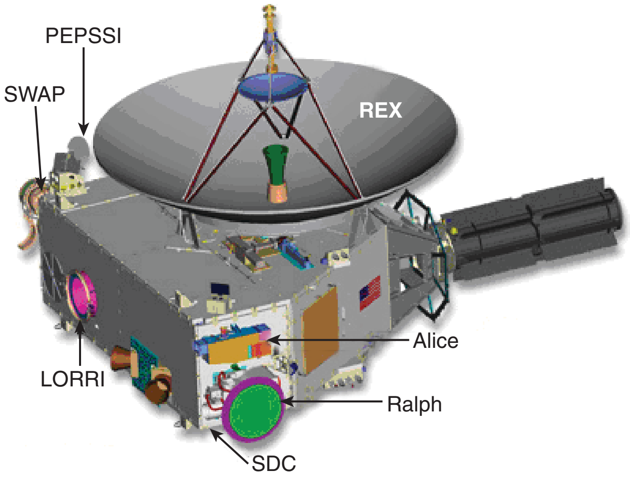

Figure 3. The New Horizons spacecraft. Alice, ultraviolet mapping spectrometer; LORRI, Long Range Reconnaissance Imager; PEPSSI, Pluto Energetic Particle Spectrometer Science Investigation; Ralph, multispectral visible imaging camera and infrared spectrometer; REX, Radio Science Experiment; SDC, Student Dust Counter; SWAP, Solar Wind Around Pluto.

dominant design driver in managing both its thermal and radiation environments. The RTG not only dictated the location of the scientific instruments but also was required to be electrically and thermally isolated from the rest of the spacecraft. The New Horizons spacecraft was designed to operate spinning or in a three-axis-stabilized mode, and it houses six scientific instruments.

A comparison of these three interplanetary spacecraft in terms of their power, volume, and mass is illustrated in Table 1.

SPACECRAFT PACKAGING

The packaging drivers for the MESSENGER spacecraft were the harsh thermal environment and a propulsion system that represented more than 60% of its launch mass. The thermal environment dictated that the spacecraft had to operate behind a large sunshade. This limited the location of instruments, as did trying to maintain adequate fields of view (FOVs). The large amount of propellant reduced the available packaging volume as well as the available mass for the instrument payload and the required subsystems. The configuration for the spacecraft structure was in the form of an egg-crate and fabricated by using a graphite epoxy composite to achieve minimum weight design. Both the structural configuration of the spacecraft and the choice of materials caused several design challenges. First, the transition from the composite rectangular egg-crate structure to the circular aluminum adaptor ring at the launch vehicle interface required a dramatic change in geometry along with a large difference in the thermal expansion coefficient between these two materials made for a difficult problem. The resolution was to segment the composite transition structure in order to minimize the impact these thermal expansion coefficients would have on the integrity of the spacecraft. Second, the majority of the spacecraft subsystems were fabricated using aluminum chassis, thus requiring the use of slip joints between these subsystems and the composite structure. The mass required for the propulsion subsystem drove all of the subsystems to meet their allocated mass at almost all costs. Finally, the spacecraft required the development of solar arrays capable of having operational temperatures greater than twice the existing state-of-the-art designs.

The major packaging drivers for the New Horizons spacecraft were the RTG and the spacecraft's pointing requirements. New Horizons operates both as a spinning and as a three-axis-stabilized spacecraft. The structural configuration for the spacecraft structure employed a central aluminum cylinder to which conventional aluminum honeycomb panels and decks were attached. The key design challenge was to accommodate the cantilevered RTG, which is ≈5 feet long and represents ≈18% of the launch mass of the spacecraft. The greatest structural loads occurred at third-stage burnout when the interface temperature at the base of the RTG was in excess of 230°C, a temperature at which the aero shell of the RTG exhibits approximately one-half of its structural strength. This interface was complicated in that it had to be structurally sound but at the same time provide the necessary thermal and electrical isolation from the

Table 1. Characteristics of three interplanetary spacecraft.

Characteristic	MESSENGER	STEREO (A)	STEREO (B)	New Horizons
Typical power (W)	550	490	490	245
Spacecraft volume (ft^3)	85	100	100	65
Total spacecraft mass at launch (kg)	1101.1	620	654.5	478.3
Total mass (%)				
Science instruments	4.28	22.90	22.70	6.84
Spacecraft structure	10.35	23.21	25.97	26.0
Propulsion system	7.42	5.41	5.12	5.85
Fuel/pressurant	54.64	9.82	9.32	16.10
Power	8.53	12.63	12	18.04
Telecommunications	2.88	5.50	5.20	8.10
Command and data handling (IEM)	1.06	1.15	1.12	4.85
Attitude control	3.37	5.76	5.47	4.10
Thermal	5.10	3.45	3.50	5.81
Harness	2.37	10.17	9.60	4.31

spacecraft. A titanium pyramid structure was attached to one side of the spacecraft to provide the thermal isolation and support for the RTG such that it could withstand the severe launch environments of the Atlas-V and the third-stage burnout loads. Its 3-billion-mile journey to the outer edge of the solar system required precise RF boresite alignment with the spacecraft's spin axis.

The presence of the RTG-influenced package design meant that the science instruments had to be located as far away from the RTG as possible, and thermal view factors, radiation effects, etc., also had to be considered. Finally, the RTG had to be horizontally integrated into the launch vehicle by using the same hardware integration scheme and heritage employed on the previous Cassini mission.

The packaging drivers for the STEREO spacecraft were the stacking of two nearly identical spacecraft on one launch vehicle, as well as the location of the science instruments and their FOVs. When stacked together on the launch vehicle, the stack height was ≈2.7 m high. The primary structural configuration for these spacecraft was a central cylinder to which the aluminum honeycomb panels and decks were attached. The bottom spacecraft's cylinder was heavier in order to transfer the launch loads from the top spacecraft down through the launch vehicle adaptor. Similarly, the structural panels on the top spacecraft were heavier to provide for the lifting of the stacked spacecraft. Each spacecraft carries a total of 16 scientific instruments. Satisfying this large number of instruments, their FOVs, and center of mass requirements for each spacecraft made locating them on the spacecraft difficult. This spacecraft stack was required to be spin-stabilized, which significantly affected the spacecraft layout and mechanical design.

