THE MESSENGER SCIENCE PAYLOAD

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ABSTRACT

The MESSENGER spacecraft will orbit Mercury and gather data for one Earth year with a miniaturized scientific payload. The MESSENGER project is in the integration and test phase in mid 2003. Seven assembled and calibrated instruments are mounted on the spacecraft. The Gamma-Ray and Neutron Spectrometer has a Gamma-Ray Spectrometer to measure atomic composition with a high-purity germanium detector and a Neutron Spectrometer that uses lithium-glass and boron-loaded plastic scintillators for sensing thermal, epithermal, and fast neutrons. The X-Ray Spectrometer measures Mercury surface elemental abundances by examining solar-flare-induced X-ray fluorescence lines. Three gas-filled proportional counters detect the X-ray fluorescence lines from the planet's surface, and a solid-state solar monitor measures the X-ray input to the planet. The Mercury Dual Imaging System (MDIS) has both wide-field and narrow-field cameras to map the surface of the planet. MDIS is also multi-spectral, with a 12-position filter wheel for the wide-field camera. The Mercury Atmospheric and Surface Composition Spectrometer measures both surface spectral reflectance in the visible and near infrared and exospheric emission lines in the ultraviolet and visible. The Mercury Laser Altimeter (MLA) determines the range to the planet with a resolution of 0.3 m. MLA will be combined with the radio-science investigation to map the gravitational field of the planet and determine the obliquity and physical libration amplitude. A magnetometer, mounted on a 3.6-m boom, will map the internal and external magnetic field. The Energetic Particle and Plasma Spectrometer will measure particles accelerated in the magnetosphere and the interactions of the magnetosphere with the solar wind. MDIS has its own pivot platform. All of the other instruments are fixed to the spacecraft. Pointing is accomplished by steering the entire spacecraft. All of the instruments are designed to deal with the extreme thermal environment at Mercury, where the sunward face of the spacecraft will reach temperatures above 350° C. MESSENGER will launch in May 2004 and begin orbital observations of Mercury in October 2009.

1. MSSION OVERVIEW

MESSENGER (MErcury Surface, Space ENvironment GEochemistry, and Ranging), the first orbital mission to Mercury, will launch on 11 May 2004 and make 3 Venus flybys and 2 Mercury flybys before going into Mercury orbit on 17 October 2009. A Mercury orbital mission has been a scientific priority since the Mariner 10 flybys in 1974 - 1975 [1]. However it was thought too difficult and too expensive to be attempted until now. MESSENGER has developed innovative techniques for using existing materials and technologies that have brought a Mercury mission within reach. Multiple planetary flybys have significantly eased the propulsion requirements, but MESSENGER still requires more than 2300 $\mathrm{ms^{-1}}$ of ΔV and a fuel fraction of 56% of its launch mass. A great deal of effort therefore has been expended to miniaturize the spacecraft components and lower the mass of the structure and propulsion system. An even greater challenge has been the development of a spacecraft to operate in the Mercury thermal environment. Near Mercury perihelion, the sunward-facing side of the spacecraft will reach temperatures above 350° C. The solar panels must also operate in this environment. When the spacecraft is near the Mercury sub-solar point, it will find itself with a solar input equivalent to 11 Suns on its front side and a > 400° C black body covering nearly the full hemisphere of its back side.

The key innovations that have made MESSENGER possible are (1) A ceramic cloth sunshade that keeps the spacecraft in shadow at all times; (2) three large, low-mass, fuel tanks that occupy the interior of the spacecraft; (3) solar panels that are composed of 2/3 second-surface mirrors and 1/3 cells; (4) a low-mass composite structure; (5) a pair of phased array antennas that avoid having a gimbaled dish exposed to the full solar and planetary environment; and (6) many mass-saving innovations in almost every spacecraft subsystem.

MESSENGER will map 90% of Mercury during the two flybys (Figure 1). Orbit insertion in 2009 will put MESSENGER into a highly elliptical orbit with a

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periherm of 200 km, an apoherm of 15,000 km, and an orbital period of 12 hours. During the orbital phase, the spacecraft will take data for one Earth year, which will cover a little more than four Mercury years and two Mercury solar days.

