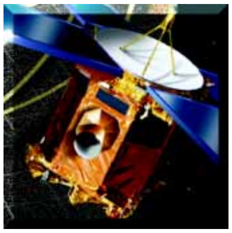

The NEAR Multispectral Imager

S. Edward Hawkins III

The Multispectral Imager, one of the primary instruments on the Near Earth Asteroid Rendezvous (NEAR) spacecraft, uses a five-element refractive optics telescope, an eight-position filter wheel, and a charge-coupled device detector to acquire images over its sensitive wavelength range of ≈400–1100 nm. The camera operates at a frame rate of 1 Hz, and the detector is passively cooled. The primary science objectives of the Multispectral Imager are to determine the morphology and composition of the surface of asteroid 433 Eros. The camera will have a critical role in navigating to the asteroid. Seven narrowband spectral filters have been selected to provide multicolor imaging for comparative studies with previous observations of asteroids in the same class as Eros. The eighth filter is broadband and will be used for optical navigation. The Multispectral Imager has a focal length of 168 mm and a 2.93 × 2.25° field of view. The spatial resolution of the instrument is 16.1 × 9.5 m at a range of 100 km. An overview of the instrument is presented, and design parameters and tradeoffs are discussed in the context of the fast-paced, low-cost Discovery Program.
(Keywords: Imager, MSI, Multispectral Imager, NEAR.)

INTRODUCTION

NASA's Discovery Program has set a new standard in the exploration of space. The initiative is for small planetary spacecraft to be developed in under 36 months and to cost less than $150 million, which includes all development costs, construction of the spacecraft, and 30 days of postlaunch operations. The Near Earth Asteroid Rendezvous (NEAR) mission succeeded in all these areas: the spacecraft was developed in 27 months, it was launched on time, and the final cost was significantly below budget.

With the liftoff of the Delta II rocket carrying the NEAR spacecraft,[1] on 17 February 1996, a milestone was achieved in the NASA Discovery Program: the first launch. The primary mission[2] of NEAR, to begin in February 1999, is to study one of the largest (14 × 14 × 40 km) near-Earth asteroids, 433 Eros. En route to Eros, the trajectory of NEAR will provide a flyby and permit imaging of another asteroid, the very large main-belt, type-C asteroid 253 Mathilde,[3] using one of the primary instruments from the spacecraft's scientific payload: the Multispectral Imager (MSI).

The MSI was designed to measure the size, shape, and rotation of Eros. It will be used to map the asteroid's surface morphology at small scales, measure the spectral properties of the surface, and search for natural satellites of Eros. The image data from MSI will be used in conjunction with the Near-Infrared Spectrometer and X-Ray/Gamma-Ray Spectrometer to characterize Eros's mineralogic and elemental composition.

Critical to the success of the primary mission is the period just before the rendezvous phase of the program. Fine adjustments must be made to the spacecraft's trajectory to successfully intercept the gravitational sphere of influence of the asteroid. Optical navigation images will be acquired by the MSI during this critical phase of the mission.

The low-cost, fast development initiative of the Discovery Program put constraints on the schedule and development of the spacecraft. The NEAR instruments were designed, fabricated, assembled, tested, and calibrated within 20 months. Fundamental to the success of NEAR was the development of instruments based on proven flight designs. By adapting existing designs and concentrating on and improving the important features, we reduced the development cost and risk. This article gives a brief overview of the MSI in the context of the low-cost, fast-paced schedule of the Discovery initiative.

INSTRUMENTATION

The MSI consists of two main mechanical subassemblies: a camera head and a data processing unit (DPU). These assemblies are physically separated by about 10 cm and are mounted on the aft deck of the spacecraft. Each subassembly was developed and tested independently, with the flight units integrated and tested just before delivery to the spacecraft. A functional block diagram of the MSI is given in Fig. 1, identifying the major system components and interfaces to the spacecraft.