Power-System Packaging

The power-system needs for MESSENGER, New Horizons, and STEREO were driven by requirements that were dictated by three drastically different deep-space missions. The power-system architecture for these spacecraft was chosen based on the worst-case solar distance expected during the mission. Typically, spacecraft operating between slightly inside of Mercury perihelion and slightly outside of Mars aphelion are powered by solar arrays coupled with a battery. Spacecraft missions that are to operate inside of Mercury perihelion or outside of Mars aphelion will most likely be powered by an RTG that requires no battery. Because MESSENGER and STEREO operate between Mercury and the Earth, both spacecraft use (although completely dissimilar in design and construction) solar arrays combined with batteries to generate and store power. Conversely, New Horizons uses an RTG.

Typically, the placement of spacecraft batteries is driven by thermal and spacecraft center-of-gravity considerations. The batteries' relatively tight temperature requirements coupled with the high heat dissipation generated during discharge dictates that the batteries be placed such that their thermal impact on the rest of the spacecraft is minimized. Heaters are then used to control the temperature within the desired limits. The battery on MESSENGER was placed directly behind the sunshade and on the same deck as the main engine. The STEREO battery placement was driven by requirements that were different from those for MESSENGER. Conceptually, the STEREO battery could have been located on any one of the other five sides, but placement was driven by (*i*) minimizing electrical harness between the power-system electronics (PSE) and the power distribution unit (PDU), (*ii*) mechanical balance, and (*iii*) instrument FOV. The RTG on the New Horizons spacecraft produces a steady power output; as a result, no battery was required, and the current was controlled by a large bank of capacitors.

Solar-array placement is typically driven by the mission-defined spacecraft attitude with respect to the Sun. The STEREO spacecraft maintains a fixed Sun-pointing attitude, which also allows for the solar arrays to maintain a fixed Sun-pointing attitude once they are deployed after launch. Placement of the solar arrays was primarily driven by instrument viewing requirements and the need to keep the solar arrays normal to the Sun. The STEREO array system consists of two wings composed of two fully packed panels per wing. Each wing was folded for launch, and deployment was done using a double-hinge system. Once deployed, the arrays are locked in place. Any off-normal solar-array pointing will require spacecraft attitude changes. In contrast, MESSENGER used two solar-array wings that consist of one panel per wing. Each panel was populated, or packed, with 33% solar cells and 67% optical solar reflectors. Figure 4 illustrates the difference between the STEREO and MESSENGER

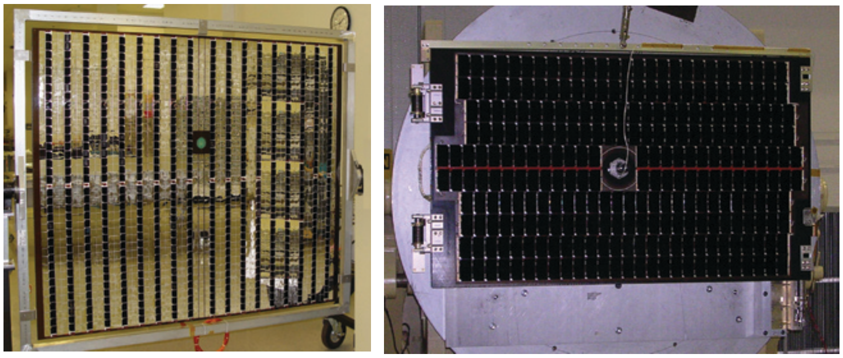

Figure 4. The MESSENGER (left) and STEREO (right) solar arrays before spacecraft integration.

solar-array designs. The MESSENGER solar arrays are capable of full independent rotation, giving the spacecraft the ability to rotate the panels as a function of solar distance to maintain cell temperature at desired levels while producing adequate amounts of power. Each wing was stowed for launch by using a double-hinge boom. The final size of the MESSENGER solar arrays was dictated by the launch vehicle fairing. For the purpose of comparison, the New Horizons RTG exhibited the lowest specific power, ≈2.8 W per pound, as compared with STEREO's 6.6 W per pound.

Propulsion System

The propulsion-system design and packaging for MESSENGER, New Horizons, and STEREO were driven by requirements that were dictated by total change in velocity (ΔV) needed for the drastically different mission trajectories. The propulsion-system architecture for each of these spacecraft was chosen based on the worst-case total change in velocity expected during the respected mission.

The MESSENGER propulsion system (MPS) was driven by the mission requirement to deliver a total change in velocity of 2300 m/s with a total wet mass of 600 kg, and the size and complexity of the MPS were primary drivers during spacecraft package layout. The MPS is a pressurized bipropellant dual-mode system using hydrazine (N_2H_4) and nitrogen tetroxide (N_2O_4) in the bipropellant mode and N_2H_4 in the monopropellant mode. Three main propellant tanks (two fuel and one oxidizer), a refillable auxiliary fuel tank, and a helium pressurant tank provide propellant and pressurant storage. The helium tank contained 2.295 kg of helium at a launch pressure of 3375 psia.

The MPS also includes 16 monopropellant thrusters for spacecraft maneuvers and a large bipropellant large-velocity adjustment thruster