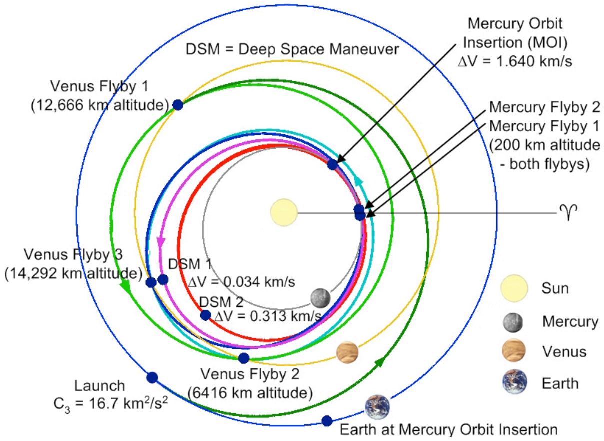

Figure 1: MESSENGER trajectory from launch in May 2004 to orbital insertion in October 2009.

2. SPACECRAFT AND PAYLOAD

The MESSENGER spacecraft and payload have been described elsewhere [2, 3]. Building such a complex mission within the limits of the NASA Discovery Program stretches all of the available resources [4]. The basic layout of the spacecraft is shown in Figure 2. The sunshade is always kept pointed within 12° of the vector to the Sun. As the spacecraft heads inward from the Earth toward Mercury where there is a large excess of power available, the solar panels are tilted toward edge-on to the Sun to keep their temperature from getting too high.

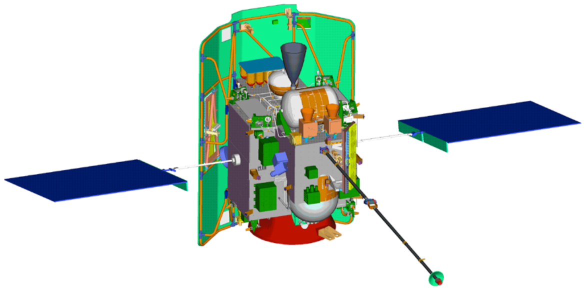

Figure 2: Orbital configuration of the MESSENGER spacecraft.

The MESSENGER Payload consists of seven instruments: a Gamma-Ray and Neutron Spectrometer (GRNS), an X-Ray Spectrometer (XRS), a Mercury Dual Imaging System (MDIS), a Magnetometer (MAG), a Mercury Laser Altimeter (MLA), a Mercury Atmospheric and Surface Composition Spectrometer (MASCS), and an Energetic Particle and Plasma Spectrometer (EPPS) [2, 5]. The instruments communicate to the spacecraft through fully redundant Data Processing Units (DPUs). The mass and power of the payload elements are listed in Table 1.

Table 1. Payload Resources

Payload	Mass (kg)	Power (W)
MDIS	**7.9**	**7.6**
GRNS	**11.6**	**13.3**
XRS	**3.0**	**6.9**
MAG with boom	**4.1**	**4.0**
MASCS	**3.1**	**6.7**
MLA	**7.4**	**16.4**
EPPS	**3.0**	**7.8**
DPU (2)	**3.4**	**5.3**
Misc. (harness, etc.)	**6.5**	**1.3**
Total	**50.0**	**69.3**

During normal orbital operations and short eclipse times, all instruments can operate at full power and at their highest data rates. However, when the Mercury eclipses extend beyond 35 minutes, as they do during 4 weeks of the mission year, the payload will be restricted to only one or two instruments operating at a time. Because of the varying distance to Earth, the data return varies widely from day to day. However, the total data return from the orbital phase of the mission is about 75 gigabits. Each payload element has an allocated data return allowance with significant freedom to adjust its daily data volume to meet the current science conditions.

