# The Spatial Infrared Imaging Telescope III

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The Spatial Infrared Imaging Telescope III (SPIRIT III) is a mid- through long-wave infrared instrumentation package built and managed by the Space Dynamics Laboratory at Utah State University for the Midcourse Space Experiment. SPIRIT III contains a radiometer and an auto-aligning interferometer–spectrometer that share a telescope designed for high off-axis rejection. A solid-hydrogen cryostat, the first of its kind to be used in a space/satellite application, cools the entire sensor system to cryogenic operating temperatures. This hardware will measure the spectral, spatial, temporal, and intensity characteristics of Earth-limb backgrounds, celestial objects, and other upper atmospheric phenomena. Collected data will provide answers to fundamental questions about Department of Defense surveillance systems and supply invaluable information for system planners and designers of future threat detection systems.

## INTRODUCTION

The Spatial Infrared Imaging Telescope III (SPIRIT III) sensor system (Fig. 1) is a mid- through long-wave infrared instrumentation package built, tested, integrated, and managed by the Space Dynamics Laboratory (SDL) at Utah State University. SDL is under contract to the Ballistic Missile Defense Organization to build and support this primary remote sensing system for the Midcourse Space Experiment (MSX). SPIRIT III[1] contains a radiometer and a spectrometer that share a high off-axis rejection baffle and foreoptics telescope assembly. The entire sensor system is cooled to cryogenic operating temperatures by a cryostat containing solid hydrogen with an estimated 15-month on-orbit life span.

SPIRIT III will characterize Earth-limb and celestial backgrounds and measure the spectral, spatial, temporal, and intensity parameters of stars and upper atmospheric phenomena, including airglow and aurora. The sensor system will also characterize the signatures of selected targets operating against natural backgrounds and assist investigators in identification and evaluation of the chemical and physical properties of the upper atmosphere on a global scale. Much of the technology used in SPIRIT III is the legacy of SDL-provided sensor

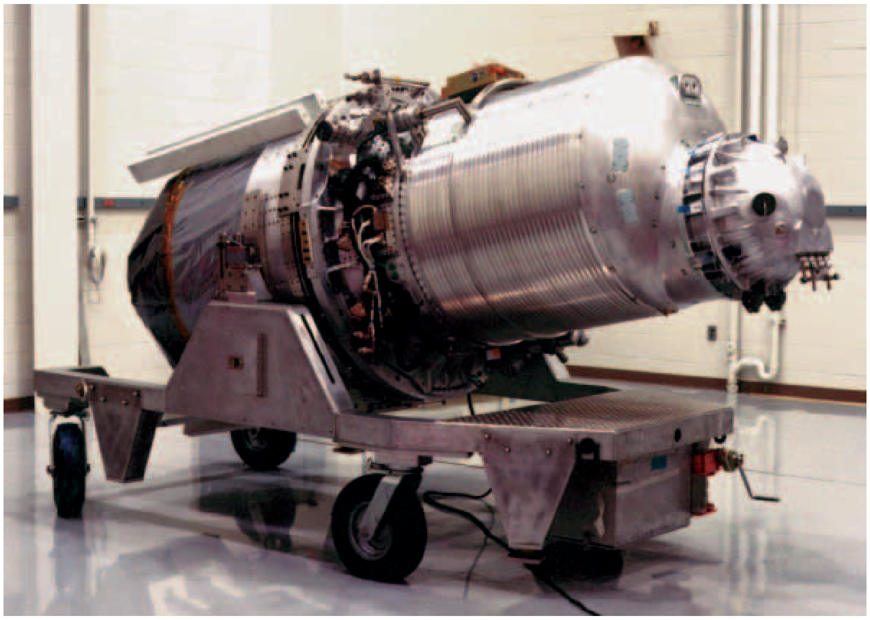

**Figure 1.** SPIRIT III prior to installation in the MSX spacecraft.

systems for similar DoD programs such as SPIRIT I and II, CIRRIS-1A,[2] and Excede I and II.

The SPIRIT III sensor system consists of a high-off-axis-rejection imaging telescope; a six-color, high-spatial-resolution, multispectral radiometer; and a six-channel, high-spectral-resolution Michelson interferometer–spectrometer (Fig. 2). The sensor components are conductively cooled and maintained at operating temperatures via thermal links connecting them to the solid-hydrogen tank of the cryostat subsystem. Power consumption ranges from 50 to 410 W, depending on the mode of operation. Total system weight is approximately 965 kg.

## OPTICS

Integrated with the radiometer and spectrometer subsystems, optical components of the SPIRIT III telescope (Fig. 3) operate at temperatures ranging from 10 to 20 K. Inside the telescope aperture, a series of knife-edge baffles, painted flat black, reject stray light. The baffle assembly operates at temperatures up to 70 K. The afocal foreoptics (M1, M2, M3) are a series of superpolished, gold-coated, nickel-plated aluminum mirrors, including a 36.83-cm-diam. primary collection mirror. A flat reflective mirror (F5) inserted in the optical path extracts a portion of the incoming energy and diverts it to the interferometer–spectrometer. The baffle and foreoptics were provided under contract to SDL by The Sensor Systems Group of Bedford, Massachusetts.