Camera Head

Figure 2 shows a photograph of the MSI camera head with key components identified. A protective cover on the light baffle assembly protects the first optic from contamination during launch and the initial phases of the mission. A reduced aperture viewport in the cover permits flight operations to continue with the cover closed. The full field of view (FOV) is still available even when imaging through the viewport, although the collecting area is reduced from 18.60 to 4.35 cm^2. The cover may be opened by firing a wire-cutters type pyrotechnic device. Once the beryllium–copper wire latching the cover closed is cut, two stiff springs force the cover to swing open approximately 135° until it strikes a stop mounted on the deck.

The camera head weighs 3.7 kg and occupies an envelope of 42.7 × 20.5 × 17.1 cm. Functionally and mechanically, the sensor may be divided into three constituent parts: the telescope optics, the filter wheel

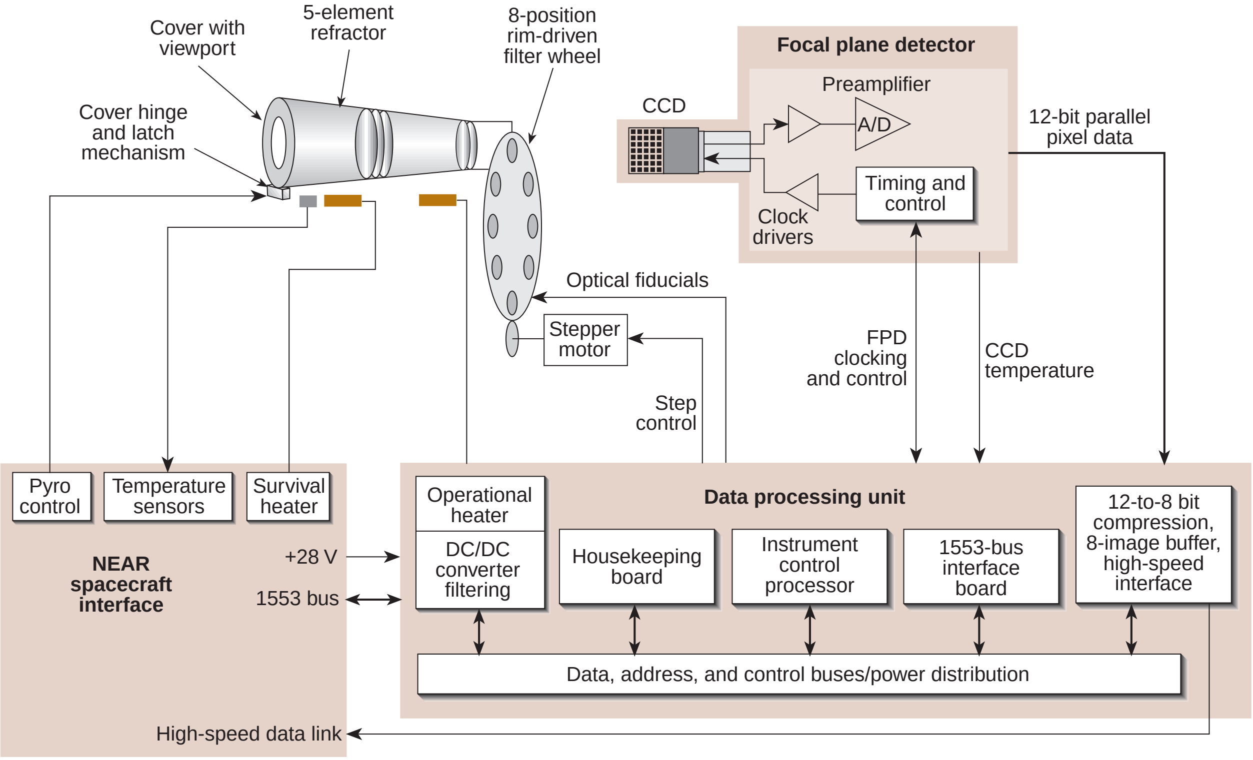

Figure 1. Functional block diagram of the NEAR MSI instrument, which consists of two subassemblies: a camera head and a DPU (A/D = analog-to-digital converter.)