3. MERCURY DUAL IMAGING SYSTEM (MDIS)

MDIS will map the entire planet to a resolution of 125 m per pixel or better. Because of the highly elliptical orbit at Mercury, MDIS has been constructed with both wide-angle (WA) and narrow-angle (NA) imagers and on-board pixel summing to provide images of nearly uniform resolution throughout the orbit while minimizing the downlink requirements. Because of the geometry of the orbit and the limitations of off-Sun pointing by the spacecraft, the WA and NA imagers are mounted on opposite sides of a pivoting platform to provide for optical navigation and planetary mapping during the Mercury flybys. MDIS is the only instrument with independent pointing capability. The MDIS pivot can point from 50° toward the Sun to 40° anti-sunward centered on nadir, where it is co-aligned with the other optical instruments.

The MDIS thermal design was the greatest challenge to its development. The instrument must work in cold space and yet be able to point at the 450° C sub-solar region of Mercury for extended intervals and still produce high-quality images. Throughout this range of environmental conditions, the charge-coupled device (CCD) camera heads are kept between –5 and –40° C to minimize their dark noise. The MDIS thermal protection system includes high-heat-capacity beryllium radiators, 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.

The WA imager is a refractive design with 10.5° field of view and a 12-position filter wheel to provide full-color mapping. The NA imager is an off-axis reflective design with a 1.5° field of view and a single band-limiting filter. The passband is a compromise between limiting the light at Mercury to keep the exposure times reasonable and providing high throughput for stellar imaging during optical navigation.

The layout of MDIS is shown in Figure 3, and its physical location on the payload deck, inside the adapter ring to the launch vehicle, is shown in Figure 4. Key characteristics are listed in Table 2. The instantaneous fields of view for a single pixel are listed at the extreme altitudes of 200 km and 15,000 km.

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 FOV	5.2 m - 390 m	72 m - 5.4 km
Quantization	12 bits/pixel	
Signal/noise	> 200:1	

The MDIS pivot platform drive is a redundant-winding stepper motor system and a resolver to measure the platform rotation to a precision < 140 μrad.

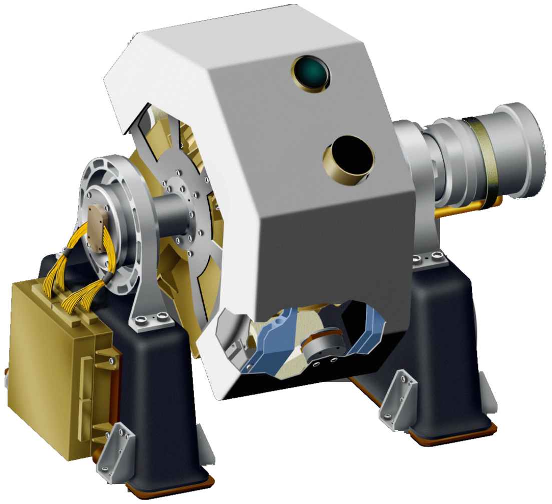

Figure 3: MDIS configuration.

The CCD camera heads use highly integrated, low-mass electronics with 12-bit intensity resolution. The CCD detectors are 1024 x 1024 frame-transfer devices with electronic shuttering. There is no mechanical shutter. There are both manual and automatic exposure controls, and the exposure range is from 4 ms to 10 s. The cameras can be commanded to perform on-chip summing of 2 x 2 pixels for 512 x 512 images as required. The imager hardware can also decimate the images from 12-bit to 8-bit quantization with a variety of lookup tables. Images are sent directly to the spacecraft solid-state recorder. They are later read back into the main spacecraft processor for additional image compression as commanded on an image-by-image basis. Several lossless and lossy compression types are available. Full images can be taken every 4 s, and subframe or pixel-binned images may be taken every second.