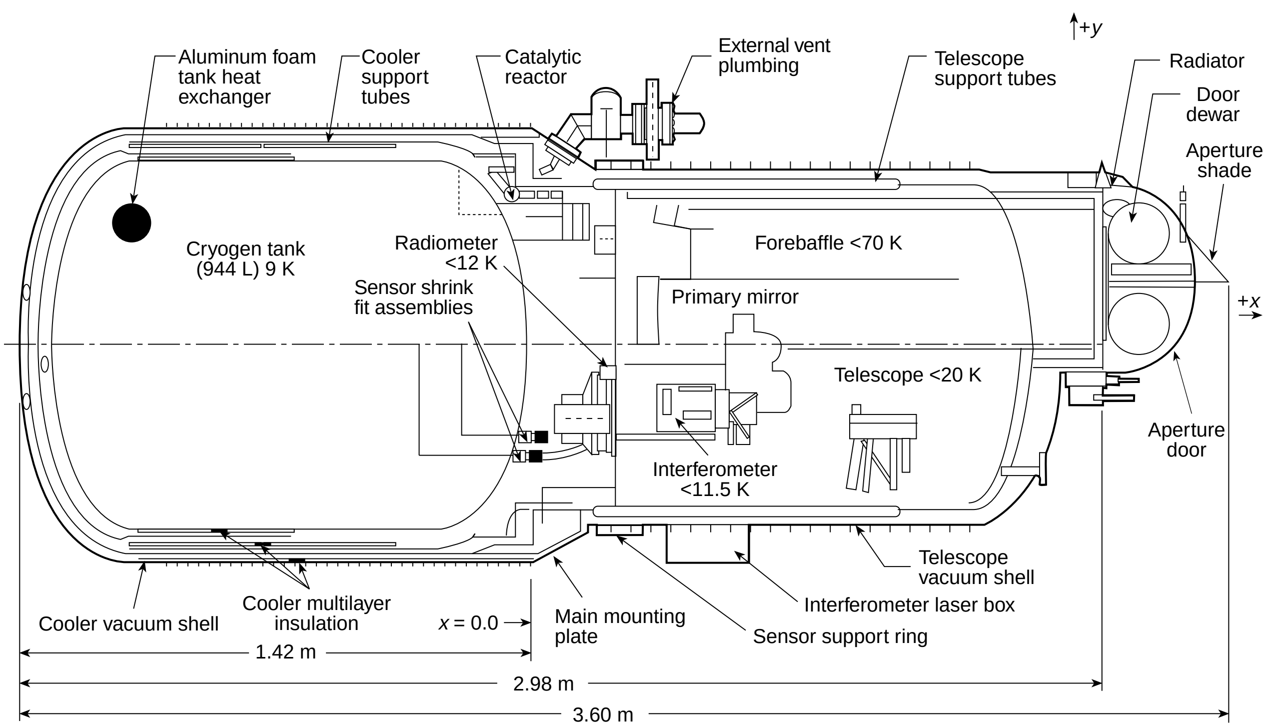


**Figure 2.** SPIRIT III mechanical configuration.

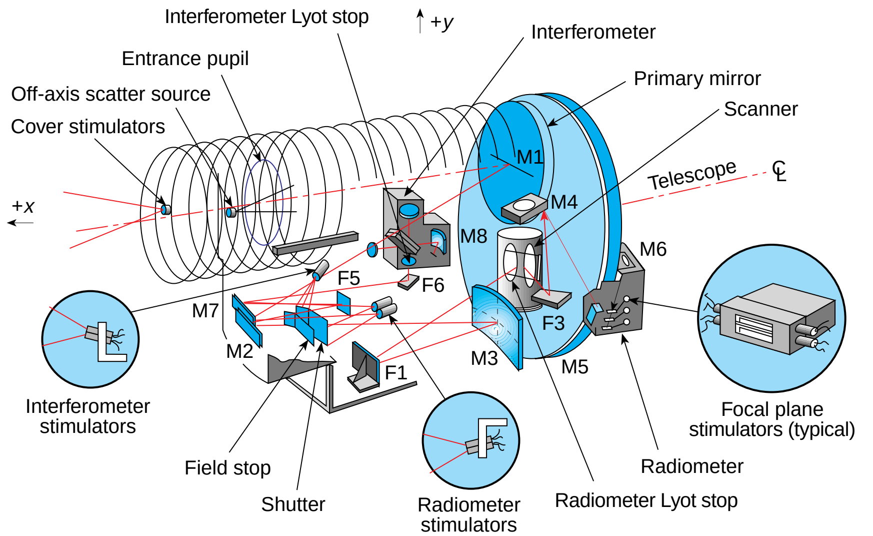


**Figure 3.** SPIRIT III optical layout. M1 through M8 are mirrors, and F1, F3, F5, and F6 are fold flats.

colors. Multilayer interference filters, mounted in the focal plane assemblies, are designed to reject out-of-band radiance while maximizing in-band radiance.

A servo-controlled mirror in the radiometer optical path allows the focal planes to sweep or scan a desired scene in field-of-regard increments of 0.75°, 1.50°, or 3.00° (Fig. 5). The primary mirror drive consists of a rotary actuator motor with an inductive tachometer for control feedback. The secondary or backup drive has an identical drive motor that uses a capacitive tachometer. Both control systems can lock the mirror in the center position for the staring, or fixed-mirror, mode of operation, sometimes referred to as the Earth-limb (EL) mode. In this mode, the spacecraft movement creates the scan motion. The Earth-limb mode uses 5-Mbps telemetry, whereas the mirror scanning (MS) mode uses 25-Mbps telemetry to accommodate the additional information collected.

## RADIOMETER

The SPIRIT III radiometer[3] (Fig. 4) responds to low-level infrared radiation ranging spectrally from 4.2 to 26.0 $\mu$m. Using a total of 3840 detectors in six separate color bands, the radiometer can image a 1 × 3° field of regard with 90-$\mu$rad resolution while maintaining a high signal-to-noise ratio. Two dichroic beamsplitters separate the incident radiance into three spectrally distinct bands. Filters integrated into the focal plane assemblies further separate these bands to obtain six total bands or "colors." The use of dichroic beamsplitters allows simultaneous registration of color bands A, D, E and B, C (defined in Table 1). Band B is divided into two separate

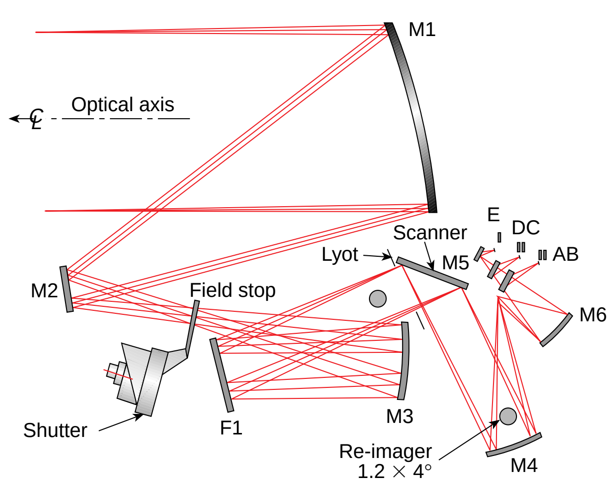


**Figure 4.** SPIRIT III radiometer optical layout and band separation. M1 through M6 are mirrors, F1 is a fold flat, and A through E are color bands defined in Table 1.

