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THE MESSENGER SPACECRAFT AND PAYLOAD

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ABSTRACT

The MErcury, Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission will send the first spacecraft to orbit the planet Mercury. A Mercury orbiter mission is challenging from thermal and mass perspectives. MESSENGER overcomes these challenges while avoiding esoteric technologies by using an innovative approach with commonly available materials, minimal moving parts, and maximum heritage. The key concepts are a ceramic-cloth sunshade, an integrated lightweight structure, a high performance propulsion system, and a solar array incorporating optical solar reflectors. A miniaturized set of seven instruments, along with the spacecraft telecommunications system, satisfy all scientific objectives of the mission. The payload includes a combined wide-angle and narrow-angle imaging system; gamma-ray, neutron, and X-ray spectrometers for remote geochemical sensing; a vector magnetometer; a laser altimeter; a combined ultraviolet-visible and visible-infrared spectrometer to detect atmospheric species and map mineralogical absorption features; and an energetic particle and plasma spectrometer to characterize ionized species in the magnetosphere. MESSENGER construction is nearly complete, and the integration and test phase is just beginning. The launch date is March 10, 2004.

INTRODUCTION

MESSENGER will be the first spacecraft to visit Mercury in more than 30 years and the first to orbit the planet. It will launch in March 2004 and enter Mercury orbit in 2009 following two flybys of Venus and two flybys of Mercury. It will perform orbital operations at Mercury for one Earth year. The spacecraft is currently in the final stages of development and will start its integration and test phase at the beginning of 2003. Previous descriptions of MESSENGER by Solomon et al.[1], Santo et al.[2], and Gold et al.[3] have described the MESSENGER project following the completion of the preliminary design phase. The nearly final design of the trajectory and the spacecraft are given by Santo et al.[4].

The MESSENGER payload has been selected to meet the measurement requirements that flow down from the six scientific questions to be addressed by the mission:

1. What planetary processes led to the high metal/silicate ration in Mercury?
2. What is the geological history of Mercury?
3. What are the nature and origin of Mercury's magnetic field?
4. What are the structure and state of Mercury's core?
5. What are the radar reflective materials at Mercury's poles?
6. What are the important volatile species and their sources and sinks near Mercury?

These science questions lead to a set of measurement objectives that are fulfilled by seven instruments in the payload. Along with the spacecraft telecommunications system, these instruments provide multiple means of approaching each of the scientific objectives. The payload includes the Mercury Dual Imaging System (MDIS), a Gamma-Ray and Neutron Spectrometer (GRNS), a Magnetometer (MAG), the Mercury Laser Altimeter (MLA), the Mercury

Atmospheric and Surface Composition Spectrometer (MASCS), an X-ray Spectrometer (XRS), an Energetic Particle and Plasma Spectrometer (EPPS), and Radio Science (RS). With the exception of GRNS and MDIS, of all of the instruments remain essentially unchanged from their preliminary designs as presented in Gold et al.[3].

Several of these instruments have multiple detector heads. MDIS has both a wide-angle (WA) and a narrow-angle (NA) imager. MASCS includes an Ultraviolet-Visible Spectrometer (UVVS) and a Visible-Infrared Spectrograph (VIRS). EPPS has an Energetic Particle Spectrometer (EPS) and a Fast Imaging Plasma Spectrometer (FIPS). GRNS has separate gamma-ray and neutron spectrometers, and XRS has a sensor for monitoring the solar X-ray input as well as sensors for the X-ray fluorescence of Mercury. Basic characteristics of each element of the payload, including its mass, power, and data rate, are listed in Table 1.

The MESSENGER mission to Mercury is extremely challenging, with a very severe thermal environment, a very large propulsion capability that brings the fuel fraction at launch to > 55%, the miniaturization needed to meet these demands, and numerous other technical challenges. However, it must all be accomplished within the budget limitations of the NASA Discovery Program.