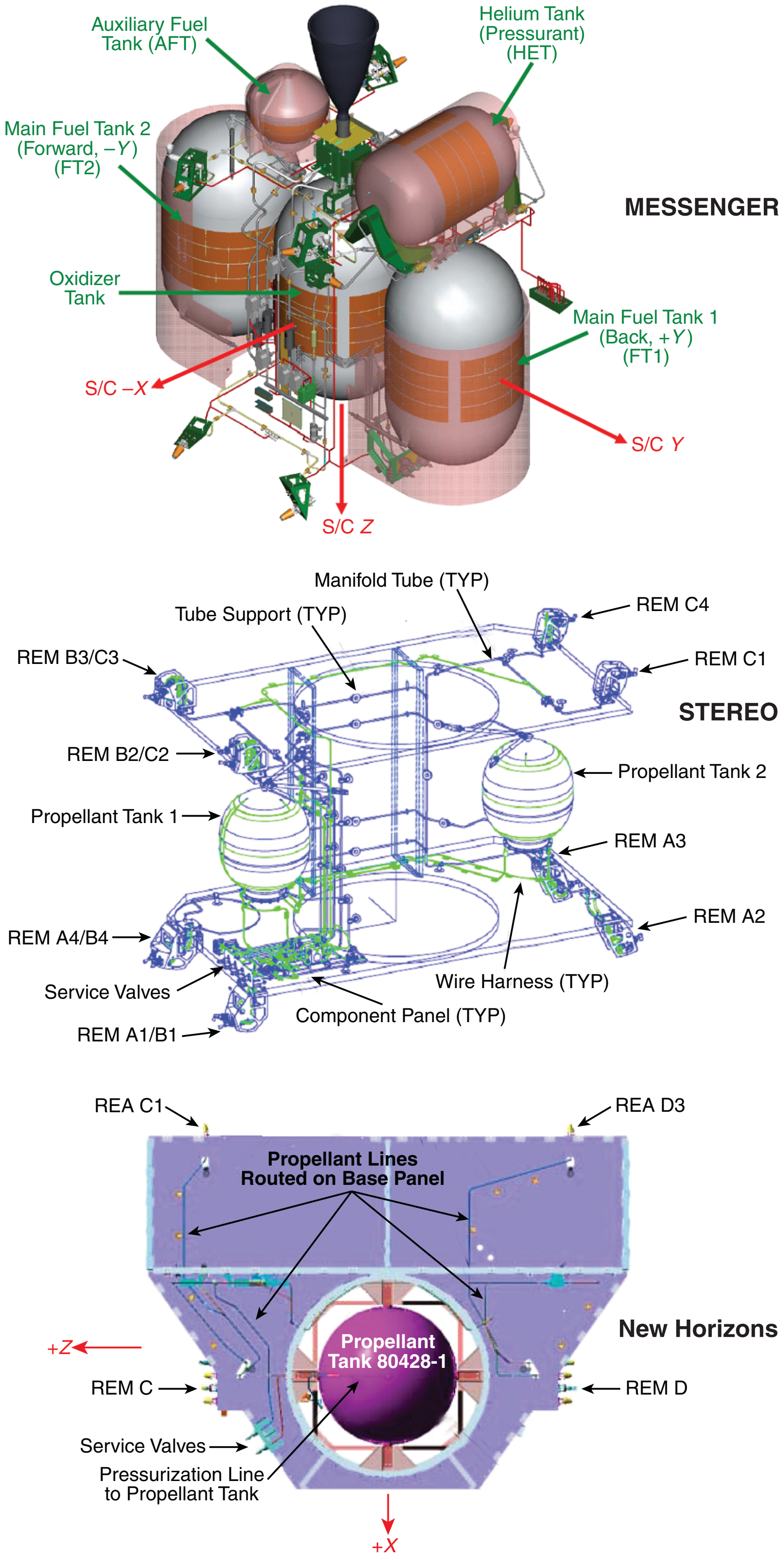

Figure 5. The MESSENGER, STEREO, and New Horizons propulsion systems. REA, Rocket Engine Assemblies; REM, Rocket Engine Modules; S/C, spacecraft.

for trajectory adjustment burns. The large-velocity adjustment thruster requires relatively constant fuel and oxidizer feed pressures, which means that the thermal control of the propellant tanks is very important. Packaging of the propellant tanks and selection of the heater sizes, locations, and circuits were designed to ensure proper inlet conditions throughout the long flight to Mercury.

Both STEREO and New Horizons used conventional blow-down hydrazine propulsion systems, which are simple in design and operation when compared to MESSENGER (see Fig. 5). New Horizons and STEREO are designed to deliver 374 and 175 m/s velocity change, respectively, by using single-tank and dual-tank blow-down pressure delivery systems. A total of 16 monopropellant thrusters for New Horizons and 12 monopropellant thrusters for STEREO will deliver the mission ΔV from the respective systems. The packaging requirements imposed on the spacecraft for these propulsion systems proved to be less of a design driver. As for any propulsive system integrated on a spacecraft, clear FOVs for the thrusters and structural mounting integrity for the propellant tank usually drive the design.

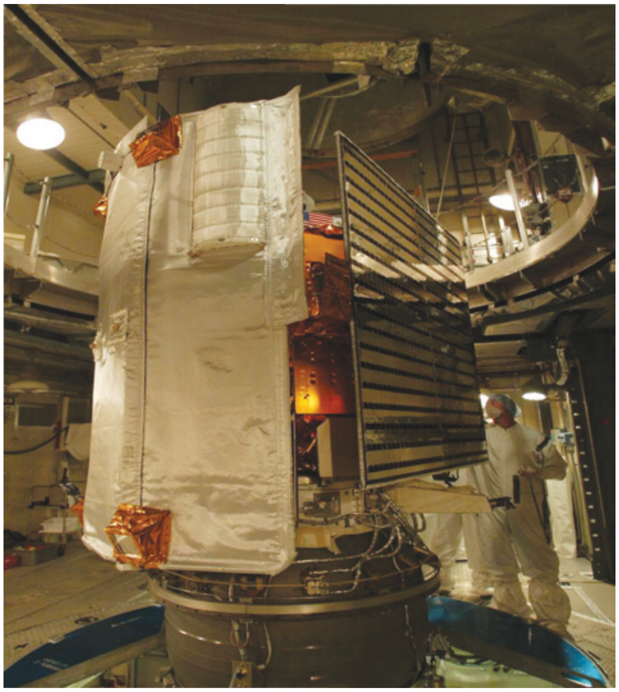

Figure 6. The MESSENGER spacecraft before launch.

Thermal Control

The thermal control system design and packaging for MESSENGER, New Horizons, and STEREO were driven by requirements that were dictated by the mission-specific thermal environments, component temperature limits, and waste heat dissipations. Each of these spacecraft has used different thermal control technologies to maintain temperature while reducing heater power usage.