The radiometer, with its large array of detectors, can image sources of interest over a broad spectrum and sensitivity range, as summarized in Table 1. Ensquared energy (EE) is a figure of merit for the image quality of an optical system. It is the fraction of energy in the point-spread function derived from a point source contained in one 90-$\mu m^2$ pixel as measured during ground calibration. The noise equivalent radiance differs for each integration time. Integration time is defined as the time required to read out all 192 rows of the array columns. There are three times for the mirror scanning mode: 1, 6, and 27 $\mu$s. For the mirror fixed mode, the times are 0.2, 0.8, 3.4, and 13.8 ms.

This new generation of radiometer shows a dramatic increase in the number of detectors and corresponding data channels in comparison with previous systems. An analog signal processor conditions the output from each pixel before sending it to the telemetry encoder. The output is then available to be formatted for the spacecraft flight recorder or decoded for ground operations.

To allow insight into system operation during all phases of system lifetime, a user friendly and readily accessible diagnostic display has been developed. The SPIRIT III sensor ground support equipment (SGSE), i.e., the ground data collection–radiometer (GDC-R) or the flight data collection–radiometer (FDC-R), displays radiometer performance and general health. Both the GDC-R and FDC-R consist of a SunSparc 370 UNIX workstation connected to a server. A decoder

**Table 1. Radiometer detector characteristics.**

| Band | EE (%) | Mfr. | Wavelength ($\mu$m) | Noise equivalent radiance for MS1 mode ($W \cdot cm^{-2} \cdot sr^{-1}$) |
|---|---|---|---|---|
| A | 69 | RI | 6.03–10.91 | $1.4 \times 10^{-10}$ |
| B1 | 57 | RI | 4.22–4.36 | $1.6 \times 10^{-9}$ |
| B2 | 57 | RI | 4.24–4.46 | $1.6 \times 10^{-9}$ |
| C | 60 | AES | 11.10–13.24 | $8.6 \times 10^{-10}$ |
| D | 62 | AES | 13.50–15.90 | $2.7 \times 10^{-10}$ |
| E | 56 | AES | 18.30–25.00 | $7.1 \times 10^{-10}$ |

Note: EE = ensquared energy, Mfr. = Manufacturer, RI = Rockwell International, and AES = Aerojet Electro-Systems. Values are approximate and were derived from engineering measurements. Final numbers that will be used to certify data will come from on-orbit measurements.

accesses data separated from the main MSX telemetry stream at the APL ground station. The GDC or FDC software then allows each of the radiometer columns to be displayed in a separate window.

Windows for all focal plane columns can be displayed on one screen. The amount of black in the window indicates the number of counts recognized on each row of the 2–8 column × 192 row detector array. Counts can be set to a linear or logarithmic scale and increase as the black bars move vertically.

Internal lamp sources are sequenced on and off to stimulate the individual detector arrays. This procedure provides an end-to-end system check that can provide a baseline for each experimental data set. A standard data-collection-event bracketing sequence, as defined by the Data Certification and Technology Transfer Committee, provides information on radiometer responsivity, dark noise, and dark offsets. The FDC-R displays the detector array output shown in Fig. 6.

## SPECTROMETER

The Fourier transform interferometer–spectrometer[3] (Fig. 7) provides sensitive spectral measurements over a wide dynamic range and has the advantage of multiplexing all of the wavelengths in its spectral range of 2.5 to 28.0 $\mu$m. It is a Michelson-type design with six arsenic-doped silicon detectors for measuring the spectral radiance of extended sources. The detectors have non-overlapping fields of view and use spectral filters to select bands of particular interest and reduce out-of-band aliasing. The mirror, movable at a constant 0.25 cm/s and suspended by flexible pivots, achieves translational accuracy of 1–2 arcsec in the three available scan modes: long, medium, and short. In each mode, the scan is symmetrical about the