Near Mercury perihelion at 0.3 astronomical units (AU), the front of the spacecraft is exposed to the equivalent of 11 Suns and reaches temperatures > 350° C. The rest of the spacecraft must balance being exposed to cold space most of the time but occasionally being in front of the subsolar point of Mercury, where the surface temperature of the planet is > 350° C planet is fully illuminates the rear of the spacecraft.

The spacecraft thermal design provides a benign environment for body-mounted boxes. Therefore, the design of electronics follows standard space practices. However, sensor heads that must keep detectors cold, while looking directly at the hot planet, have been very difficult to design.

MESSENGER PAYLOAD

The seven instruments in the MESSENGER payload are mostly body mounted and fixed to enhance reliability and reduce cost. The exceptions are the MDIS pivot mount and the MAG boom. The four instruments with narrow fields of view (MDIS, MLA, MASCS, and XRS) are mounted inside the adapter ring between the spacecraft and the launch vehicle, and they are co-aligned. Pointing for data collection is accomplished by moving the entire spacecraft. The pointing range is limited to < 15° in all directions because the spacecraft sunshade must always keep the spacecraft body in shadow for thermal protection.

The payload communicates with the rest of the spacecraft via a redundant pair of data-processing units (DPUs). Six of the seven instruments also have their own versions of the same processing unit for internal event processing. In addition, the DPU and six of the seven instruments use copies of a common low-voltage power supply unit. While the DPU and its power system are fully redundant, the individual instruments are single string. Their reliability is enhanced, where possible, through limited internal redundancy, internal functional redundancy, and an overlap in science measurement objectives through which more than one instrument will contribute to each of the science goals.

Table 1: Payload Characteristics

Payload	**Mass (kg)**	**Power (W)**	**Data (b/s)**
MDIS	6.8	6.7	1340
GRNS	13.4	23.6	125
XRS	3.4	5.4	90
MAG with boom	3.7	5.3	35
MASCS	3.1	5.9	145
MLA	6.9	25.6	55
EPPS	2.6	6.4	160
DPU (2)	3.3	4.2	15
Misc. (harness, etc.)	6.8	1.3	N/A
RS	*	*	*
Total	**50.0**	**84.4**	**1965**

* RS is included as part of engineering subsystems

Because of the limited downlink bandwidth available to MESSENGER, data compression is vital for this mission. Each instrument is compressing its data through one, or a combination of, lossless and lossy data compression techniques. Image compression from the MDIS imagers form a special case where raw images may be written to the spacecraft data recorder and read back at a later time by the spacecraft main processor and compressed for downlink. This compression activity runs as a background task in the main processor.

Mercury Dual Imaging System (MDIS)

MDIS has a wide angle (WA) and narrow angle (NA) imager arranged in an "under-over-shotgun" fashion with the WA and NA imagers mounted on opposite sides of a pivoting platform. MDIS is the only moveable instrument. This motion is required for optical navigation and planetary mapping during the Mercury flybys. These measurements must be made at angles beyond the Sun-keep-in limits for the full spacecraft. MDIS can point from nadir, where it is coalligned with the other instruments up to 50° toward the Sun and 40° anti-sunward.

The WA imager has a 10.5° field of view and a 12-position filter wheel to provide full-color mapping of the entire planet. The NA imager has a 1.5° field of view and a single filter that is a compromise between high throughput for optical navigation and limiting the light at Mercury to prevent overexposure at even the shortest exposure times. The layout of MDIS is shown in Figure 1, and its key characteristics are listed in Table 2. The pixel field row in Table 2 refers to the instantaneous field of view for a single pixel at 200 km and 15,000 km altitude.

Table 2: MDIS Characteristics

MDIS	Narrow Angle	Wide Angle
Scan Range	+50° to –40°	
Field of view	1.5°	10.5°
Filters	Single	12
Detector	CCD 1024x1024, 14-μm pixels	
Pixel field	5.2 m - 390 m	72 m - 5.4 km
Quantization	12 bits/pixel	
Signal/noise	> 200:1	

The MDIS pivot platform is driven by a redundant-winding stepper motor system with a resolver to measure the platform position to < 140 μrad precision. The charge-coupled device (CCD) camera heads use highly integrated, low-mass electronics with 12-bit intensity resolution. The WA optics are refractive, and they are inherently small due to the short focal length. The two imagers are co-aligned. Spectral information is provided by the 12 filters of the WA imager. It has a 10.5° FOV and uses a modified Cooke-triplet lens with excellent image quality over the full FOV and wavelength range. Radiation-resistant glasses are used throughout.