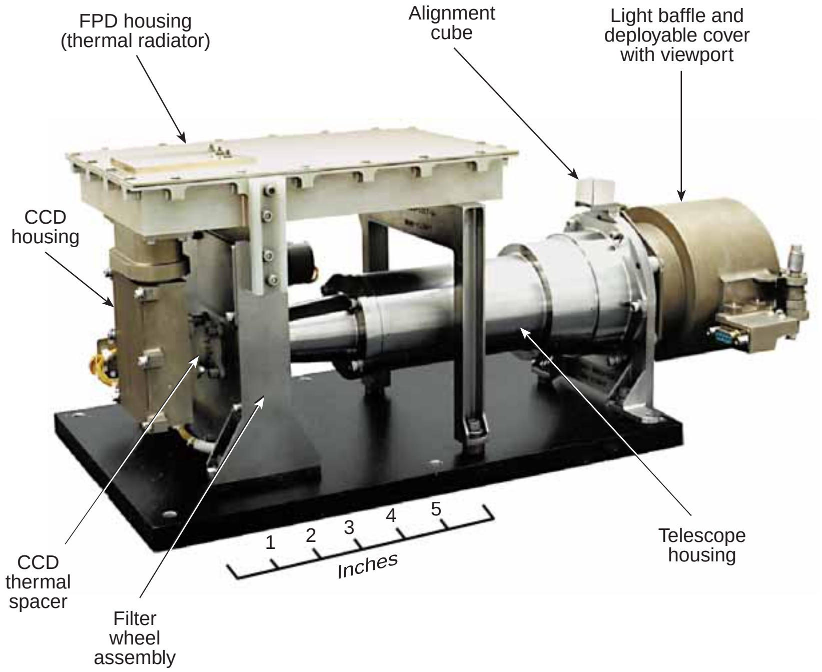

Figure 2. Photograph of the MSI camera head.

assembly, and the focal plane detector (FPD). The camera head is thermally isolated from the spacecraft, and the charged-coupled device (CCD) detector is passively cooled. Table 1 summarizes the primary characteristics of this assembly.

Telescope Optics

Based on the science requirements, the optical design was specified to have an FOV of 2.93 × 2.25° with a resolution limited by the CCD. In an effort to minimize the overall mass of the instrument, a compact design was desired. A refractive optical design was selected for the MSI telescope and was based partially on the Wide-Field Visible Imager from the Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI)[4] experiment on the Midcourse Space Experiment (MSX) spacecraft.[5] The refractive design was selected over a bulky, three-mirror reflective design primarily because of the requirement for a large FOV with high resolution.

As a design goal, an infinitely distant point source was to subtend less than 100 μrad across a 2.93 × 2.25° FOV. This FOV is mapped onto the 537 × 244 pixels of the flat CCD solid-state detector. The physical dimensions of a pixel are 16 × 27 μm (i.e., 95 × 161 μrad per pixel). The design of an *f*/3.44 telescope coupled with the relatively small pixel size resulted in the depth of focus of the system being ≈20 μm. This small tolerance became the driver for the choice of materials of the telescope, filter wheel, and thermal spacer to the CCD.

Each element of the five-element refractor was ground from radiation-hardened glass, even though the total dose level for the mission is expected to be less than 3 krd. (The NEAR mission takes place early in the rise of Solar Cycle 23.) The titanium telescope interior surface is black and the optics are held fast with threaded retaining rings bonded in place. Assembly of the telescope took place in a Class 100 clean room, and the optical components were cleaned until the surfaces were visually free of particulates. This goal of keeping surface particulate contamination to a minimum was set to achieve the best possible point source rejection ratio (PSRR).

Figure 3 shows the PSRR measured during the MSI ground-based calibration in the Space Department's Optical Calibration Facility (OCF). These measurements were acquired through the 700-nm (broadband) filter, at various

Table 1. MSI specifications.

