An Introduction to the Department of Energy's Multispectral Thermal Imager (MTI) Project Emphasizing the Imaging and Calibration Subsystems

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Abstract. MTI is a comprehensive research and development project that includes up-front modeling and analysis, system design, fabrication, assembly and testing, on-orbit operations, and experimentation and data analysis. The satellite is designed to collect radiometrically calibrated, medium resolution imagery in 15 spectral bands ranging from 0.45 to 10.70 μm. The combination of spectral bands, very accurate radiometry and good spatial resolution make MTI unique among current and planned space-based imaging systems. The imaging system includes a three-mirror anastigmatic off-axis telescope, a single cryogenically cooled focal plane assembly, a mechanical cooler, and an onboard calibration system. The single focal plane sensor design alleviates the need for a beam splitter to separate spectral components, and it permits cold operation for ground test and alignment, while the telescope and electronics are at laboratory ambient temperature and pressure. Payload electronic subsystems include image digitizers, real-time image compressors and a solid state recorder. All payload components have been fabricated and tested, and the payload is integrated and currently undergoing environmental testing in preparation for calibration.

Introduction

This paper will introduce readers to the Department of Energy's (DOE's) Multispectral Thermal Imager (MTI) project with emphasis on the payload imaging and calibration subsystems. MTI is a Research and Development (R&D) project, sponsored by DOE's Office of Nonproliferation and National Security and executed by Sandia National Laboratories, Los Alamos National Laboratory and Savannah River Technology Center. Other government participants include the Air Force Research Laboratory, the National Institute of Standards and Technology and the Air Force Space Test Program, which is funding and managing the launch. Major industry participants include Ball Aerospace, Raytheon Optical Systems, Santa Barbara Research Center and TRW. Over fifty government, private and academic organizations are involved in the development. The satellite is scheduled to launch in the fall of 1999 from Vandenberg Air Force Base on an Orbital Sciences Corporation Taurus Launch Vehicle.

As suggested by Figure 1, DOE's primary objective for MTI is to develop and evaluate advanced multispectral and thermal imaging, image processing and associated technologies for detecting and characterizing nuclear and other Weapons of Mass Destruction (WMD) facilities. To achieve this objective, the project will launch and operate a satellite with an advanced multispectral pushbroom imaging payload, capable of imaging sites in 15 spectral bands, ranging from visible to long-wave infrared, with extremely accurate radiometry.

The project combines and advances five technologies:

(1) Multispectral imaging
(2) Thermal imaging
(3) Advanced radiometric calibration
(4) Atmospheric characterization
(5) Modeling and analysis

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[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy under Contract DE-94AL85000.

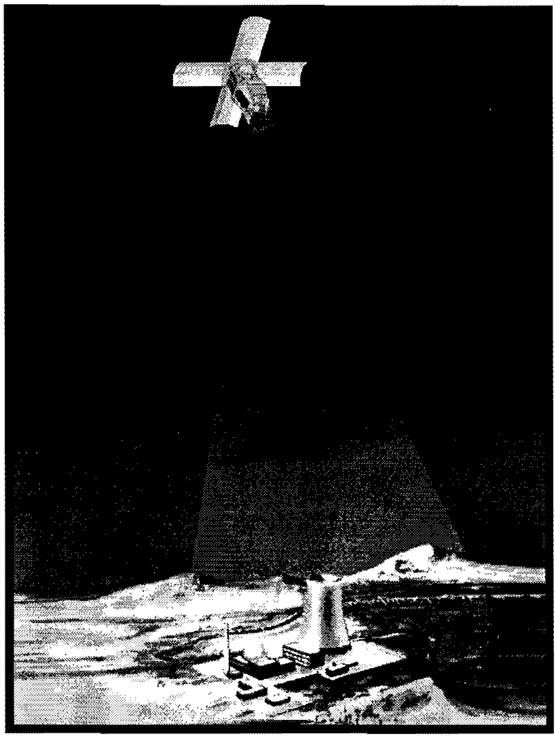

Figure 1. Mission Objective
MTI depicted imaging an industrial site.

Advances in these technologies, together with the experimental data MTI will provide, are needed to develop more capable treaty monitoring systems.