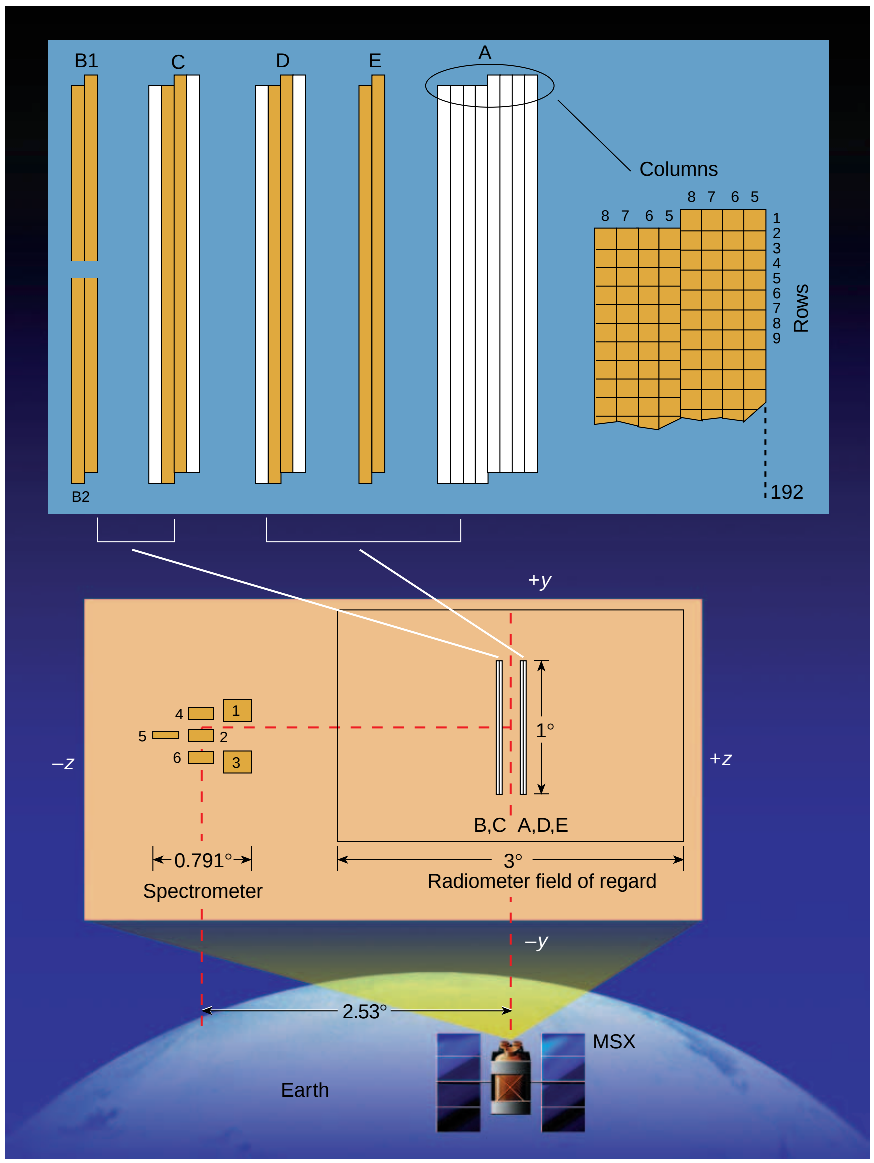


**Figure 5.** SPIRIT III focal plane arrays as projected into object space. A through E are color bands defined in Table 1.

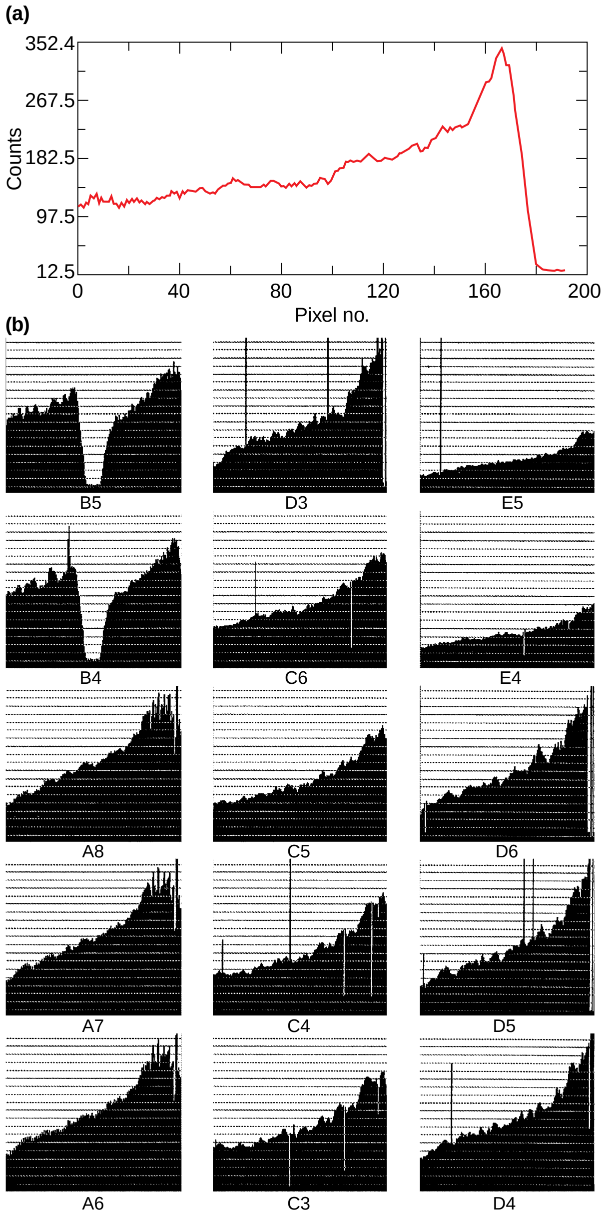


**Figure 6.** (a) Mean pixel count for color band A, column 1 ($\mu$ = 162.58). (b) The sensor ground support equipment display of some active radiometer array columns. The gradient observed is due to the source, not detector responsivity.

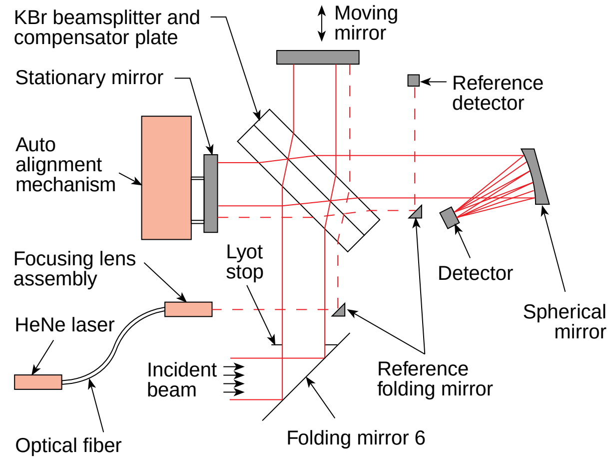


**Figure 7.** SPIRIT III interferometer–spectrometer layout.

zero-path-difference position, and nominal scan lengths are 0.06, 0.28, and 0.53 cm, respectively. These scan lengths give nominal spectral resolutions of 16.0, 3.6, and 1.9 cm$^{-1}$ (full width, first zero crossing, and unapodized), respectively.

During spectrometer operation, a collimated incident beam strikes the potassium bromide beamsplitter, where it is divided into two beams. The first of these is directed toward a stationary mirror along one arm of the interferometer. The second is directed toward a moving mirror along the other arm. These beams reflect off their respective mirrors and are recombined at the beamsplitter and directed toward the detectors. The combination of all wavelengths arriving at the detectors in their respective phases creates an optical interference pattern. A detector converts the optical pattern to an electronic signal known as an interferogram.