Parameter	Measurement
FOV	2.93 × 2.25°
Spectral range	≈400–1100 nm
Refractive optics	5 elements
Focal length	167.35 mm
Clear aperture (no cover)	18.60 cm^2
Clear aperture (with cover)	4.35 cm^2
Frame size	537 × 244 pixels
Frame rate	1 Hz
Frames size (no compression)	1.6 Mb
Quantization	12 bits
Exposure control	1–999 ms
Filter wheel	8 position
Broadband	700 nm
Green	550 nm
Blue	450 nm
Red	760 nm
IR1	950 nm
IR2	900 nm
IR3	1000 nm
IR4	1050 nm

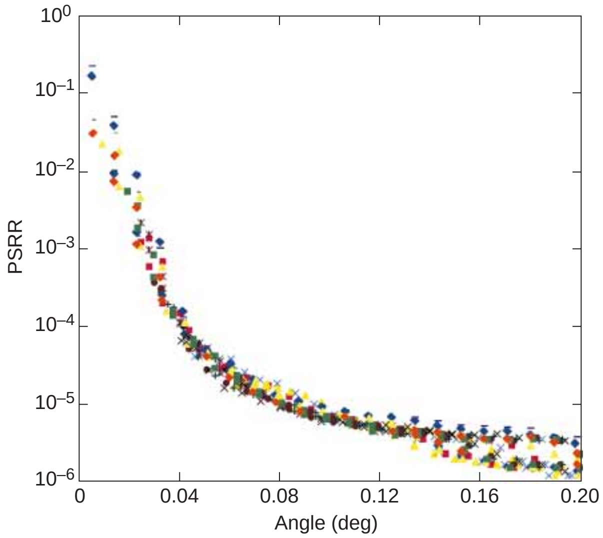

Figure 3. The PSRR measured under worst-case conditions during ground-based calibration of the MSI.

exposures, with the MSI protective cover in place and under operating conditions. Because these measurements were taken through the MSI's cover viewport, one expects additional scatter from the window and cover, and these conditions should represent the worst-case scatter measurements. The data shown in this figure suggest that the signal due to scatter in the pixel adjacent to the peak is down to about a percent, and the signal about 0.15° away from the peak is already well below the digitization limit. This wide dynamic range was measured through the use of neutral density filters. The PSRR shown is consistent with the design goals and demonstrates that the painstaking effort of keeping the optics clean is directly proportional to the instrument's scatter rejection performance.

Direct sunlight or spacecraft glint into the optical system aperture is not a major concern for the MSI because of the imager's location on the spacecraft. The solar panels and instrument deck provide most of the glint protection. In addition, the MSI includes a light baffle assembly that was designed to minimize any residual stray light.

Filter Wheel Assembly

The filter wheel assembly contains a rim-driven aluminum gear, eight spectral filters, and four optical switches to provide wheel positions. The titanium housing serves as the primary support structure of the camera head. A stepper motor drives the wheel rim, which can be turned to any adjacent filter position within 1 frame period (1 s) or to any position within 3 frames.

Eight bandpass filters permit color imaging over the ≈400–1100 nm sensitive range of the silicon detector. These filters all have very high transmissivities, as shown in Fig. 4. To keep the size and weight of the filter wheel and the filters themselves to a minimum, the filters were placed in the converging beam in front of the detector.

The desired resolution for the MSI proved difficult to achieve over the very broad spectral range of the CCD because of the limited selection of radiation-tolerant glasses available; however, this problem was overcome in a unique way. The optical thickness of each filter was carefully specified, and very tight tolerances were placed on the manufacturer of the filters to eliminate most of the residual chromatic aberration. This demand on the filter manufacturer was the most critical tolerance of all the optical components, because the optical thickness tolerance of the filters was required to be less than the imager's depth of focus (≈20 μm).

Seven of the eight filters were chosen primarily to discriminate between the various iron-containing silicates and metals common to type-S asteroids. One broadband filter (700 ± 100 nm) was selected for low-light imaging and optical navigation.