The narrow FOV of 1.5° for the NA imager requires a focal length of 550 mm. The NA optics use a compact, off-axis section of reflective telescope. The mirrors correct spherical aberration and coma. Focal-plane curvature and astigmatism are small, and a correction lens is not required. Performance at 0.4° off axis is diffraction limited, and the spot size is smaller than a pixel over 80% of the FOV.

The CCD detectors are 1024 x 1024 frame-transfer devices with electronic shuttering. There is no mechanical shutter, with its attendant reliability concerns. MDIS has manual and automatic exposure control over a range from 5-ms to 10-s exposures. On-chip summing of 2 x 2 pixels can be commanded for 512 x 512 images as required. Combined hardware and software

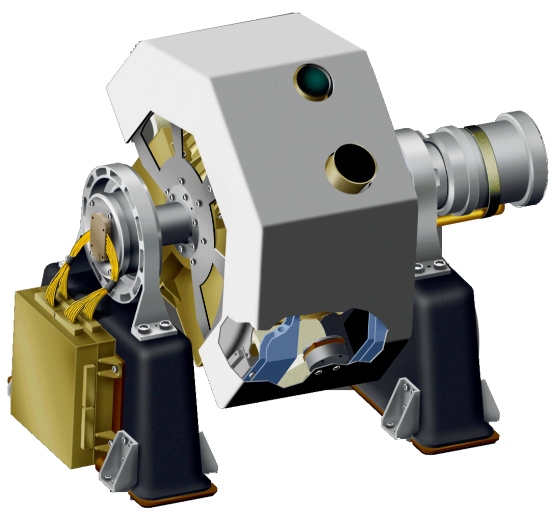

Figure 1: MDIS configuration.

enable subframing so the Science Team may specify that only a chosen rectangular segment of the full image will be saved and transferred to the ground.

The thermal design for MDIS has necessitated an unusual combination of design elements. The imager will spend most of its time in cold space but will pass across and face the sunward side of Mercury every 12 hours during two seasons of the Mercury year. To keep the dark noise to reasonable levels, the CCDs are kept between –5 and –40° C. The thermal protection system includes beryllium radiators for their high heat capacity, diode heat pipes to shut off thermal conduction when looking at the hot planet, phase-change "wax packs" to limit temperatures when riding out the hot periods, and flexible thermal links to tie these elements together.

Full images can be taken every 4 s, and subframe or pixel-binned images may be taken every second. Images are transferred directly from the imager to the spacecraft recorder. Several image-compression techniques are available and may be used individually or in combination. Pixel summing, subframing, and image compression all contribute to the most efficient use of the limited downlink bit rate.

Calibration of MDIS will be done at the JHU/APL Optical Calibration Facility. The point-spread function, geometric distortion, flat field, dark current, radiometric response, wavelength calibration, scattered light, and detector alignment will be measured.

Gamma-Ray and Neutron Spectrometer (GRNS)

GRNS has an active-shielded gamma-ray detector that measures a wide range of elemental abundances (O, Si, S, Fe, H, K, Th, U) and a neutron spectrometer to look for possible H_2O ice at Mercury's poles. Data from the gamma-ray sensor on the Near Earth Asteroid Rendezvous (NEAR) mission led to a basic change in the GRNS design after the MESSENGER Preliminary Design Review (PDR). GRNS is body mounted, and the original design was based on a large scintillator gamma-ray detector, similar to that on NEAR. However, the spacecraft background on NEAR was large, and NEAR obtained acceptable data only after it landed on 433 Eros. To mitigate the spacecraft background, GRNS was changed to a cryogenically-cooled, high-purity, germanium detector. This sensor has a 50x50 mm detector with a Stirling-cycle cooler and an active scintillator shield of boron-loaded plastic shown in Figure 2. The central cylinder in the figure encapsulates the germanium detector, and the