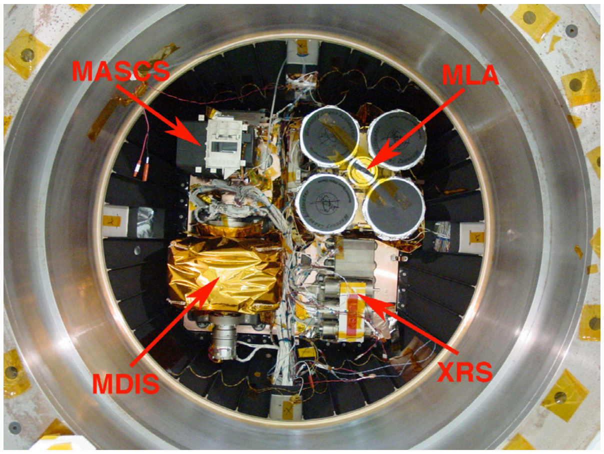

Figure 4: Directional instruments are mounted inside the adapter ring between the spacecraft and the launch vehicle. The MDIS imager is rotated with the apertures pointing toward the deck. MLA has its ground protective covers.

MDIS was calibrated at the JHU/APL Optical Calibration Facility under a close collaboration between the Science Team and the development engineers. Several optical quirks were identified and corrected. The completed MDIS imager meets all of the scientific requirements.

4. GAMMA-RAY AND NEUTRON SPECTROMETER (GRNS)

The Gamma-Ray Spectrometer (GRS) sensor on GRNS is a cryocooled, high-purity germanium detector with an active shield. It measures elemental abundances of O, Si, S, Fe, H, K, Th, and U. The design was changed from a scintillator-based system after the data from the gamma-ray sensor on the Near Earth Asteroid Rendezvous (NEAR) mission showed that the background from local spacecraft gamma-rays would give it a very low signal-to-background ratio (SBR) at Mercury. Since it was not practical to put the GRS on a long boom in the Mercury thermal environment, the SBR was maximized by using a high-resolution germanium detector. Developing an actively cooled detector to operate at 85 K in the > 700 K environment at Mercury was a significant design challenge.

The GRS sensor has a 50 x 50 mm detector with a Stirling-cycle cooler and an active scintillator shield of boron-loaded plastic shown in Figure 5. The Stirling cooler is the grey cylinder on the right. Its cold finger connects to the central cylinder in the figure that encapsulates the germanium detector.

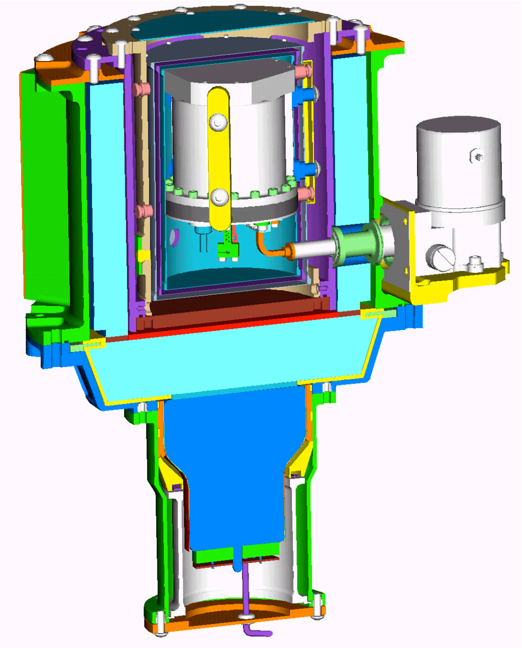

Figure 5: Gamma-ray spectrometer.

A triple-layer thermal shield surrounds the germanium detector to minimize heat leaks. The boron-loaded-plastic scintillator shield is shown as light blue in the figure. It is viewed by a large photomultiplier tube (PMT). The anti-coincidence shield removes the cosmic ray background and softer component of the spacecraft background. The shield will also respond to neutrons and supplement the Neutron Spectrometer data. The GRS electronics use a novel signal processing design that achieves resolution and stability that nearly equals the performance of a full digital signal processing system with a minimal amount of radiation-hardened electronics.