The telescope and filter wheel housings are thermally isolated from the spacecraft deck. An epoxy-glass thermal spacer (see Fig. 2) is used to support the CCD housing and maintain the large thermal gradient (an interval of ≈50°) between the CCD housing and the filter wheel assembly. Because of the very small depth of focus tolerance, the material selected for this

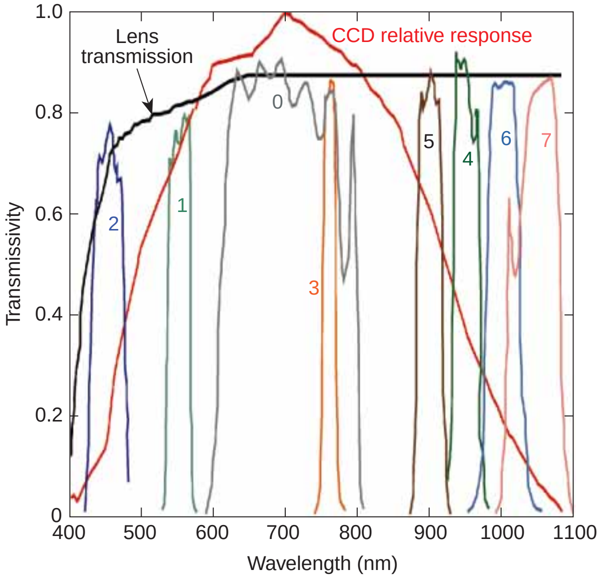

Figure 4. Manufacturer's transmission efficiency of the MSI optics. The response of the CCD as a function of wavelength is also shown. Numbers in the figure correspond to the coded filters in the camera, as follows: 0 = broadband, 1 = green, 2 = blue, 3 = red, 4 = IR1, 5 = IR2, 6 = IR3, 7 = IR4.

spacer was also required to have a very low coefficient of thermal expansion and low thermal conductivity. The epoxy-glass thermal spacer satisfied these requirements. It permitted assembly and testing of the imager at room temperature, because the instrument remained in focus when the CCD was warm as well as when the CCD was at its baseline operating temperature of −30°C.

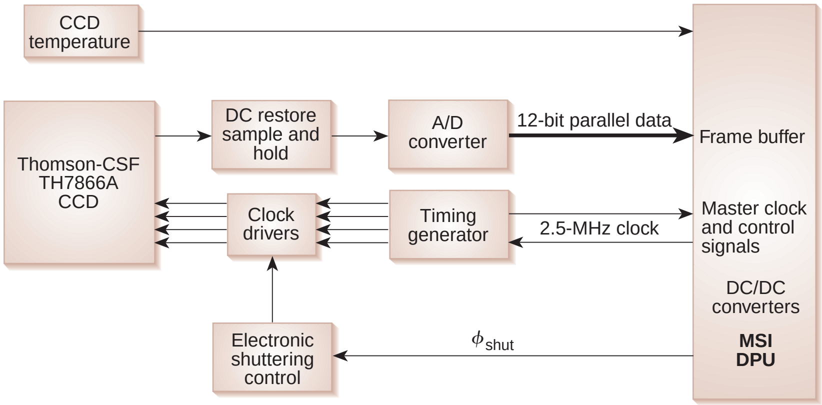

Figure 5. Detector electronics block diagram for the MSI FPD.

Focal Plane Detector

To meet the development schedule of the MSI and minimize the reliability risk, the camera electronics in the FPD were largely based on the design of the MSX UVISI focal plane unit (FPU) detector electronics. An FPU is the photon counting detector assembly in each of the nine sensors, which together make up the suite of sensors defining UVISI. These sensors use image intensified technology.

The UVISI FPU design was adapted and simplified by eliminating the high-voltage power supply, image intensifier, fiber-optic taper, and fiber-optic window on the CCD. The Thomson-CSF TH7866 CCD, chosen for the UVISI design, was retained for the MSI, but in the UVISI imager designs, adjacent pixels were summed to form nearly square pixels in an array of 256 × 244 elements. The decision not to sum adjacent pixels was made to provide an additional factor of 2 in resolution.

The MSI FPD contains the electronics needed to control the CCD and digitize its output. The electronics housing is a simple box-like construction that holds a single, 4-layered printed circuit board. Silver–Teflon tape on the FPD cover enhances its emissivity, enabling it to serve as a radiator, passively cooling the CCD. The CCD housing is loosely coupled mechanically to the electronics housing. An electromagnetic interference gasket serves as the interface between the aluminum electronics housing and the magnesium CCD housing. The CCD is mounted on its own rigid-flex printed circuit board, eliminating the need for a bulky internal harness from the CCD to the camera electronics board. The rigid-flex design provided 2 degrees of freedom for positioning the CCD during the determination of best focus.