Defined by the protective sunshade, the MESSENGER spacecraft is the first three-axis spacecraft designed to operate at solar conditions in excess of 10 Suns and while in orbit at Mercury. The sunshade not only protects the spacecraft from the solar environment but also provides a platform on which to mount the phased-array antennas, fan-beam antennas, low-gain antennas (LGAs), digital Sun sensors, and solar monitors (see Fig. 6). Each of these devices was thermally tested in the flight configuration before launch. The size of the sunshade, constrained by both mass and the Delta-II fairing envelope, defined the size and shape of the spacecraft. The higher-powered spacecraft electronics (e.g., the PSE) were connected by diode heat pipes to space-facing radiator panels. Four such radiator panels (two per spacecraft side) are located common to the solar arrays. Because the core of the MESSENGER structure contained the three main propellant tanks, the spacecraft's lower-powered electronics (e.g., the magnetometer electronics) were mounted to the perimeter of the spacecraft around the main tanks, allowing the waste heat to be used to help minimize main tank heater power (because when MESSENGER is flying with the sunshade toward the Sun, the propulsion system uses ≈200 W of heater power). When MESSENGER was between 0.95 and 1.10 astronomical units (AU), it flew with the sunshade opposite the Sun, allowing for solar illumination of the spacecraft. This flight configuration reduced the total heater power usage by almost 250 W. Because the view direction for all spacecraft radiators is always orthogonal to the Sun, regardless of sunshade orientation, the spacecraft thermal design had to accommodate this flight condition. Once inside of 0.95 AU, there was enough solar-array power margin to fly the spacecraft with the sunshade toward the Sun and absorb the 250-W increase in heater power that was needed to protect the propulsion system, instruments, and spacecraft components from getting too cold.

The New Horizons spacecraft thermal design utilizes a "thermos-bottle" approach that minimizes heat leaks and uses the electronics waste heat to maintain the average structure temperature near room temperature. The electronics and propulsion components are conductively mounted to the internal spacecraft structural panels and are designed to free radiate throughout the spacecraft core, minimizing temperature gradients and efficiently utilizing all heat dissipations. Most of the electronic packages were placed diametrically opposite the RTG to help efficiently balance the spacecraft around the spin-axis. Louvers located on the spacecraft deck were used during the early part of the mission when the spacecraft was near Earth and was sensitive to the heat input from the Sun. Excess heat absorbed by the spacecraft was rejected by the fully opened louvers. As the distance between the spacecraft and Sun grows, the louvers will close and the spacecraft temperature will become totally dependent on internally dissipated heat.

The STEREO thermal design uses the spacecraft flight geometry to provide cold-facing directions for the majority of the electronic packages. Maintaining a single Sun-pointing face allows flexibility for package and instrument placement. Fixed radiators used in combination with thermostatically controlled heaters provided temperature control during the operational and nonoperational phases of the mission. This flexibility in the thermal design allowed for optimal placement of the instruments, spacecraft subsystems, and sensors without compromising temperature control. The battery, for instance, was placed close to other power subsystem electronics to minimize harnessing and other complexities; this decision was made because, except for the Sun-facing side, the external thermal environments elsewhere around the spacecraft are equitant and did not provide the battery with a better thermal environment.

Electronic Packaging

The design of any spacecraft electronic subsystem involves tradeoffs among the electrical, mechanical, and environmental requirements of the mission. The function of electronic packaging in a spacecraft mission is to ensure the functionality and integrity of electronics in space environments, which often are characterized by severe vibration during launch, substantial temperature fluctuation throughout the mission, and radiation degradation when in orbit.

In the late 1990s, APL began to integrate some of the spacecraft's subsystems, including command and data handling, the solid-state recorder, and the flight computer with its guidance and control functions, into an integrated electronics module (IEM). The objective was to reduce the overall mass of the system, simplify the interconnections, and improve the overall reliability of the system.

The IEMs on MESSENGER, STEREO, and New Horizons are functionally very similar. They require five commercially available compact peripheral component interconnect (cPCI) printed wiring boards (PWBs), with a standard 6U format (9.2 inches long × 6.2 inches wide). This system architecture was chosen to reduce development cost and allow the use of commercial off-the-shelf test equipment and software.

The MESSENGER IEM packaging design has several unique features, including the RAD6000 processor developed by BAE Systems, 64-Mb Hyundai thin small-outline packages (TSOPs) stacked two high for 1 GB of synchronous dynamic random access memory (SDRAM) on the solid-state recorder assembly, and a 32-mm ceramic column grid array as the PCI bridge chip.

The MESSENGER IEM chassis was fabricated by using investment casting to save weight. The spacecraft structure was fabricated with a graphite epoxy composite material that is relatively nonconductive through its thickness, which hindered the conductive heat transfer from the IEM chassis to the external environment. A spreader plate with thermal vias was used to conduct heat to a heat pipe located under the composite deck. Slip joints were designed to accommodate the differences in the coefficient of thermal expansion between the composite-deck structure and the aluminum chassis. This design was required to minimize the thermal strain that would otherwise develop in these joints. The STEREO and New Horizons IEMs were mounted on a conventional spacecraft structure (i.e., a honeycomb panel with aluminum face sheets that provided for the typical conductive heat transfer through the base of these units). Neither of these IEMs had severe weight limitations. However, the electromagnetic interference (EMI)/EMC requirement imposed on the STEREO mission dictated the slight design change of the chassis to accommodate the front and back covers, as shown in Fig. 7.

The PDU contains the circuitry for the spacecraft's pyrotechnic firing control; power distribution switching; load current and voltage monitoring; fuses; external relay switching, reaction wheel relays, and power-switching relays; solar-array drives; propulsion thruster firing; propulsion latch valve control; and selected IEM relays. The PDUs on MESSENGER, STEREO, and New Horizons are functionally very similar.

The significant challenge in the packaging design of the MESSENGER PDU was how to implement state-of-the-art technologies to minimize system mass while still meeting the stringent reliability required by the MESSENGER power system. The MESSENGER PDU chassis was fabricated with magnesium to save weight. The packaging design featured a PWB design with very small feature sizes, a compact interconnection scheme, and a modular packaging design, as illustrated in Fig. 8.