Figure 6 shows the GRS mounted on the spacecraft. The cryocooler is the small cylinder near the top of the photo. A “pump hat” covers the main aperture of the sensor to allow the GRS to be evacuated during ground testing and prevent condensation when the detector is cooled.

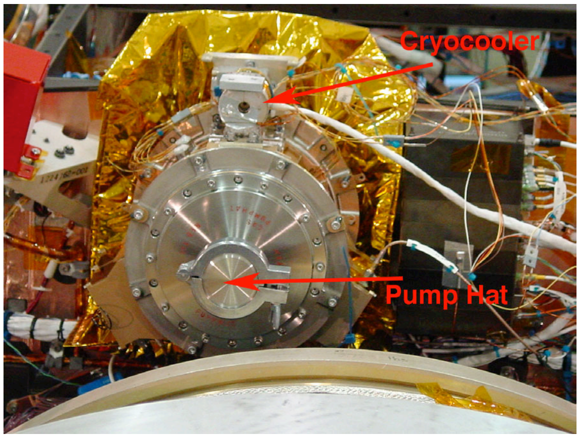

Figure 6: Gamma-ray spectrometer mounted on the spacecraft. The large disk is the main aperture, covered by the pump hat.

The Neutron Spectrometer (NS) sensor on GRNS is shown in Figure 7. It has two lithium glass scintillators on the ends separated by a thick slab of neutron-absorbing, borated plastic scintillator. The glass scintillators are loaded with ^{6}Li to measure thermal neutrons to a concentration of 20% by weight. Because the MESSENGER orbital velocity is about 3 km/s, the ratio of counts in the ram and wake greatly enhances the sensitivity to thermal neutrons. The borated-plastic central scintillator counts fast neutrons. All three scintillators are viewed by individual photomultiplier tubes (PMTs).

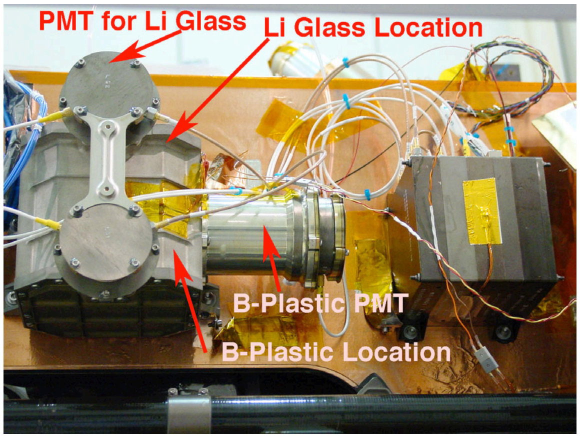

Figure 7: Neutron Spectrometer mounted on the spacecraft.

5. X-RAY SPECTROMETER (XRS)

XRS is an improved version of the NEAR Shoemaker X-ray spectrometer to measure the atomic surface abundances of Mg, Al, Si, Ca, Ti, and Fe by solarinduced X-ray fluorescence. Three improved gas proportional counters measure low-energy X-rays from the planet, and a Si-PIN detector mounted on the spacecraft sunshade views the solar X-ray input. The detectors cover the energy range from 1 to 10 keV. XRS has a 12° FOV, provided by a high-throughput, Cu honeycomb collimator. A “matched filter” technique is used to separate the lower energy X-ray lines (Al, Mg, and Si). The proportional counter tubes are improved from the NEAR design by the addition of anti-coincidence wires surrounding most of the tube and a low-emission carbon liner in the sensitive volume. Figure 8 shows the planet-viewing portion of the instrument. It is mounted in the spacecraft adapter ring along with the optical instruments (Figure 4).

The XRS solar monitor peers through the sunshade with a small (0.1 mm^2) detector protected by a pair of thin Be foils. The outer foil reaches > 500° C and is the hottest component on the spacecraft, while the detector, just 4 cm away, sits below 0° C.