Figure 5 shows a block diagram of the FPD electronics. The camera electronics require a variety of voltages that are internally regulated. The FPD electronics only receive +15 V and −12 V from the power converters within the DPU. Signal ground is tied to chassis ground at the camera head.

The detector is a space-quality grade, Thomson-CSF TH7866A CCD. The silicon solid-state detector is protected by a quartz window with an antireflective coating. The CCD is a four-phase, frame transfer device with 244 × 550 pixels (of which the MSI only uses 244 × 537 pixels to maximize the efficiency in which images are stored in the image buffer). Antiblooming control prevents a saturated pixel from spilling into adjacent pixels.

The CCD operates essentially in three modes: integration, frame transfer, and readout. The active or image zone of the device serves as the focal plane. Bias voltages applied to each pixel create potential wells in which charges become trapped. At the end of the desired exposure time, the entire image of accumulated charges is quickly transferred from the image zone to a region covered by an opaque aluminum mask, referred to as the memory zone. The image is read out of the memory zone serially, and each pixel is digitized to 12 bits. The conversion of the analog signal to a digital one limits the MSI throughput; digitization of an entire image requires 904.2 ms and is the limiting factor in the 1-Hz fixed frame rate.

The time required to transfer the image from the active image zone to the memory zone is 0.895 ms. This may be compared with the nominal integration times of 10–999 ms. Because the MSI does not have a mechanical shutter, integration times comparable to the frame transfer time will have an additional signal contribution as a result of signal charge accumulated during the transfer period. Recent image processing algorithms remove this smear extremely effectively. It is therefore possible to use exposures as short as 1 ms.

A correlated double-sample circuit enables an accurate measure of the signal charge in each pixel by reducing noise induced by the reset signal on the chip. Each pixel is then digitized to 12 bits in the FPD, and each 12-bit pixel is transferred to the DPU in parallel for storage in a memory buffer. With this digitization, each least-significant bit corresponds to about 60 electrons, thus defining a maximum signal level of about 250,000 electrons.

Data Processing Unit

The MSI DPU is the interface between the spacecraft and the camera head. The DPU houses all the instrument's power converters, filter wheel control electronics, and master clocks and provides the digital interface to the FPD of the camera head. A magnesium chassis measuring 20.5 × 18.4 × 19.7 cm houses the DPU electronics; the DPU weighs 3.67 kg.

Each NEAR instrument communicates with the spacecraft and receives power through a DPU. A common design was implemented for the DPUs, and instrument-specific boards were developed to meet the unique requirements of each sensor. Each instrument's DPU communicates between its instrument and the two redundant command and telemetry processors (CTPs) via a MIL-STD-1553 bus (one for each CTP). Specific features of the MSI DPU include an eight-image buffer, filter wheel drive electronics, and a 2-Mb/s high-speed serial link, which provides a direct path to store the image data onto one of the two redundant solid-state recorders.

All of the DPUs contain an RTX2010 processor with all flight code programmed in the FORTH language. Provisions are made in the MSI software to implement both lossy and lossless compression routines. The necessary compression tables (up to seven) are initialized at power-up and may also be uploaded from the ground. Common aspects of the DPU software were shared, just as with the hardware design. Such parallel efforts in hardware and software significantly reduced the development time for the complement of instruments making up the science payload.

DEVELOPMENT UNDER PROGRAM CONSTRAINTS

As described previously, the development schedule was driven by the constraints imposed by the NEAR Program. In the design, development, and testing of the MSI, every effort was made to satisfy all the instrument science objectives, yet still deliver the instrument to the spacecraft within 20 months.

Design Heritage

The overall philosophy of the NEAR instrument designs was to develop the most reliable hardware and software possible, within the guidelines of the Discovery initiative. By adapting existing designs or tailoring a new design to use a previously qualified component, we were able to devote more time to other aspects of the design process, such as instrument performance and calibration.