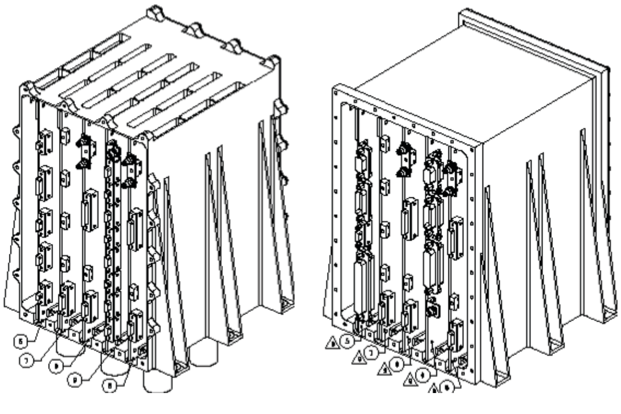

Figure 7. IEMs of MESSENGER (left) and STEREO (right). The front covers are removed for clarity.

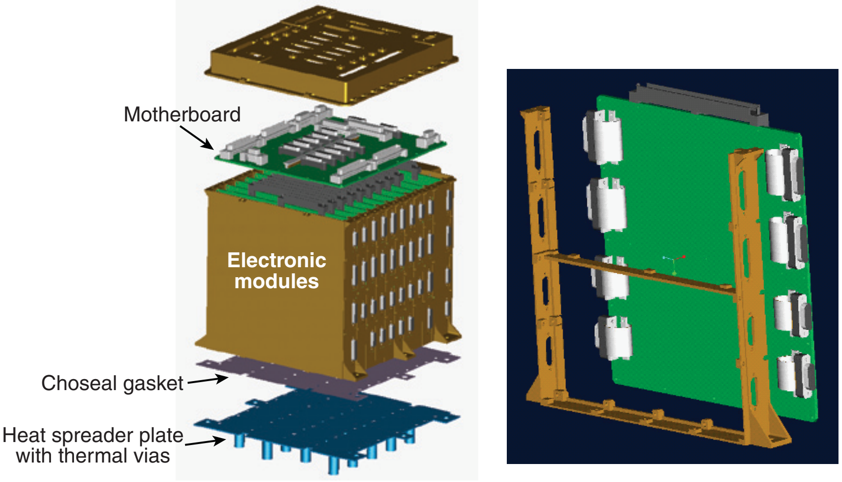

Figure 8. MESSENGER PDU. (Left) PDU modular design. (Right) A slice within the PDU.

The PWBs in the PDU slice design consist of 10–16 layers of interconnections with 127 × 127-µm line width and spacing for the signal lines. For the switching circuits, 2-oz. copper planes and wider traces were used to accommodate the high current requirement. To minimize the magnetic field generated by the supplied current and return lines, a cross-strapping feature was included in the board layout to cancel out such effects. The PWB design of the PDU also includes rigid-flex technology as well as blind and buried vias technology.

The MESSENGER PDU package used a modular design where each circuit board was bolted to the chassis frame along three sides. These attachment points provide the primary structural supports and thermal paths for the electronic assemblies. Each electronic module (slice) plugs into the motherboard assembly located on top of the unit. The motherboard provides interconnections between the modules, as well as interfaces for the spacecraft umbilical, pyros, battery, and all fuse modules. The STEREO and New Horizons PDUs were not under the same volume and mass constraints as MESSENGER; as such, their chassis were fabricated with aluminum. To improve manufacturability, the size of the New Horizons PDU was increased to allow for the use of the more conventional PWB fabrication techniques.

Spacecraft Harness System Cabling

APL uses two methods to segment the primary harness subsystems. The first can best be described as an octopus design of multiple connector branches extending from the main bundle. The wire conductors are separated into bundles of same characteristic signals (e.g., power) and routed to all interfacing units. The second method, called the segmentation method, is used for fabricating less complex cable assemblies. The designer limits the number of connectors per cable by selecting same characteristic signals to interface between fewer electronic units.

It has been a practice of APL to use a flight-like spacecraft wiring mock-up with all finished dimensions of the actual spacecraft (Fig. 9). The harness is built-up on the 1:1 scale mock-up so that the bends and lengths are an exact fit to the flight structure. The use of the mock-up gives the assembly technician insight into typical harness details (e.g., spacing between structures, service loops, harness rotation about hinges, and placement for supporting harness attachments, to name a few).

The octopus harness construction method was selected for both the STEREO and New Horizon spacecraft. The disadvantage with this method was that only two technicians could work in the mock-up area at a time, and harness completion depends on the finalized contact assignments of each interfacing electronic unit. MESSENGER used the segmentation method, which allowed the technicians to assemble the cable on the bench after gathering the required physical information from the mock-up. This method allowed for multiple cables to be fabricated and tested away from the spacecraft. However, there were disadvantages with this method as well. First, some of the cables not built-up on the mock-up had measurements errors. Second, the documenting and kitting of individual cable assemblies was more time-consuming than anticipated.

It is vital that all subsystems be protected from signal corruption, including signal cross-coupling, electromagnetic fields, and radiation exposure. Ideally, orthogonal routing of noncompatible signals would resolve most signal-to-signal interference concerns, but in the spacecraft's compact areas, the wire routing is typically nonorthogonal, thus presenting ample opportunity for

Figure 9. STEREO harness on mock-up with an octopus construction.

unwanted coupling. EMI coupling-reduction techniques are used to achieve safe and trouble-free operation. These techniques include

- Bundling compactable signals together, segregating and bundle-shielding as needed
- Twisting power signals with their return
- Incorporating shielded wire for low-level analog signals
- Using a twisted shielded pair for ordnance
- Using coaxial for digital high frequency
- Employing proper grounding per spacecraft EMI requirements

The STEREO instruments had strict EMI requirements. The harness incorporated protective EMI shielding layers to isolate wire bundles. The baseline shielding required two layers of EMI shielding along with a third outer layer of insulating Kapton tape wrap for each bundle. The inner wrap was Lamiglas, providing 100% optical coverage. A middle layer of mesh braid, either tin-plated, copper-clad steel (Monel) wrap or electrically conductive composite tubular braid (Aracon), was added to shield against lower-frequency interference. The Aracon composite braid initially was chosen for STEREO for mass-saving reasons. It was later discovered that the tubular construction complicated the assembly process by limiting the maximum size diameter of bundles, resulting in the fabrication of additional harnesses (Fig. 10). The Monel allowed the harness to be electrically tested for connectivity and continuity before the braid wrap was applied. The final Kapton insulating layer of tape encapsulated the bundle and prevented undesired grounding to the metal structure (Fig. 11). The harness routed externally on STEREO had another layer of copper wrap added to protect against deep dielectric charging. The deep dielectric discharge effect is the result of high-energy electrons and ions penetrating the wire insulator and accumulating a substantial charge in the dielectric. When the local voltage exceeds the breakdown voltage of the dielectric or the gap voltage of a floating conductor, the charge will arc to the local ground, which could possibly damage any nearby circuits or propagate to other connected electronic units.