During its three year mission, the MTI satellite will periodically record images of participating government, industrial and natural sites in fifteen visible and infrared spectral bands. These bands are selected to provide a broad range of data on potential proliferant facilities, including surface temperatures, materials, water quality, and vegetation stress. To achieve thermometric and reflectance accuracies required by the mission, the system also includes bands selected to collect simultaneous information on the intervening atmosphere, such as column water vapor, aerosol content and subvisual clouds. The combination of spectral bands, very accurate radiometry and good spatial resolution make MTI unique among current and planned space-based imaging systems. Participating sites will be instrumented to record ground truth data to permit investigators to compare, analyze and validate satellite images against ground truth. MTI is a complex, comprehensive R&D project that emphasizes up-front modeling and analysis, experimentation and data analysis.

MTI technology has a broad range of national security and civilian applications in addition to treaty monitoring. To ensure the nation realizes maximum benefit from this multi-use potential, DOE has organized an MTI Users Group (MUG) with over 100 members representing over forty national defense and civilian organizations. MUG members advise DOE on multi-use objectives and will conduct their own experiments utilizing MTI images. MUG membership is open to government sponsored investigators who desire to utilize MTI imagery for R&D in the national interest.

In addition to the primary DOE sensor, the MTI satellite will carry a High energy X-Ray Spectrometer (HXRS) sponsored by the National Oceanic Atmospheric Administration (NOAA), with additional funding from the Astronomical Institute Academy of Sciences of the Czech Republic, and built by Space Devices, Ltd. of the Czech Republic. HXRS is designed to record a rare species of solar flare associated with high-energy proton storms known to damage satellites and potentially endanger astronauts. From HXRS, NOAA hopes to obtain data needed to design a system capable of forecasting such storms.

System Overview

The system includes a single satellite in a circular, sunsynchronous (1:00 AM/1:00 PM) orbit, initially injected at 575 kilometers, a ground station and operations center located in Albuquerque and a Data Processing and Analysis Center located in Los Alamos.

The satellite will autonomously collect, compress and store six 2-look, 15-band, 12 x 12 kilometer images per day. During each of two daily passes over the ground station, the system will downlink image data and uplink a new target list. Raw image data will be forwarded to the Data Processing and Analysis Center where it will be processed and converted to standard data products and distributed to various experimenters. The satellite has no propulsion system so the orbit will decay as the mission progresses, and the orbit plane will drift about one hour over three years.

The project is also developing advanced computerized site, atmospheric transport and system models, which have been employed in the system design and will be used in the analysis of project data.

Major system performance goals are:

Spectral Bands. Visible, shortwave infrared (SWIR), midwave infrared (MWIR), and longwave infrared (LWIR), per Table 1.

Ground Sample Distance (GSD). Per Table 1.

Absolute Radiometric Accuracy. 3 % in the reflective bands and 1% in the thermal emissive bands, per Table 1.

Table 1
Spectral bands and band dependent specifications

Band	Wavelength Range (microns)	GSD (meters)	Radiometric Accuracy (percent)
A	0.45 - 0.52	5	3
B	0.52 - 0.60	5	3
C	0.62 - 0.68	5	3
D	0.76 - 0.86	5	3
E	0.86 - 0.90	20	3
F	0.91 - 0.97	20	3
G	0.99 - 1.04	20	3
H	1.36 - 1.39	20	3
I	1.55 - 1.75	20	3
J	3.50 - 4.10	20	1
K	4.87 - 5.07	20	1
L	8.00 - 8.40	20	1
M	8.40 - 8.85	20	1
N	10.20 - 10.70	20	1
O	2.08 - 2.35	20	3

Field of View. 12 x 12 km (nominal).

Field of Regard. ± 200 km from ground track.

Geographic Coverage. All CONUS sites covered.

Pointing Accuracy. ± 0.5 degrees.

Temporal coverage. Average site revisit time is 7 days at 1300 or 0100 hours ± 1 hour.

View angles. 2-looks, one near nadir and another at 45-55 degrees off nadir.

Imaging capacity. Six 2-look, 15-band images per day.

Mission duration. 1 year requirement, 3 year goal.

Satellite Overview

A full-scale mockup of the satellite is shown in Figure 2. It weighs 614 kilograms and is roughly cylindrical in shape, 135 cm in diameter and 260 cm in length. The satellite normally flies with the back of its solar paddles toward the sun (payload is antisun pointing). To image, it executes required attitude maneuvers to point the payload at the target, then returns to its antisun pointing orientation after imaging.

Figure 3 illustrates the basic MTI sensor concept. The satellite consists of a spacecraft bus and imaging payload. The bus, built by an integrated Ball Aerospace/Sandia team, provides the payload with a 3-axis stabilized platform, 315 watts of average power, radio frequency communications, and command and data handling.