To accurately sample the interferogram for the digitization and Fourier transform process, a reference signal must be generated. This signal is provided by sending a single-frequency light source through the same optical path as the incident scene, where it will generate a sine wave that is a function of the position of the moving mirror and can serve as the sample trigger for the data acquisition system. The light source is derived from one of two independent external laser beams, i.e., the primary laser or the backup laser, both of which are standard HeNe gas lasers operating at 0.6328 $\mu$m. At every fourth zero crossing of this laser-generated sine wave, the analog-to-digital converter on channels 1, 3, and 5 is triggered to read the detector output. At every second zero crossing of the laser-generated sine wave, the analog-to-digital converter on channels 2, 4, and 6 is triggered to sample the detector output. In the unlikely event that both primary and backup lasers fail, a clock oscillator can be used to obtain data of a reduced spectral resolution.

The fixed mirror is manually adjustable to achieve the critical optical alignment necessary for this instrument to function properly. Interferometers are normally considered a laboratory type of spectrometer because of their sensitivity to proper alignment. SDL developed an automatic alignment system to detect and correct misalignments that may occur during ground handling and launch operations.

The SPIRIT III interferometer–spectrometer focal plane consists of six detector elements (Fig. 8) physically separated on individual substrates with no

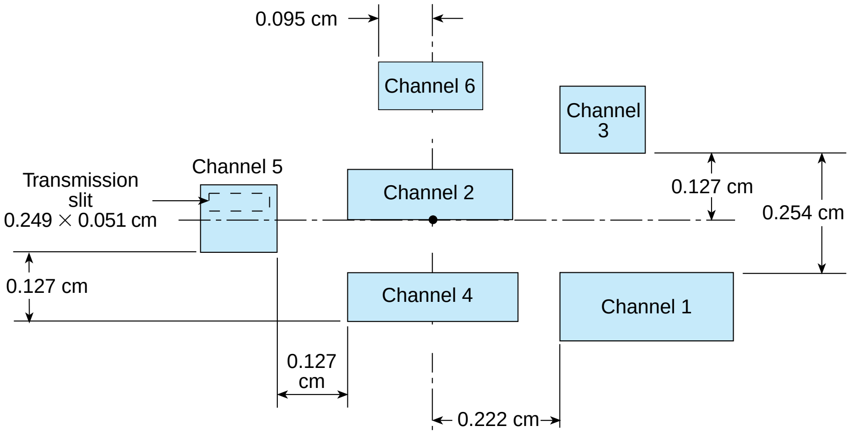


**Figure 8.** SPIRIT III interferometer–spectrometer detector layout. (See Fig. 9 for channel wavelengths.)

overlapping fields of view. The detectors are similar to the radiometer detectors in composition but are significantly larger. They are arsenic-doped silicon, blocked-impurity-band conductor detectors with spectral responsivity ranging from 2.5 to 28.0 $\mu$m. The focal plane arrays were provided by Rockwell International under contract to SDL.

As with the radiometer, the primary tool for tracking and trending the spectrometer sensor performance is a set of standard sequences. The sequences turn on internal emission sources that provide detector stimulation for an end-to-end system check. A typical sequence, such as the data collection event bracketing sequence, provides a standard set of repeatable information on sensor system dark noise and spectral response. Interferometer support equipment, known as FDC-I, displays the output.

FDC-I presents six graphical displays to the operator, one for each of the interferometer channels. Each display contains the interferogram created by energy from the stimulator, as well as the spectrum resulting from the fast Fourier transform calculation performed on that interferogram. Figure 9 shows the six available channels, where channel 6 is the full spectral window. A notch filter (pre-white) attenuates the effects of strong