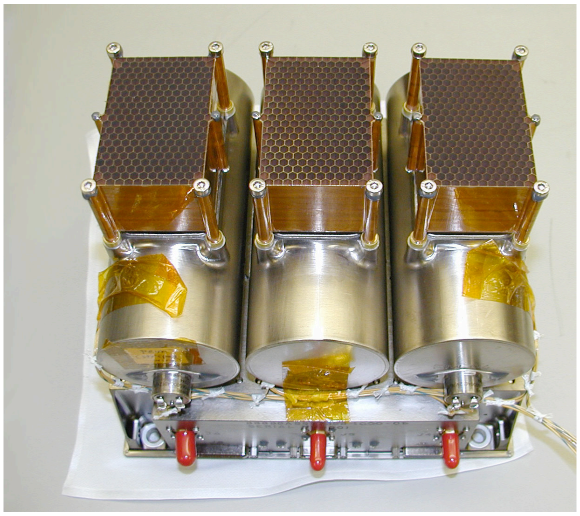

Figure 8: Planet-viewing portion of XRS.

6. MAGNETOMETER (MAG)

MAG is a miniaturized version of the three-axis, ring-core, fluxgate magnetometers that have flown on many planetary missions. MAG is mounted on a light-weight, 3.6-m carbon-fiber boom extending in the anti-sunward direction. Since the sensor can protrude from the shadow of the spacecraft when the spacecraft is pointed near its allowable off-Sun limits, the sensor has its own sunshade. The MAG detector samples the field at a 20-Hz rate, and hardware anti-aliasing filters plus software digital filters provide selectable readout intervals from 0.04 s to 1 s. Readout intervals greater than 1 s generate a 0.5-s average at the time of the readout. MAG has 16-bit quantization, which eliminates the need for range switching during orbital operations. Figure 9 shows the MAG sensor at the end of the boom as stowed for launch.

Spacecraft-induced stray fields have been minimized by working with individual subsystems to eliminate the causes where possible and by applying a range of mitigation techniques to the remaining fields. Only the reaction wheels and a few propulsion system valves required any shielding or magnetic compensation.

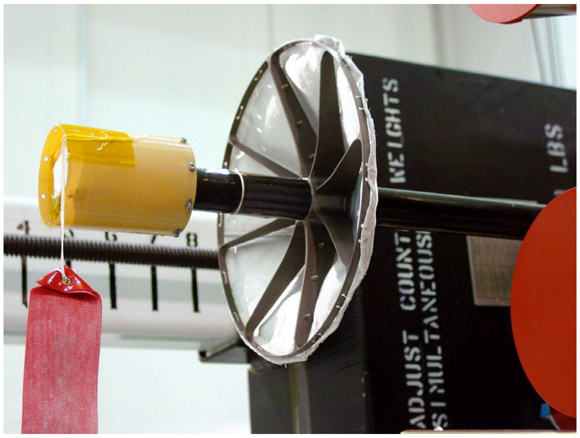

Figure 9: MAG sensor on the end of the boom. The ceramic cloth sunshade ensures that the MAG sensor does not overheat when the spacecraft slews. The red tag attached to the end of the boom denotes a temporary protective cover around the sensor.

7. MERCURY LASER ALTIMETER (MLA)

MLA has a diode-pumped, Q-switched, Cr:Nd:YAG laser transmitter operating at 1064 nm and four receiver telescopes with sapphire lenses (Figure 10). MLA is located within the adapter ring to the launch vehicle, along with the other optical instruments (Figure 4). A photon-counting detector and a time-interval unit, based on an application-specific integrated circuit (ASIC) chip, measure altitudes up to 1000 km with 30-cm resolution. Because of the highly elliptical orbit at Mercury, MLA will operate for about 30 minutes around the periapsis of each orbit.

The laser transmits pulses at 8 Hz through a beam expander with a heat rejection filter. 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 before going to the detector, a hybrid avalanche photodiode.

8. MERCURY ATMOSPHERIC AND SURFACE COMPOSITION SPECTROMETER (MASCS)

MASCS has both a moving-grating Ultraviolet-Visible Spectrometer (UVVS) and a Visible-Infrared

Spectrograph (VIRS). UVVS will observe emissions from the tenuous Mercury exosphere during limb scans, and VIRS will observe the planetary surface. The two spectrometers are contained in the same package, fed by a single front-end telescope (Figure 11).