The payload includes a telescope, cryogenically cooled focal plane with 15 linear spectral-sensitive detector arrays, built-in calibration sources and mechanisms, supporting structure, and associated readout and control electronics (not shown). The telescope images scenes onto the focal plane arrays. Data required to form

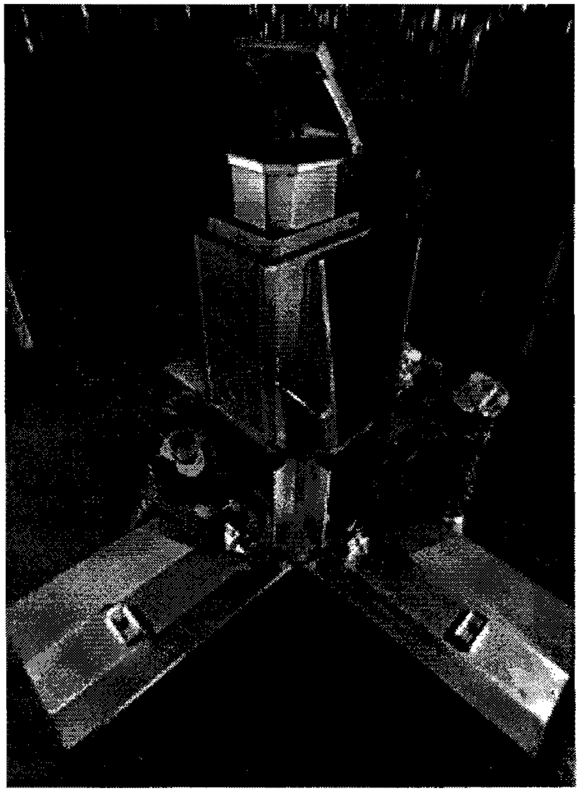

Figure 2. Full-scale satellite mockup.
This full-scale mockup of the satellite was used to qualify the bus and payload structures. Technicians handle it the same way they will handle the flight article.

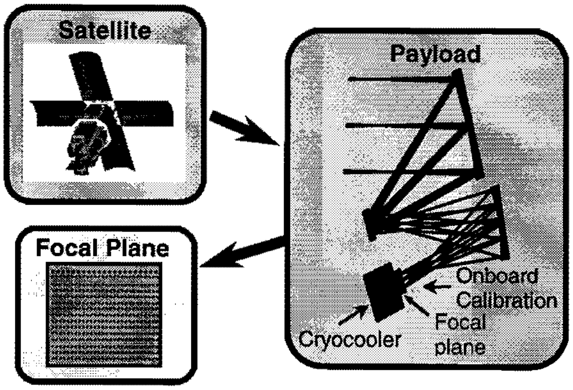

Figure 3. Satellite/Sensor Concept.
The sensor consists of an off-axis telescope and cooled focal plane with linear detector arrays. The motion of the satellite (perpendicular to the sensor arrays) scans the image across the arrays.

images in 15 spectral bands is recorded as the satellite ground track motion scans the image over the 15 linear detector arrays in "pushbroom" fashion. The individual pixels provide spatial resolution in the cross-track direction and temporally consecutive readouts of the detector provide spatial resolution in the along-track direction. The cross-track field is approximately 12 km. The system is designed to record two images (2 looks) of a given site–one near nadir and another at about 45-55 degrees.

The nominal nadir ground sample time in the along track direction is 715 microseconds for bands A-D (12.4 µm pitch detectors) and 2.86 milliseconds for bands E-O (49.6 µm pitch detectors). A single detector array scans a 12 km image in about 1.7 seconds. The detector arrays are staggered in the along-track direction, so the system images a given point on the ground at slightly different times for each of the spectral bands. The focal plane readout electronics allows individual programming of start and stop times for each band. A single 12 x 12 kilometer image requires about 4.5 seconds.

High-speed analog-to-digital converters digitize outputs of each pixel with 12-bit resolution. When imaging in all bands, the focal plane readout electronics generate 266 megabits/second of data for real-time compression and storage. A compressed 2-look image set in all 15 bands is approximately 500 megabits in size.

Payload subsystems include: Imaging, Thermal, Calibration, Data Compression and Storage and Structure. These subsystems are implemented by a set of component subassemblies shown schematically in Figure 4. Figure 5 is a photograph of the assembled flight payload (without thermal radiators) showing the aluminum payload structure with various subassemblies mounted. The remainder of this paper describes the major imaging and calibration system components.