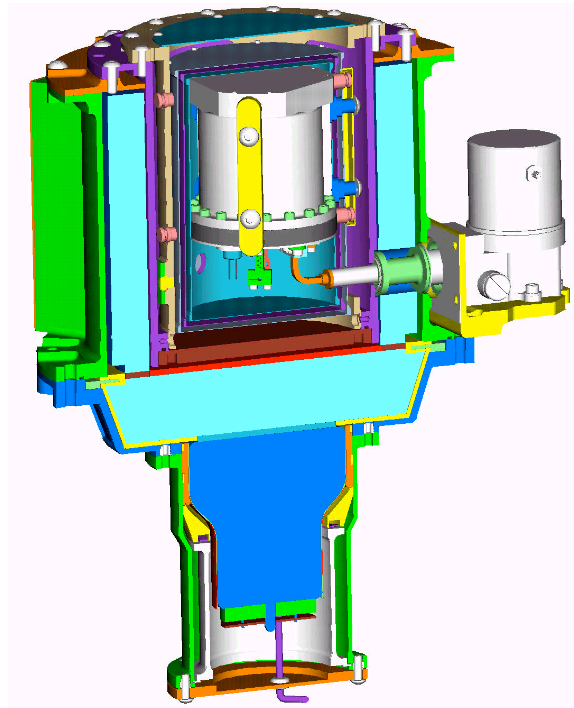

Figure 2: Gamma-ray spectrometer.

cylindrical body at the right is the Stirling-cycle cryo-cooler. There is a three-layer thermal shield surrounding the germanium detector to minimize heat leaks. The plastic scintillator shield is viewed by a large photomultiplier tube (PMT). The shield is operated in anti-coincidence with the germanium detector to remove the signals from cosmic rays and much of the spacecraft background. Since the shield is made of borated plastic, it will also respond to neutrons and supplement the neutron spectrometer data.

The Neutron Spectrometer (NS) subsystem is shown in Figure 3. It has two lithium glass scintillators on the ends separated by a thick slab of neutron-absorbing, borated plastic scintillator. Because the orbital velocity around Mercury is about 3 km/s, the ratio of counts in the ram and wake glass scintillators, loaded to 20% by weight with ^{6}Li, greatly enhances the sensitivity to thermal neutrons. The central scintillator, between the two slabs of lithium glass, counts fast neutrons. All three scintillators are viewed by individual PMTs.

X-Ray Spectrometer (XRS)

XRS determines the atomic composition of the surface of Mercury by solar-induced X-ray fluorescence. It is sensitive to 1 keV to 10 keV, covering the emission lines of Mg, Al, Si, Ca, Ti, and Fe. XRS is an improved version of the NEAR Shoemaker X-ray spectrometer design. Three gas proportional counters measure low-energy X-rays from the planet, and a Si-PIN detector mounted on the spacecraft sunshade views the X-ray input from the Sun. Figure 4 shows engineering model of the planet-viewing portion of the instrument.