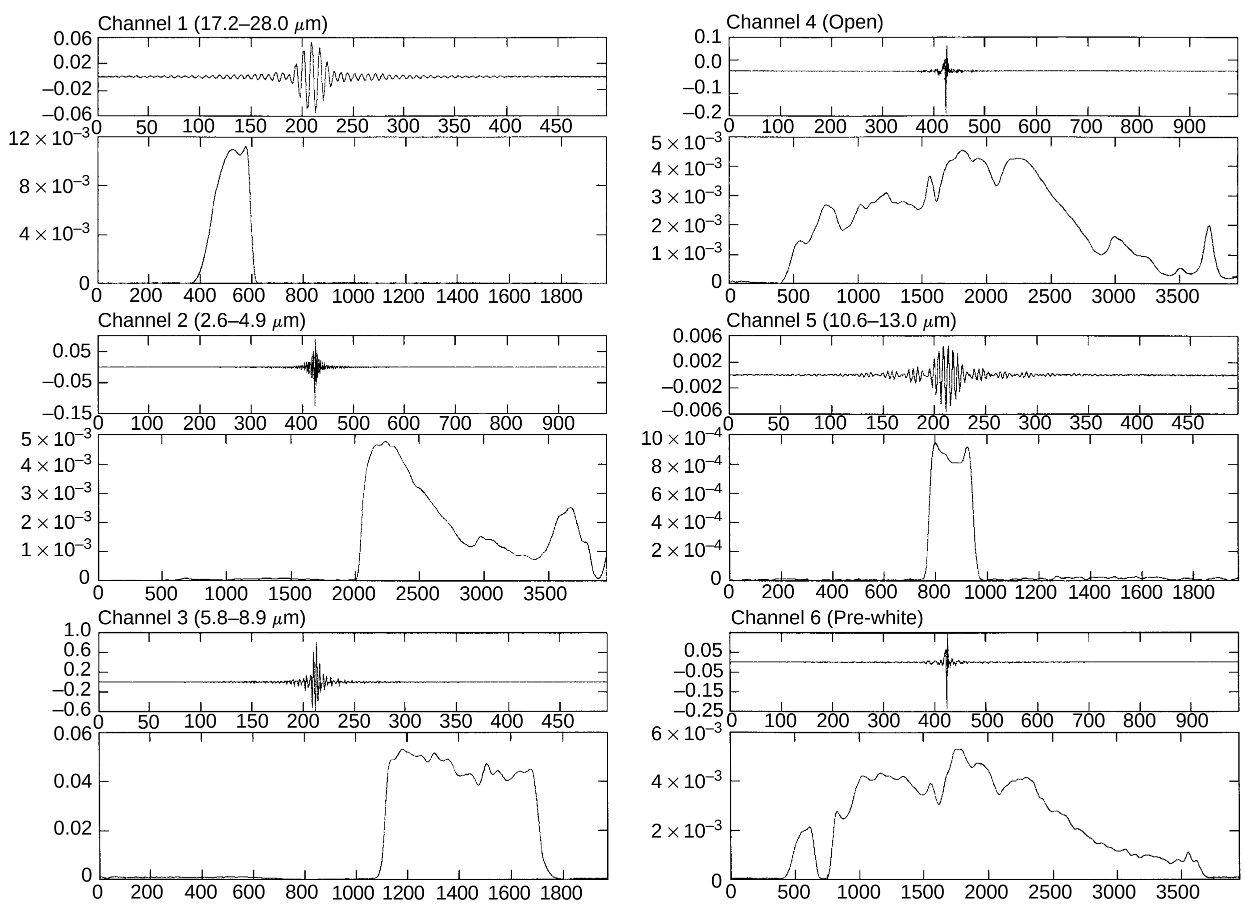


**Figure 9.** Display output from spectrometer ground support equipment. The *x* axis is the sample number for the interferograms (smaller plots) and the wavenumber (cm$^{-1}$) for the spectral plots. The *y* axis is the voltage for the interferograms and the relative amplitude for the spectral plots.

$CO_2$ emissions near 15 μm, a technique developed and proved during the CIRRIS-1A program. Channel 3 displays the spectrum resulting from the use of a medium-bandwidth 5.8- to 8.9-μm filter. Channel 5 illustrates the expanding interferogram resulting as the filter gets narrower in bandwidth, approaching that of a line source or single frequency.

## CRYOSTAT

A cryostat subsystem provided by Lockheed-Martin of Palo Alto, California, under contract to SDL, maintains SPIRIT III at cryogenic operating temperatures and is the first cooler to use solid hydrogen as a cryogen in a space application. It has a capacity of 944 L of hydrogen, frozen within a 1.7% dense aluminum foam structure that acts as the heat conductor between the hydrogen and the tank walls. The hydrogen is solidified in place during the fill process by circulating liquid helium through cooling coils surrounding the cryostat tank. This process takes place just prior to installation of the MSX spacecraft on the Delta II launch vehicle.

Because of the numerous safety hazards posed by hydrogen processing, liquid helium is used as the cryogen during all ground operations leading up to the final filling of SPIRIT III with cryogen at the Astrotech payload processing facility located near the Vandenberg Air Force Base launch pad. Because liquid helium is colder than hydrogen, some of the sensor components must be heated, regulated, and monitored with an external set of support equipment to simulate the hydrogen environment.

A gold-plated aperture sunshade is attached to the front end of the cryostat and telescope assembly. It extends approximately 62 cm beyond the vacuum shell, rejecting out-of-field radiation from the aperture, reducing baffle temperature, and extending cryogen life. The exterior of the cryostat is coated with a silicon-based white paint, as opposed to thermal blanketing, to maintain the shell as cold as possible and minimize parasitic heat loss. External temperatures are monitored by thermocouples whose output is routed through the MSX telemetry system.

Internal monitors supply information on temperature via SPIRIT III 16-kilobyte housekeeping telemetry but only when SPIRIT III is powered. A small, independent, solid-argon cryogen subsystem is contained within the telescope aperture cover to maintain the inner surface of the cover near 90 K. Maintaining the temperature of the internal surface is critical to prevent contaminants from depositing on the sensitive optics just inside the cover. While SPIRIT III is on the ground, automated readouts of temperature are available to operators. In a flight configuration, no wires cross the mechanical interface, so the temperature of this cryogenic subsystem must be measured radiometrically with the radiometer. The cover is nominally ejected after MSX achieves orbit and the external contamination levels reach acceptable limits.

## ANCILLARY SUBSYSTEMS

The main SPIRIT III sensor subsystems are augmented by a variety of ancillary or diagnostic components, including an autocollimator with 5-μrad accuracy that can measure telescope alignment with respect to the optical bench of the spacecraft attitude control system; a cryogenic quartz crystal microbalance for use in monitoring internal optical contamination; and the Onboard Signal and Data Processor for performing real-time signal/data processing in a space environment to identify and track objects and provide their trajectories.

A total of 15 internal stimulation sources provide health and status information on instrument performance, as well as a transfer of calibration information from the ground calibration chamber. The sources are incandescent bulbs emitting between 0.5 and 3.0 mm. Ten bulbs are located on the radiometer focal plane assemblies—two per module. They stimulate the focal planes directly; none of their radiation passes through any optics or filters. Two more bulbs, primarily used for the radiometer, are the main broadband blackbody and the backup broadband blackbody, referred to as dual broadband blackbody when operated together. They direct energy from the back surface of the shutter into the radiometer. Two shortwave spectrometer stimulation sources, main and backup, reflect light from the shutter into the spectrometer subsystem. Another stimulator source is located near the front of the baffle and reflects light off the cover, through the entire optical path, and into both the radiometer and spectrometer. This stimulator is useful during ground operations and the first few days on-orbit, but it is useless once the cover is ejected.