Development of the MSI was significantly influenced by a number of existing mechanical, optical, and electrical designs. The wire-cutters pyro assembly used in the MSI cover latch mechanism was based on the Ulysses HI-SCALE instrument. The UVISI Wide-Field Visible Imager and the FPU also served as major building blocks in the MSI design. Although the MSI filter wheel assembly was a new design, the stepper motor used in this assembly is the type selected and extensively tested in the Energetic Particle and Ion Composition instrument on Geotail and in the Ultra Low Energy Isotope Spectrometer experiment on the Advanced Composition Explorer spacecraft.

Design heritage played a key role in the success of the MSI. To streamline costs and schedule, the MSI team adapted proven designs, flight hardware, and test equipment from previous missions. Care was taken in the design of the FPD to keep the interface to the MSI DPU as similar as possible to the interface of the UVISI FPU. This permitted the use of an existing rack of ground support equipment, vital to the successful testing and calibration of the flight instrument. The use of existing, reliable ground support equipment to test the flight hardware was probably the single most important factor that enabled the instrument team to meet the tight schedule of the NEAR program.

Focus Determination and Performance

Critical to the performance of the instrument was the accurate determination of best focus for the MSI; focus was also one of the most challenging aspects of the mechanical and optical design. Because of the tiny depth of focus ($\approx$20 μm) and the inherent mechanical uncertainties, best focus was determined empirically using a point source imaged around a 1° circle, centered at the instrument's boresight.

The final focus measurements were made in the OCF shown in Fig. 6. The OCF consists of several large, linked vacuum systems. The largest of these holds the instrument under test, which mounts on a two-axis motion stage. In one orientation, the instrument looks into an off-axis parabolic collimating mirror through a long narrow beam tube. Illumination sources placed at the focus of the collimator, outside the vacuum chamber, will be imaged at infinity by the instrument.

We significantly reduced the time required to determine best focus of the instrument by minimizing the number of iterations required to pump the system down and cool the instrument to its operating temperatures. The CCD is fixed-mounted to the detector housing by four precision standoffs. Because of the