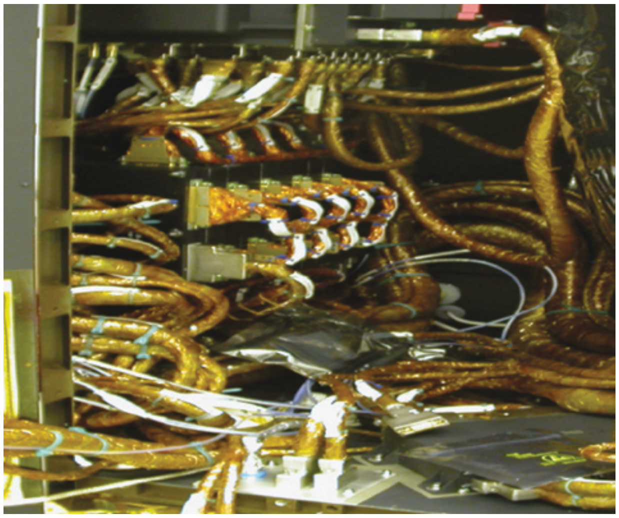
Figure 11. STEREO completed harness wraps.

Deployable mechanisms such as sensor booms or solar panels introduce additional complexity into harness packaging. The rigidity of the harness cannot restrict the movement of deployable mechanisms from reaching their full range of motion. These cables often are routed externally to the spacecraft and are exposed to thermal extremes, which can retard their flexibility. Thermal blankets are added to protect against the thermal effects of the environment.

The solar-array cabling for the MESSENGER spacecraft was not EMI-shielded and only had a layer of thermal blankets. This was a flexible construction and allowed for full deployment. In contrast, the STEREO

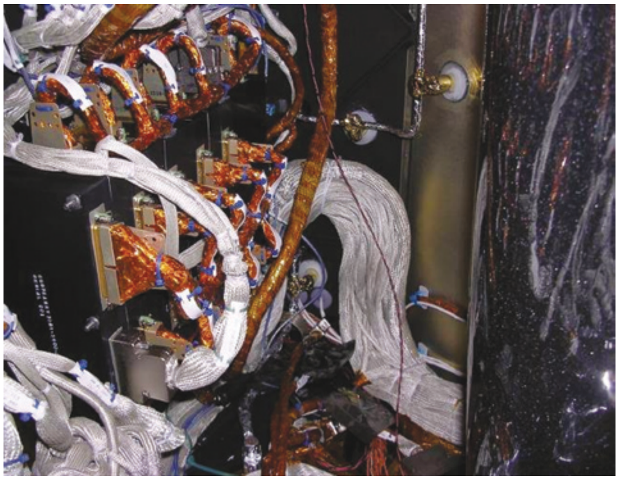
Figure 10. STEREO harness with Aracon.

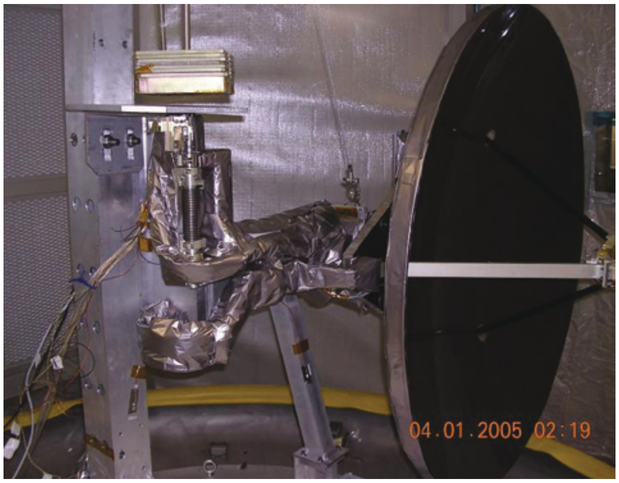

Figure 12. HGA subsystem with thermal blankets installed.

solar-array cabling had several layers of shielding, as discussed earlier, along with thermal blankets. STEREO had two deployable mechanisms: the solar arrays and the high-gain antenna (HGA). The HGA subsystem (Fig. 12) was the most complex because after it was deployed, the high-gain dish had to be capable of rotating 180° about its mast.

TELECOMMUNICATIONS

The telecommunications systems selected for these three missions were driven by their own unique set of requirements. The MESSENGER antenna system architecture was chosen based on the severe operational thermal environment. The New Horizons antenna system architecture was driven by a mission requirement to spin-stabilize the bus during lengthy hibernation periods, with no ground contact, to minimize mission operations costs. The STEREO antenna system required a deployable HGA to enable stacked spacecraft configuration and satisfy the variety of science instrument FOV requirements.

The MESSENGER spacecraft's high-data-rate downlink required the use of the first electronically scanned HGA for a deep-space telecommunication application. Because of this orientation and the geometry associated with an inner-planet mission, the Earth may be in any direction around the spacecraft in a plane aligned with the ecliptic. The orientation restriction precludes using a traditional fixed antenna and spacecraft maneuvering to achieve Earth-pointing, although rotation about the spacecraft–Sun line is permitted.

Although one-dimensional electronically scanned antennas (1-D ESA) and gimbaled-dish antennas both provide high gain with low mass, the 1-D ESA was chosen because it requires no moving parts and offers graceful degradation, more packaging flexibility, and high operating temperature. In addition, the extreme thermal environment precluded the use of active semiconductors directly behind the radiating elements. Because the uplink data rate is typically very low, the phased array is needed for high-data-rate downlink only, which allows the use of a narrowband antenna.