The electronic output of both the radiometer and the interferometer–spectrometer is processed through a digital telemetry encoder (Fig. 10). It is then routed through the MSX telemetry system to onboard tape recorders. SPIRIT III data are transmitted to the ground stations in three ways:

1. The 25- and 5-Mbps X band transmits all raw, time-reversed digital data (level 0) from the tape recorder.
2. The 1-Mbps S band transmits compressed images from selected radiometer array columns. In staring mode, 16 of 20 active columns are compressed and transmitted: all 8 columns of A and the 2 central columns of each of the other bands. In the scanning mode, 8 of the 20 active columns are compressed (9.91:1 ratio) and transmitted: the 2 central columns of A, C, and D, and the left columns of B and E. Any spectrometer

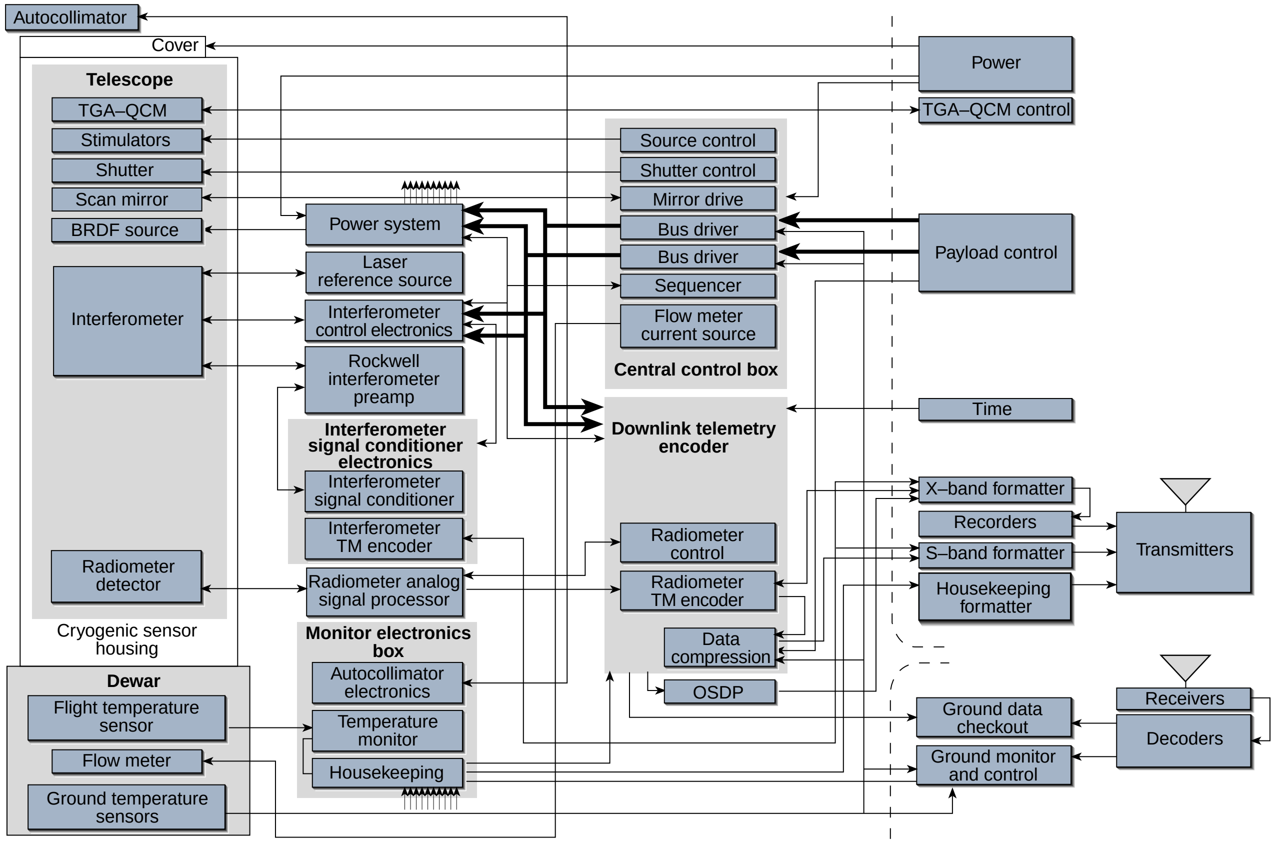


**Figure 10.** SPIRIT III sensor block diagram. Heavy lines indicate paths for spacecraft control data bus. (TGA = thermogravimetric analysis, QCM = quartz crystal microbalance, BRDF = bidirectional reflectance distribution function, and OSDP = Onboard Signal and Data Processor.)

channel may be selected for compression. These transmissions can be sent to any ground station with S-band capability and linked in real time to the SGSE located at APL.

3. The 16-kilobyte telemetry transmits SPIRIT III housekeeping data, primarily temperature and voltage information from monitors on subsystems and individual components.

After playback and downlink of the spacecraft's recorder to the ground receiver and recording station, SPIRIT III data are stripped from the MSX tapes. Header files are installed and data dropouts are identified but not corrected. The data (level 1A) are transferred to 8-mm tapes and air shipped biweekly to the SDL data processing center in Logan, Utah. The center is part of a distributed data network (Fig. 11) being used in the MSX program and is designed to ingest up to 11 gigabytes of SPIRIT III science data per day. Certified and calibrated data are available to users as level 2 and 2A data products only after they are processed by the SDL data processing center with certified "pipeline" software.

On-site users at the SDL data processing center have access to the raw and processed science data, sensor housekeeping data, and verification output products through a relational database management system. For long-term analysis and trending, the performance assessment team uses additional sensor performance analysis software customized for particular performance trending needs by the data processing center.

SDL pointing software is available to convert positional information gathered by the SPIRIT III sensor system from one coordinate representation to another. It also computes boresight coordinates for the radiometer and interferometer–spectrometer sensors.

When processing is complete, the data are archived at SDL, and certified copies are forwarded to the Backgrounds Data Center at the Naval Research Laboratory for use by MSX program scientists and others.

## MISSION OPERATIONS

SPIRIT III engineering team members who developed system hardware and operational plans[4] will