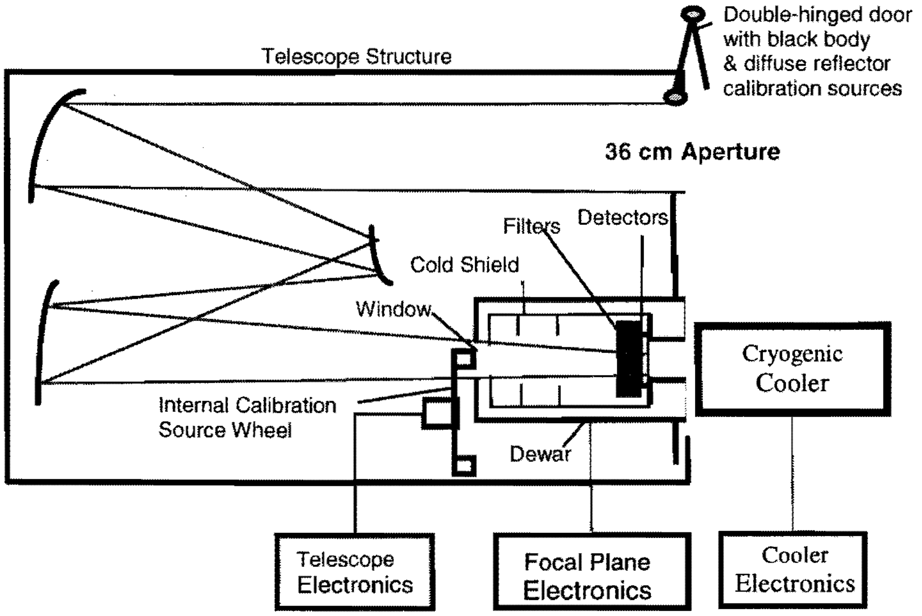

Figure 4. Payload block diagram.
The payload consists of an Optics Assembly with a 36 cm off-axis telescope, calibration sources built into a double-hinged door and internal calibration wheel, a Focal Plane Assembly (dewar) with linear detector arrays at the focal plane that operates at 75 K, and control and readout electronics.

Optical Assembly

The Optical Assembly (OA), built by Raytheon Optical Systems, is shown in the cutaway of Figure 6.[2] This assembly includes the telescope structure, optics, calibration sources built into the double hinged aperture door and internal wheel assembly, focus mechanism (not shown), various actuators and other mechanisms, and numerous thermistors and heaters for temperature control. The built-in calibration sources are described in the Calibration section, and the cryogenic cooler, shown in the bottom center of this figure, is described in the Cryogenic Cooler section.

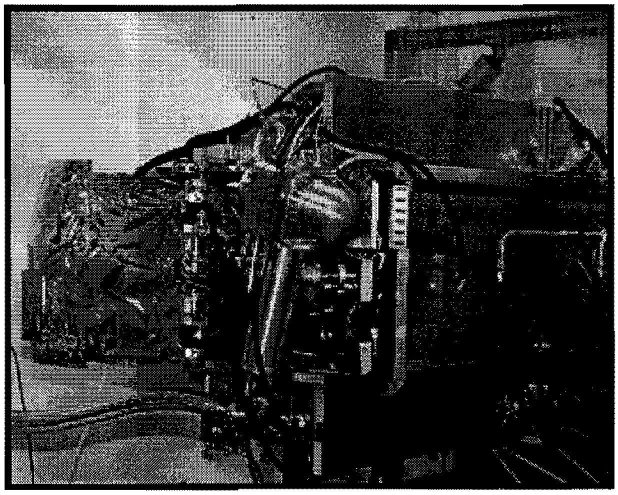

Figure 5. Flight Payload.
Photograph of the flight payload showing aluminum structure that houses and supports the various payload subassemblies.

The OA design features a 36 cm, 3-mirror, off-axis, anastigmatic, f/3.5 telescope design, housed in a composite structure for dimensional stability. The unobscured design offers near diffraction limited performance as shown in Figure 7. It also eliminates scattering and thermal emissions from structures that would be within the field of view of the focal plane arrays in an on-axis design. The design also provides an accessible exit pupil (Lyot stop) that permits effective cold shielding to thermally isolate the focal plane arrays from the telescope structure and internal components. The entire OA, including its internal components, is therefore uncooled, but thermally isolated from the rest of the satellite and temperature-controlled at 275 K.