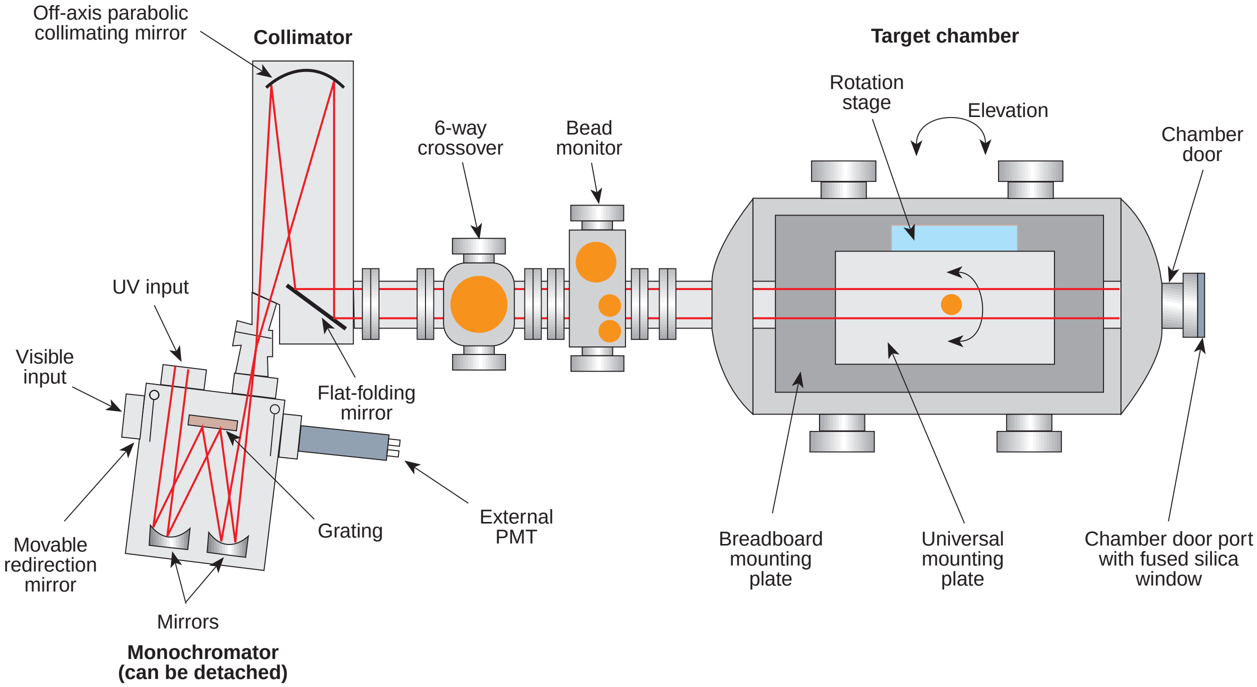

Figure 6. The Space Department's Optical Calibration Facility.

≈20-μm depth of focus, these mechanical assemblies had to be made at the limit of the machine tolerance and, therefore, had to be specified quite accurately.

Rather than using an iterative method, where the precision focus spacers were modified after each focus measurement, we started from a set of spacers made from focus measurements performed at room temperature. Once the MSI was mounted in the OCF and the chamber was evacuated and cooled, a precision micrometer was used to move a target of varying sized pinholes in the vicinity of the focus of the collimating mirror. A source behind the pinholes allowed the MSI to image the pinhole targets, in and out of focus, without ever moving the camera. Because the longitudinal magnification of an optical system is proportional to the square of the lateral or transverse magnification, this method of varying the position of the pinholes resulted in a very accurate determination of the camera's best focus. The demagnification of the collimator is ≈0.01, so by moving the pinhole source in small (≈2 mm) steps, the focal plane at the instrument moved in increments comparable to the MSI depth of focus (≈20 μm).

The resulting spot size for all filters, except the blue one, resulted in ≈50% of the energy falling within a single pixel. The green filter proved to have the best focus with as much as 60% of the measured energy falling on a single pixel. The blue filter's performance showed the spot spreading over 2 to 3 pixels, which is consistent with the predicted response from optical ray tracing.

Flat field measurements made in the MSI ground-based calibration give results that far exceed expectations and the CCD manufacturer's specification (<5% nonuniformity). Preliminary analysis suggests that response uniformity of the MSI images should be correctable to better than 1% with highly reproducible nonuniformities of approximately ≈2%. The overall scattered light rejection is excellent and is comparable to the Solid-State Imager[6] on the Galileo spacecraft, as shown in Fig. 7.

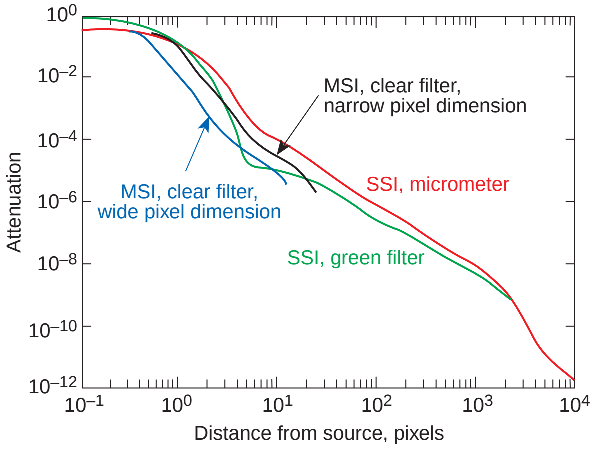

Figure 7. Comparison of the off-axis rejection between the NEAR MSI and the Galileo Solid-State Imager (SSI).

CONCLUSION

In summary, the new paradigm of the NASA Discovery Program of “faster, better, cheaper,” has been demonstrated with the success of NEAR and the MSI. Through the dedicated efforts of the MSI team, all the instrument design objectives were achieved within the cost and time constraints of the program. By adapting and improving already proven flight designs, the most efficient use of resources was made, and, through careful planning, major savings in cost and schedule were realized through the use of existing test equipment. The flexible approach and innovative ideas of the MSI team members will undoubtedly set an example for future missions.

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