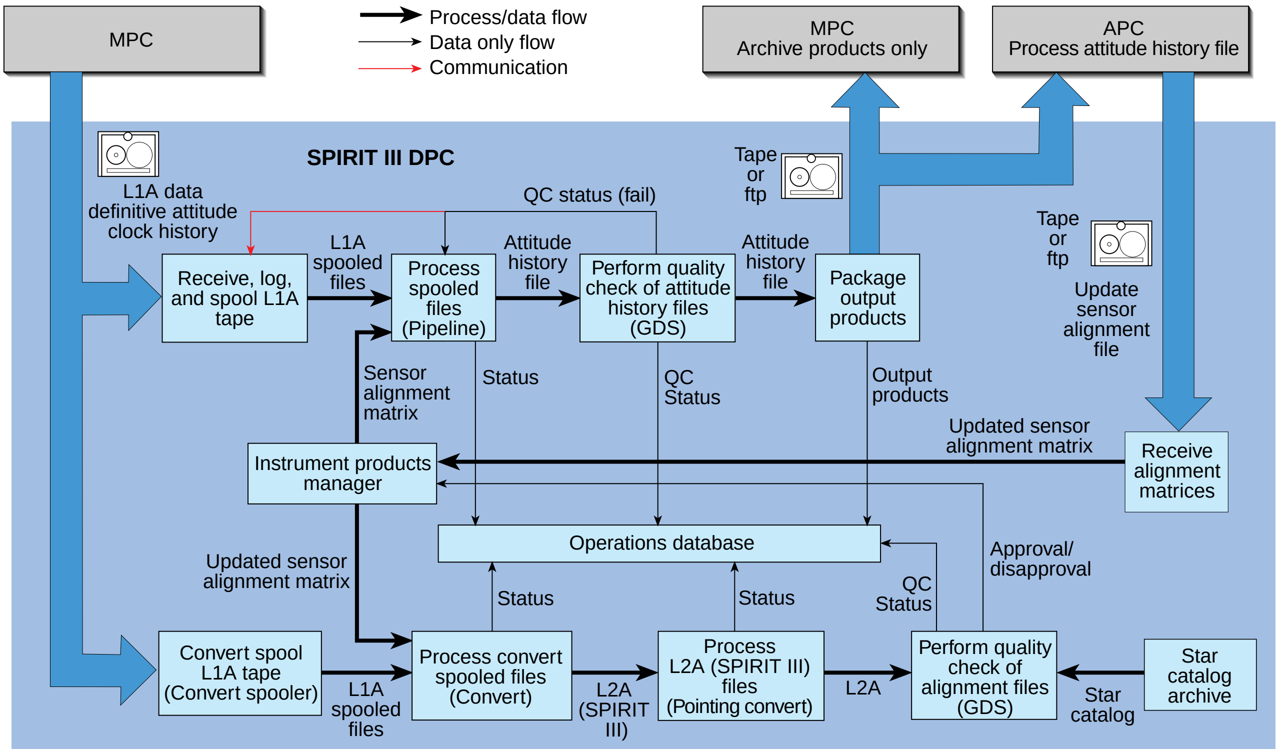


**Figure 11.** SPIRIT III data flow. (MPC = Mission Processing Center, APC = Attitude Processing Center, DPC = Data Processing Center, GDS = graphical display software, QC = quality control, L1A = level 1A, and L2A = level 2A.)

participate in the planning, execution, and analysis of daily mission activities. Some members will be stationed at the primary telemetry ground station to operate SPIRIT III equipment pre-positioned to collect “snapshots” of selected downlinks from the spacecraft as it passes overhead. These snapshots will be collected and displayed by using the same SGSE formerly used for independent sensor performance assessment during ground tests and spacecraft integration activities.

During on-orbit operations, the SGSE can process downlinked telemetry information at the APL ground station and Mission Operations Center to provide the SPIRIT III performance assessment team with daily insight into system health and status. The data will be selectively processed on a limited basis through coordination with the main body of the performance assessment team in the SPIRIT III data processing center in Logan, Utah.

## ON-ORBIT EXPERIMENTATION

SDL has developed more than 25 SPIRIT III on-orbit characterization and calibration experiments (Table 2) in conjunction with the Data Certification and Technology Transfer Committee. SPIRIT III is used in conjunction with other MSX instrumentation systems in nearly all of the more than 125 experiments planned by the MSX mission planning team and program principal investigators.

The experiments are implemented through execution of linked sequences called command packets that are uploaded into spacecraft memory by the MSX flight operations controllers. In some cases, specific modular sequences are stored in nonvolatile memory for execution on demand from the ground.

## SUMMARY

SPIRIT III is a state-of-the-art radiometer–spectrometer system covering the majority of the infrared spectrum. It will serve as a highly capable observatory for collecting data of broad scientific interest, as well as for providing answers to fundamental questions about DoD surveillance systems. It will provide invaluable information for system planners and designers of future systems for the detection of hostile threat vehicles.

**Table 2. SPIRIT III on-orbit experiments for MSX.**

| DCATT No. | Plan | SDL No. |
|---|---|---|
| DC-03 | Standard turn on/off sequence | 93-077 |
| DC-04 | Short internal stimulator sequence | 93-044 |
| DC-05 | Long internal stimulator sequence | 93-043 |
| DC-08 | Earth-limb OFVR characterization | 93-074 |
| DC-22 | Reference sphere calibration | * |
| DC-28 | South Atlantic anomaly effects | * |
| DC-29 | Pointing and alignment | * |
| DC-30 | Internal scatter source | 93-060 |
| DC-31 | Near-field OFVR characterization | 93-063 |
| DC-32 | Lunar OFVR characterization | 93-064 |
| DC-33 | Flat-field calibration, mirror scan mode | 93-070 |
| DC-34 | Flat-field calibration, Earth-limb mode | 93-071 |
| DC-35 | Stellar radiometric calibration | 93-072 |
| DC-37 | Interferometer wavelength calibration | 93-075 |
| DC-38 | Interferometer spatial domain characterization | 93-076 |
| DC-39 | DCE bracketing sequences | 93-078 |
| DC-41 | Dark offset | |
| DC-43 | SPIRIT III source transfer | 95-011 |
| DC-44 | SPIRIT III benchmark and dark offset (41 + 35) | 95-012 |
| DC-61 | Cover monitor experiment | 93-061 |
| DC-62 | Cryostat hydrogen flowmeter | 93-062 |
| DC-63 | Initial radiometer turn on | 93-057 |
| DC-64 | Interferometer carriage release | 93-058 |
| DC-65 | Initial interferometer turn on | 93-059 |
| DC-66 | Cover release and first light | 93-065 |

Note: DCATT = data certification and technology transfer, and OFVR = out of field-of-view rejection. An asterisk (*) indicates not an SDL document.

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[3] *SPIRIT III Sensor User's Guide,* Rev. 5, Utah State University Research Foundation Space Dynamics Laboratory, SDL/92-041, Logan, UT (May 1995).

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