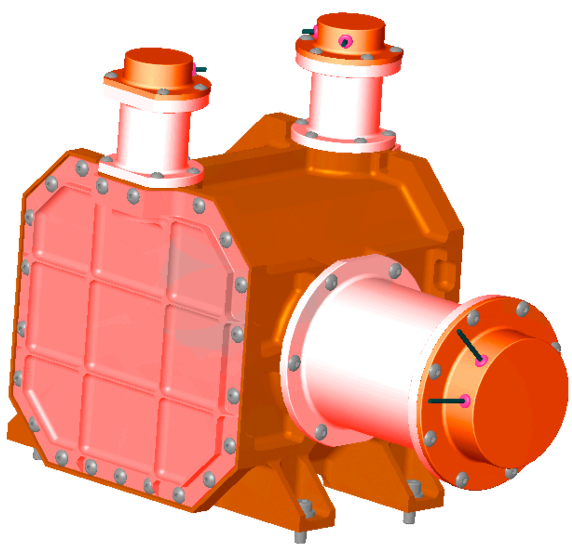

Figure 3: Neutron spectrometer

A Cu honeycomb collimator provides a 12° FOV, which is smaller than the planet at apoapsis and eliminates the X-ray sky background. At periapsis the FOV is approximately 40 km. Thin absorption filters on two of the planet-facing detectors differentially separate the lower energy X-ray lines (Al, Mg, and Si). The SNR of the planet-facing gas tubes is enhanced by a set of anti-coincidence wires, located near the periphery of the tubes, which catch penetrating cosmic-ray events, and an internal carbon liner blocks X-rays produced by cosmic rays in the detector tube walls. The solar flux monitor has a small (0.1 mm^2) detector that looks through a pair of thin Be foils that provide thermal protection. The outer foil reaches > 500° C and is the hottest component on the spacecraft.

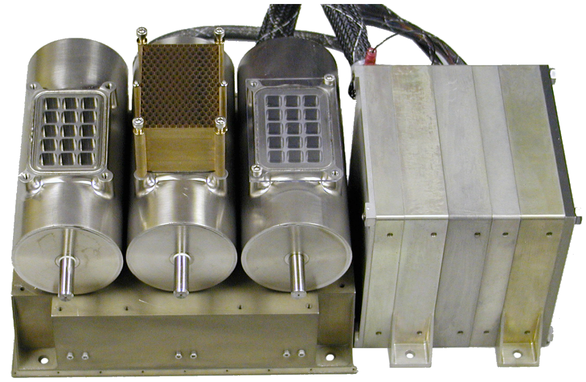

Figure 4: Engineering model of the planet-viewing portion of XRS.

Magnetometer (MAG)

MAG is a miniature, three-axis, ring-core fluxgate magnetometer similar to the magnetometers that have flown on many planetary missions. However, it has been miniaturized because of the strong mass limitations on MESSENGER. MAG is mounted on a light-weight, 3.6-m boom extending in the anti-sunward direction. The sensor at the end of the boom has its own sunshade to protect it when the spacecraft turns so that tip of the boom is no longer shadowed. MAG has two ranges with full-scale values of ± 4096 nT and ± 65536 nT. The high range is primarily for ground testing, and MAG will operate in the low range in orbit. Measurements are digitized with 16-bit resolution, which provides a minimum quantization of 0.06 nT. The detector samples at a 20-Hz rate. Hardware anti-aliasing filters and digital filtering in the MAG processor provide selectable averaging intervals from 0.04 s to 1 s. For readout intervals from 1 s to 100 s, a 0.5-s average is provided. Nominal 0.1-Hz sampling of the field will be increased to 10 Hz near periapses and 20 Hz at modeled magnetospheric boundary crossings.

Despite the 3.6m boom, stray fields from the spacecraft will limit the accuracy of the magnetic measurements. The MAG team is working closely with the spacecraft engineers to minimize stray fields. Potential magnetic field sources have been identified, and mitigation techniques have been selected. Through careful design, only the reaction wheels and a few propulsion system valves require shielding or magnetic compensation.

Mercury Laser Altimeter (MLA)

MLA measures both the libration of Mercury and the topography in the northern hemisphere. MLA is designed for orbital altitudes up to 1000 km above the surface and will operate only for about 30 minutes each orbit. It has a Q-switched, diode-pumped Cr:Nd:YAG laser transmitter operating at 1064 nm, and 4 receiver telescopes with sapphire lenses, a photon-counting detector, and a time interval unit (Figure 5).