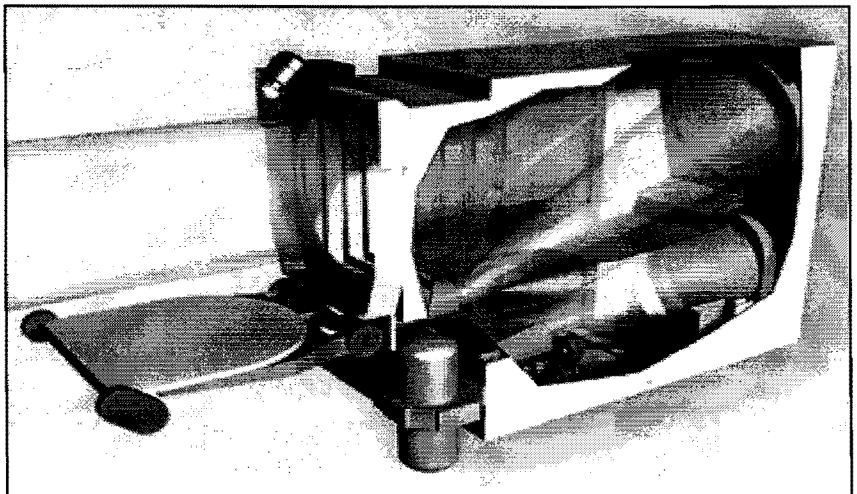

Figure 6. Cutaway of the Optical Assembly.
This cutaway reveals the optics. The primary, secondary and tertiary mirrors can be seen inside. The muzzle of the focal plane assembly dewar and the internal calibration wheel can also be seen. Outside the the double-hinged door and solar ratioing radiometer (opposite the door hinges) are also shown. The cryogenic cooler is also shown, although it is not part of Optical Assembly.

Figure 8 shows two views of the flight Optical Assembly. The top photograph (A) is a rear view of the optical assembly with a cover removed, revealing light-weighted primary and tertiary mirrors. The bottom photograph (B) is a front view showing the aperture end of the telescope. This view shows the double hinged aperture door in the closed position. The door is normally closed, and will be opened only during imaging and certain calibration operations as described in the Calibration section. It is secured during launch by a hot wax actuated launch lock.

Figure 8B also shows the aluminum can that houses the focus mechanism, which precisely adjusts the position of the secondary mirror (the smallest of the three

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[2] A more detailed description of the OA has been published by Tammy Henson, et. al., "Optical Assembly of a Visible through Thermal Infrared Multispectral Imaging System," SPIE proceedings, Volume 343a (1998).

mirrors). The opening in the top right of the OA is the Focal Plane Assembly mount.

Figure 8B also shows numerous thermistors and heaters on the sides of the OA structure. These devices are part of the thermal control subsystem that maintains the OA and its optics at 275 K, also described in the Calibration section. The entire OA is wrapped with multilayer insulation to thermally isolate it from the outer aluminum payload structure.

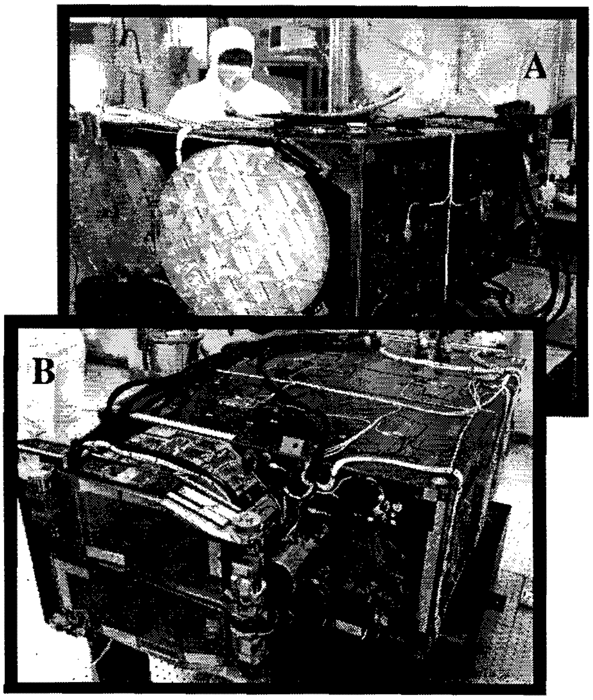

Figure 8. Flight Optical Assembly. The top photograph (A) shows the rear of the OA with a cover removed revealing light-weighted primary (right) and tertiary (left) mirrors. The bottom photograph (B) shows the front of the OA with the aperture door closed. The can to the right of the door houses the focus mechanism that adjusts the secondary mirror.