Two lightweight phased arrays, positioned on opposite sides of the spacecraft, are used for the high-gain downlink. Each phased-array antenna is electronically steered over a ±45° range. One-dimensional steering, in combination with spacecraft rotation, provides antenna coverage for all Sun–spacecraft–Earth angles. Figure 13 shows the coverage area for each array antenna relative to the spacecraft orientation. Each phased array consists of a set of eight slotted waveguide "sticks" driven by a separate amplifier channel. Electronic steering in one dimension over ±45° range is accomplished by controlling the relative phases of the eight amplifier channels. Cross-strapping between the two redundant solid-state power amplifiers (SSPAs) and the phased-array antennas provides block redundancy and, importantly, enables the RF power from both SSPAs to be applied simultaneously to either antenna. This feature gives the mission operators an option to increase the effective isotropic radiated power and downlink bit rate by a factor of four once in Mercury orbit, as described in Ref. 4.

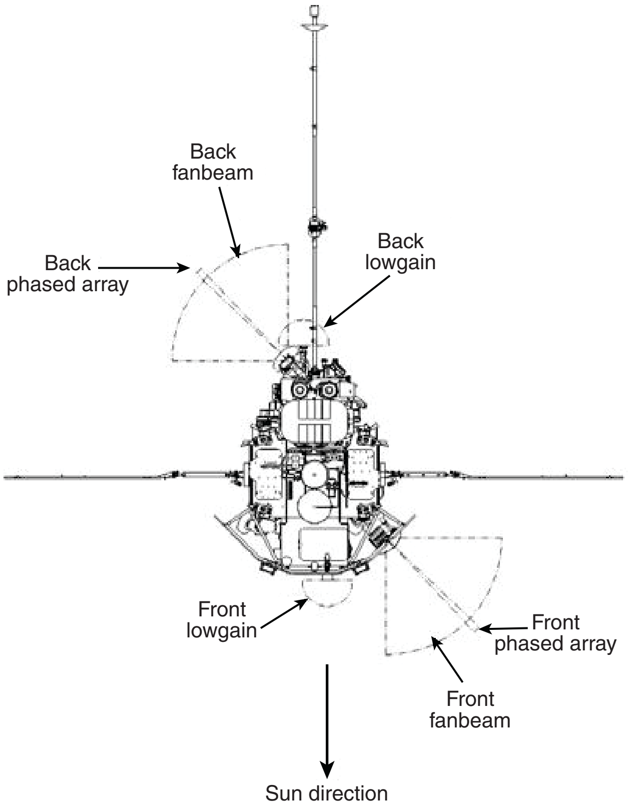

Figure 13. MESSENGER antenna pattern coverage (top view of spacecraft).

Waveguides with narrow-wall radiating slots are used so that the stick-to-stick spacing can be made small enough to suppress the grating lobes when the beam is scanned to 45°. Simple waveguide slots radiate linear polarization, while the Deep Space Network can only receive circular polarization. To eliminate the resulting 3-dB polarization mismatch loss, a novel way of producing circular polarization from a narrow-wall slotted waveguide array was developed. Parasitic monopole elements are attached to the exterior walls of the waveguides. They couple to the normal component of the electric field from the slots and can produce radiated fields orthogonal to those from the slots. By carefully adjusting the geometry of the parasitic monopoles and the gaps between the waveguide sticks, the two linear components can have equal amplitudes and be in phase and quadrature. The result is circular polarization. A sketch of the parasitic element design is given in Fig. 14. A more detailed description of the circular polarization technique is given in Ref. 5.

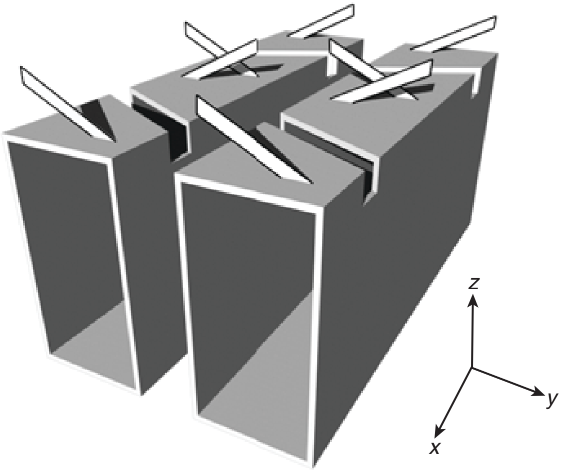

Figure 14. Parasitic elements for circular polarization.

Each waveguide of the MESSENGER phased-array antenna has 26 slots. The array 3-dB beam widths are ≈2° in the narrow plane and 12° in the broad plane. Each array assembly also includes a medium-gain (fan-beam) antenna (MGA). These MGAs, along with separate LGAs, provide for uplink and low-gain downlink during cruise phase and emergency. Radomes made from space-blanket material cover each assembly and help protect it from the intense solar radiation. However, the array temperature is still expected to reach a maximum of ≈300°C. A phased-array antenna assembly, minus the radome, is shown in Fig. 15. The RF telecommunication system, including the other antennas, has been described previously.[6,7]

The New Horizon spacecraft will encounter lengthy hibernation periods, with no ground contact, to minimize mission operations costs. The relevance to the antenna system is that the spacecraft will be spin-stabilized at all times except during encounters to maintain a fixed spacecraft attitude. All of the antenna patterns are symmetrical about the spacecraft spin axis to allow routine (telemetry and science) and emergency operations while spinning.