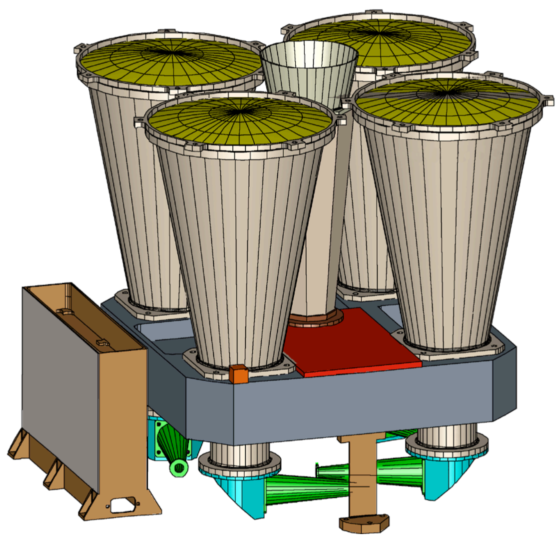

Figure 5: MLA with its separate power supply unit (lower left).

The laser transmits pulses at 8 Hz through a light-weight beam expander with a heat rejection filter and has a beam divergence of ≤ 50 μrad. The four 125-mm diameter receiver telescopes collect the laser return pulses from Mercury and pass them through an optical bandpass filter to reject the solar background. Light is detected with a hybrid avalanche photodiode. Receiver electronics use a high-resolution time-to-digital converter chip to record the arrival time of individually reflected photons with 30-cm (2-ns) range resolution.

Mercury Atmospheric and Surface Composition Spectrometer (MASCS)

MASCS is designed to observe emissions from the thin Mercury exosphere during limb scanning and to observe the planetary surface. This mix of objectives requires two very different spectrometers in the same package (Figure 6). A single front-end telescope simultaneously feeds both an Ultraviolet-Visible Spectrometer (UVVS) and a Visible-Infrared Spectrograph (VIRS).

The Cassegrain front-end telescope feeds UVVS, an Ebert-Fastie spectrometer with a moving diffraction grating that is optimized for measuring the composition and structure of the exosphere. UVVS is very similar to the Galileo Ultraviolet Spectrometer (UVS) on which it is based. There have been modifications to the aperture and sunshade to accommodate the Mercury thermal input; the grating is changed to span the UVVS wavelength range. UVVS covers the spectral range from 115 to 600 nm with three photon-counting PMT detectors. When scanning the limb, it has 25-km altitude resolution and an average spectral resolution of 1 nm.

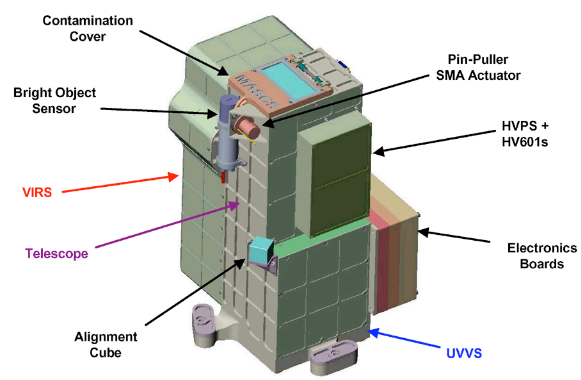

Figure 6: MASCS combines surface and exospheric observations in a small instrument.

It can detect signals as weak as 10 Rayleighs in 100 s (5σ). UVVS is protected with a bright image sensor that disables the PMT high voltage when the field of view intersects the bright planet.

The VIRS spectrograph is designed to measure the surface reflectance of Mercury in the visible through the near infrared (0.3-1.45 μm). VIRS has 100-m to 7.5-km resolution on the surface of Mercury, depending on altitude. Light is fed to VIRS through a fused-silica fiber-optic bundle. A concave holographic diffraction grating images onto two semiconductor photodiode array detectors A dichroic beam splitter separates the visible (300-1025 nm) and infrared (0.95-1.45 μm) spectra. The visible detector is a 512-element silicon line array. The IR detector is a 256-element InGaAs array, which does not require active cooling. Both detectors are digitized to 12 bits. A 1-s integration will provide SNR > 200. The 1.45-μm long-wavelength cutoff for VIRS was chosen because thermal emission from Mercury's surface beyond that wavelength is comparable to the reflected solar signal.