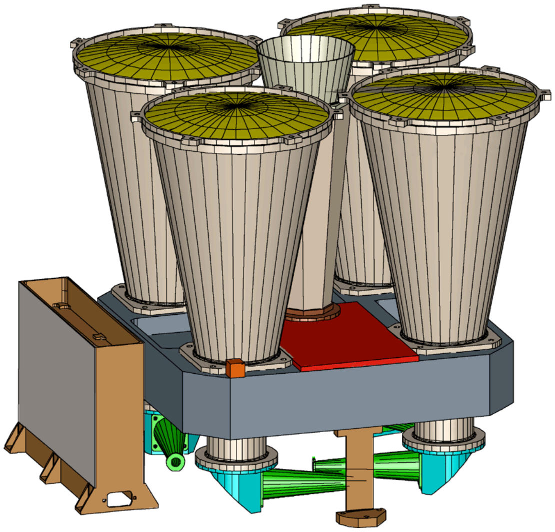

Figure 10: MLA with its central laser transmitter, four receiver tubes, and separate power supply unit.

The Cassegrain front-end telescope feeds the UVVS Ebert-Fastie spectrometer directly. Its moving diffraction grating design is optimized for measuring the very weak emissions of the exosphere with excellent signal-to-noise ratio. UVVS spans 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.

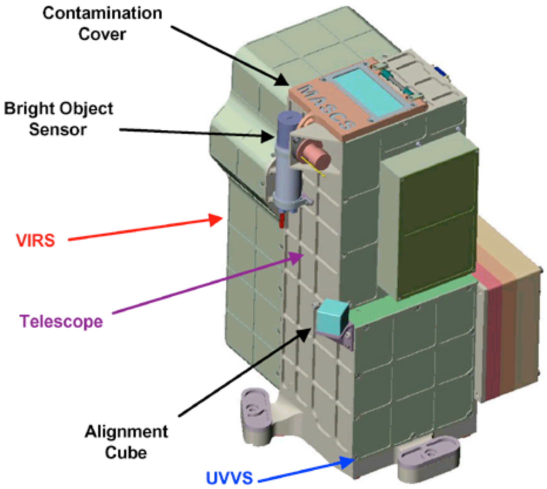

Figure 11: MASCS combines an exospheric and a surface observing instrument in a single package.

VIRS is fed by a fused-silica fiber-optic bundle from the focal plane of the front-end telescope. A holographic diffraction grating images onto two semiconductor line-array detectors. A dichroic beam splitter separates the visible (300-1025 nm) and infrared (0.95-1.45 μm) spectra. The 512-element visible detector is silicon, and the 256-element IR detector is made of InGaAs. MASCS does not require active cooling. MASCS is mounted in the adapter ring with the other optical instruments (Figure 4).

9. ENERGETIC PARTICLE AND PLASMA SPECTROMETER (EPPS)

EPPS has both an Energetic Particle Spectrometer (EPS) and a Fast Imaging Plasma Spectrometer (FIPS). FIPS measures thermal and low-energy ions with a unique electrostatic analyzer and a time-of-flight (TOF) spectrometer section. The FIPS analyzer is sensitive to ions entering over nearly a full hemisphere, with energy per charge up to > 15 keV/q. Particles of the currently selected E/q and polar angle pass through the dome-shaped electrostatic deflection system and into the position-sensing TOF telescope (Figure 12). The ions are then post-accelerated by a fixed voltage before passing through a very thin (~1 $\mu g/cm^2$) carbon foil. Secondary electrons from the foil give the initial incidence angle. Mass per charge of an ion is measured by the E/q (set by the deflection voltage) and the TOF. The deflection voltage is stepped to cover the full E/q range in about one minute. Figure 13 shows FIPS mounted on the rear side of the spacecraft where it will observe the plasma over a wide range of pitch angles.