This spacecraft design resulted in a stacked packaging arrangement of the antennas (HGA, MGA, and LGA) on the forward side of the New Horizons spacecraft, as shown in Fig. 16. This configuration is best because it satisfies the communication system requirements and stringent mass limitations imposed by the mission. A 60% efficient, X-band, 2.1-m-diameter parabolic reflector antenna (the HGA) is required to support the minimum 600-bps, 35-AU (from Earth) post-encounter return link.[3,8] The detailed design of this antenna is described in Ref. 5. This diameter reflector was selected after the New Horizons antenna team performed a detailed alignment analysis, which included effects attributable to thermal distortions on the spacecraft structure and the antenna system, dimensional tolerances, measurement knowledge of the antenna boresight, ground-station pointing errors, power margins, and antenna gain/beam width. This analysis showed that 0.2° alignment between the HGA RF boresight and spacecraft spin-axis was feasible to meet minimum off-axis gain requirements for the minimum science downlink rate. It is possible to use a larger-sized (i.e., more directive) reflector antenna on spin-stabilized spacecraft with enhanced definition, knowledge, and control of variables in the alignment budget; the downside is increased mass and cost.

The RF telecommunication system for each of the two STEREO observatories uses two LGAs (one located at each end of the spacecraft) along with an HGA. The hardware elements that comprise each of these systems are the antennas, a small deep-space transponder, a traveling-wave tube amplifier, the antenna selection switches, and the supporting waveguide hardware. From

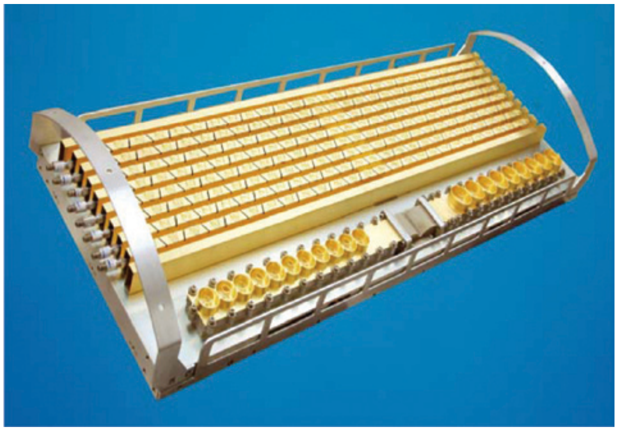

Figure 15. The flight antenna for MESSENGER.

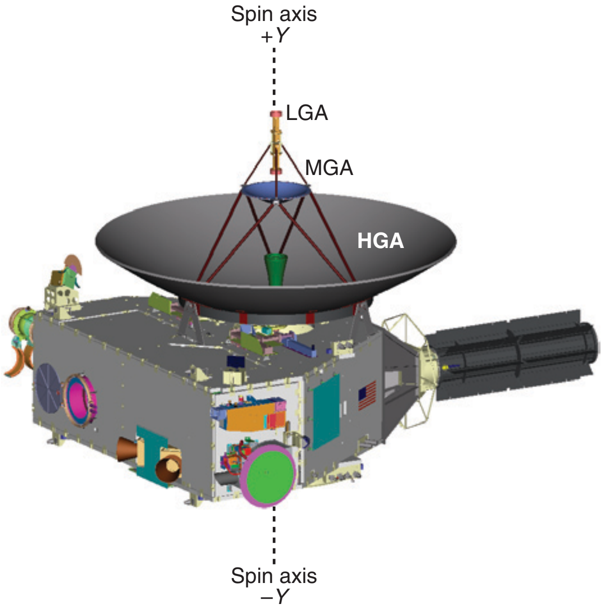

Figure 16. Forward side of the New Horizons observatory.

an RF system point of view, spacecraft A and spacecraft B are identical except for different communication frequencies. The 1.2-m parabolic reflector antenna is gimbaled and uses a rotary joint slaved to a rotary actuator, which provides the X-band signal path to the HGA feed assembly. This RF system has three modes of operation. The primary operational mode is with both spacecraft in heliocentric orbit and acquiring the mission science with a downlink data rate of 360 kbps. The second mode is the standby mode, which is used when a spacecraft problem is suspected by the onboard autonomy system. In this mode, the spacecraft's antennas are configured to maximize coverage and lower the data rate to maximize the probability of communications. The third mode, the Earth-acquisition mode, is equivalent to an emergency mode and results from the detection of a critical fault in the spacecraft. In this mode, the spacecraft powers off all instruments and other hardware as required. The operational mode of the RF system requires that the spacecraft meet the relative pointing and stability requirements for the high-data-rate communications using the HGA.

CONCLUSIONS

It has been shown that the configuration of an interplanetary spacecraft is as diverse as the mission itself. The physical appearance and the structural configurations of these three spacecraft are very different, as seen in Figs. 1–3. The MESSENGER and STEREO spacecraft power systems used solar panels combined with batteries to generate and store the required power, whereas the New Horizons spacecraft used an RTG to supply its power.

The propulsion systems used for these three spacecraft are illustrated in Fig. 5. STEREO and New Horizons used conventional blow-down hydrazine propulsion systems, and MESSENGER had a requirement for a change in velocity that was more than five times greater than either of the other two spacecraft, thus requiring a much more complex propulsion system.

The thermal control techniques used to protect these three spacecraft also were very different. The MESSENGER spacecraft, which is exposed to solar conditions in excess of 10 Suns, required a protective sunshade in order to keep the spacecraft cool. At the other extreme, the thermal protection system of the New Horizons spacecraft was designed more as a thermos bottle to retain heat on its 3-billion-mile journey away from the Sun.

The telecommunication subsystem for these three spacecraft was once again driven by mission requirements. The MESSENGER antenna system, with its high-data-rate requirements and its severe thermal environment, resulted in the use of the first electronically scanned HGA for a deep-space telecommunication application. Both STEREO and Hew Horizons used conventional parabolic HGAs; the STEREO antennas were gimbaled, and the New Horizons antenna was fixed to the spinning spacecraft.

Two areas in which these three spacecraft are functionally very similar are in electronic packaging (as demonstrated by the PDU and the IEMs) and in cabling and harnessing. To save weight, the chassis used in the electronic packaging of the MESSENGER spacecraft were investment castings and magnesium, as opposed to STEREO and New Horizons, which used conventional aluminum chasses. Both STEREO and New Horizons spacecraft used the same approach for the cabling and harnessing. However, the strict EMI requirements for the STEREO spacecraft made the harnessing more difficult. This article effectively demonstrates that the principle of "form follows function" applies not only to each of these spacecraft as a whole but also to each of their individual subsystems.

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