Energetic Particle and Plasma Spectrometer (EPPS)

MESSENGER will examine volatile ion species in and around Mercury's magnetosphere. EPPS measures ions from thermal plasmas through ~5 MeV and electrons from ~20 keV to 400 keV. EPPS combines a Fast Imaging Plasma Spectrometer (FIPS) head for thermal plasmas and an Energetic Particle Spectrometer (EPS) head for energetic ions and electrons. Both detector heads are sensitive to particles arriving from a wide range of angles so that they may characterize low-energy ions coming up from the surface of Mercury, pickup ions, and ions accelerated in the magnetosphere. FIPS can also observe the solar wind when the spacecraft is turned near its maximum allowed off-Sun pointing angle. Both EPS and FIPS use a time-of-flight (TOF) system to determine the velocity (energy/mass) of the detected ions.

EPS is a hockey-puck-sized, TOF spectrometer that measures the energy spectra, atomic composition, and pitch-angle distributions of energetic ions from 10 keV/nuc to ~5 MeV and electrons from 10 keV to 400 keV (Figure 7). Ions entering EPS pass through a very thin foil and release secondary electrons that time the entry and exit of the ion from the spectrometer. Total energy is measured by a pixelated silicon detector. A collimator defines the acceptance angles for the six pixel segments. The FOV is 160° by 12° with six active segments of 25° each. The secondary electron "start" and "stop" signals for the TOF measurements (from 100 ps to 200 ns) are detected by a micro-channel plate (MCP) electron multiplier. These signals are fed to a time-to-digital converter chip. Time intervals and total energy for each ion are passed to the processing electronics, where energy spectra for each of four species in all six pixel directions are accumulated

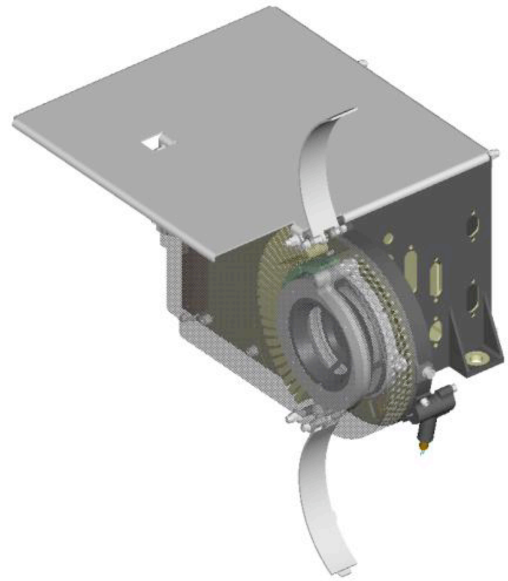

Figure 7: Cutaway view of the energetic particle spectrometer.

FIPS (Figure 8) measures low-energy plasmas with energy per charge (E/q) from a few eV/q (determined by the spacecraft potential) up to ~10 keV/q. FIPS has an innovative, wide angle, electrostatic analyzer followed by a time-of-flight spectrometer. It has nearly full hemispherical coverage. Particles of the correct E/q and polar angle pass through the dome-shaped electrostatic deflection system and into the position-sensing TOF telescope. For a given polar incidence angle, a setting of the deflection voltage allows only ions within a narrow E/q range to pass through the deflection system. The ions are then post-accelerated by a fixed voltage before passing through a very thin (~1 μg/cm^2) carbon foil. Position sensing of the start electrons with a wedge-and-strip anode in the MCP assembly determines the initial incidence angle. The mass per charge of a given ion follows from E/q and the TOF, allowing reconstruction of distribution functions for different mass/charge species. The deflection voltage is stepped over 1 minute and covers an E/q range of ~0.0 to ~10.0 keV/q. The EPPS common electronics process all of the TOF, energy, and position signals from both EPPS and FIPS again using the custom time-to-digital converter chip.