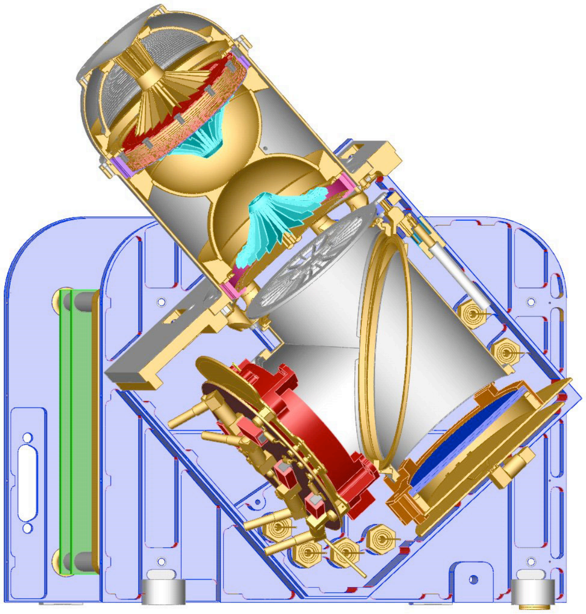

Figure 12: Internal construction of FIPS. The multiple hemispherical sections of the electrostatic analyzer are at the top. The time-of-flight section below measures where the particle exits the analyzer, through the segmented collimator disk, and the time the particle takes to reach the target at the lower right.

The hockey-puck-sized EPS sensor measures the TOF and residual energy of ions from 10 keV/nuc to ~5 MeV and electrons to 400 keV (Figure 14). Time-of-flight is measured from secondary electrons as the ions pass through two foils, while total energy is measured by a 24-pixel silicon detector array. The FOV is 160° by 12°, and it is divided into six segments of 25° each. The EPPS common electronics process all of the TOF, energy, and position signals from both EPS and FIPS. EPS is mounted on the top deck of the spacecraft, near the star cameras.

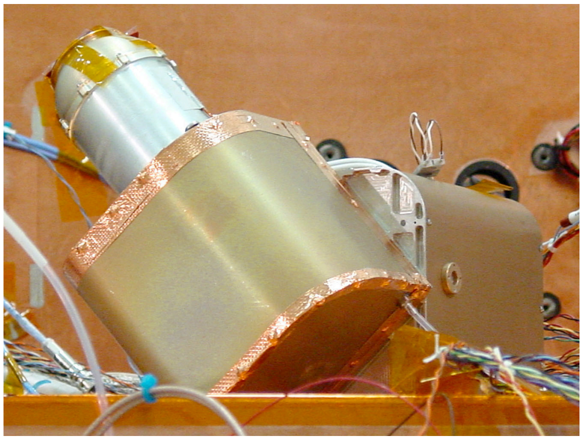

Figure 13: FIPS is mounted to ensure it can observe over a wide rage of pitch angles. FIPS can also view the solar wind when the spacecraft is turned significantly off the Sun vector.

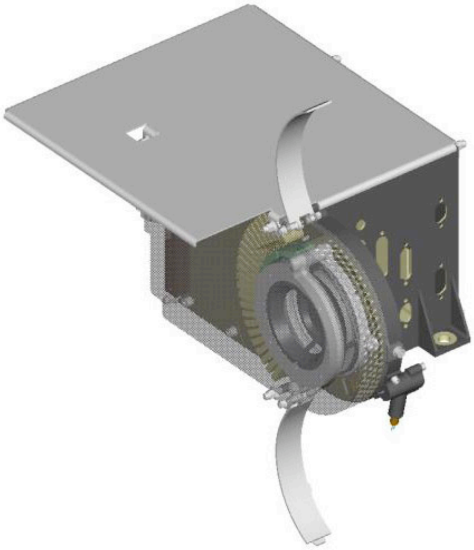

Figure 14: Cutaway view of EPS.

10. ACKNOWLEDGEMENTS

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