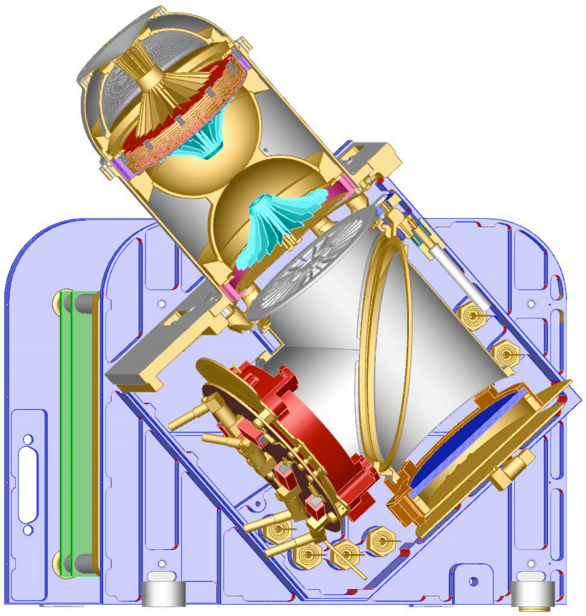

Figure 8: Cutaway view of FIPS. The electrostatic analyzer is at the top and the time-of-flight section extends to the lower right.

PAYLOAD ACCOMMODATION

The MESSENGER spacecraft must accommodate the payload mass and power, volume, FOV, and other requirements. The most difficult challenges for MESSENGER have been the thermal design while staying within stringent mass constraints. Most of the instruments are mounted on the lower deck of the spacecraft (Figure 9), with the directional instruments inside the adapter to the launch-vehicle third stage.

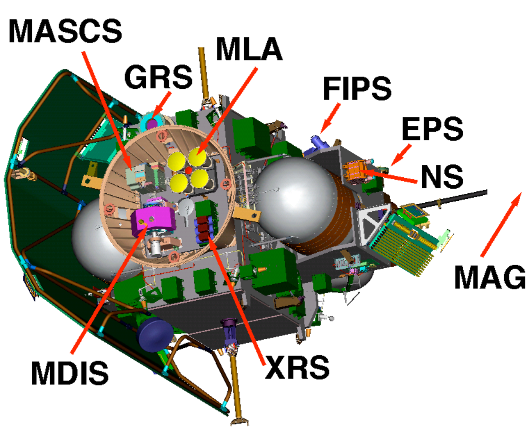

Figure 9: The directional instruments (MDIS, MASCS, MLA, and XRS) are mounted inside the launch vehicle adapter ring.

Only the MAG is boom mounted. The directional instruments are co-aligned so that they all view the same portion of Mercury simultaneously. Pointing is accomplished by spacecraft pitch and yaw to keep the spacecraft lower deck aimed at Mercury. Pointing maneuvers are limited by the maximum allowable off-Sun pointing of the spacecraft sunshade. Therefore, there are small intervals while MESSENGER is in a nearly noon-midnight orbit around Mercury when the off-Sun-pointing limits prevent the instruments from viewing the planet

The fields of view of most instruments are clear; however, the nearly full-hemisphere FOV of the EPPS FIPS head may intersect the solar panels for some panel rotation angles. The thermal environment of the spacecraft body is benign for ordinary electronic boxes. Some of the instrument sensor heads have special temperature requirements and are isolated from the spacecraft. These units have required a great deal of thermal engineering to deal individually with the thermal extremes in the Mercury environment.

SUMMARY

MESSENGER will launch on March 10, 2004, to provide the first comprehensive view of Mercury, its current state, and insight into its early history. This mission is being developed under the National Aeronautics and Space Administration's Discovery Program. This program strictly limits the development budget. The challenges of the unique thermal environment in Mercury orbit have molded the final spacecraft and instrument configurations. The seven instruments, the spacecraft, and the mission design have been tightly integrated and optimized along with an aggressive program of miniaturization. This optimization has allowed the highly constrained mission to meet all scientific measurement requirements.

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