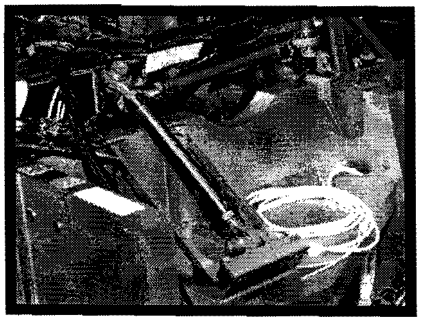

Figure 9. One of 3 kinematic mounting points.

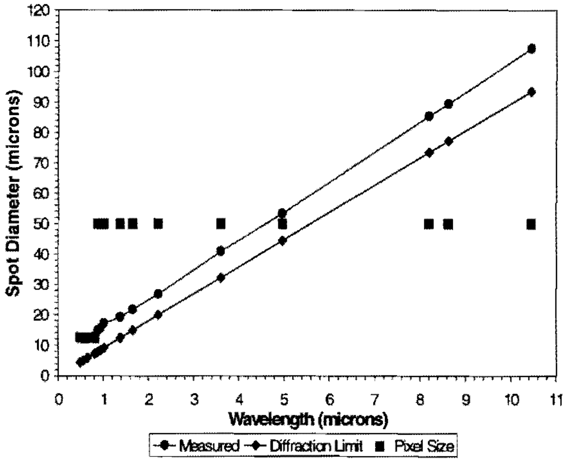

Figure 7. Comparison of measured optical performance against diffraction limit and detector pixel size for each of the spectral bands.

The OA is suspended in the payload structure by a kinematic mounting system at three points. A pair of kinematic links ties each of these points to the payload structure as shown in Figure 9. This system constrains the OA's six degrees of freedom without inducing mechanical stress from the primary structure. It also suppresses launch vibration coupled into the OA for frequencies above 45 Hz.

Focal Plane Assembly

Figure 10 is a cutaway line drawing of the Focal Plane Assembly (FPA), built by Santa Barbara Research Center.[3] At its heart are six sensor chip assemblies (SCAs) mounted on three motherboards as shown in Figures 11 and 12. Each SCA consists of photosensitive detector material and a silicon readout integrated circuit (ROIC). For bands A-D, the detectors

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[3] A more detailed description of the FPA has been published by Jeffrey L. Rienstra and Mary Ballard, Multispectral Focal Plane Assembly for Satellite Remote Sensing," 1998 IEEE Aerospace Conference Proceedings, March 21-28, 1998, 7.502.

and ROIC are implemented as a monolithic structure. For bands E-O, the photosensitive material is bump bonded to the ROIC. The ROIC provides pre-amplifiers for each pixel and circuitry for serializing pixel outputs onto analog output lines.

The three motherboards connect to cryogenic cables, which interface to warm connectors. Each SCA pair contains a set of three types of linear arrays capable of detecting the required range of wavelengths:

- Monolithic silicon PIN diodes for visible and near infrared (VIS/NIR) bands A-D (12.4 μm pitch)
- Backside illuminated photovoltaic indium antimonide (InSb) for NIR/SWIR/MWIR bands E-K and O (49.6 μm pitch)
- Backside illuminated photovoltaic mercury cadmium telluride (HgCdTe) for LWIR bands L-N (49.6 μm pitch)

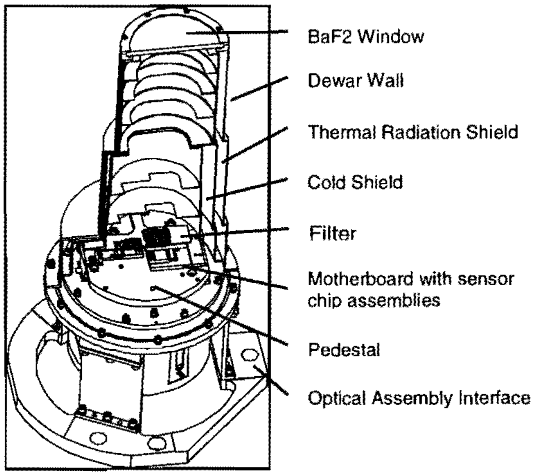

Figure 10. Cutaway drawing of the Focal Plane Assembly.

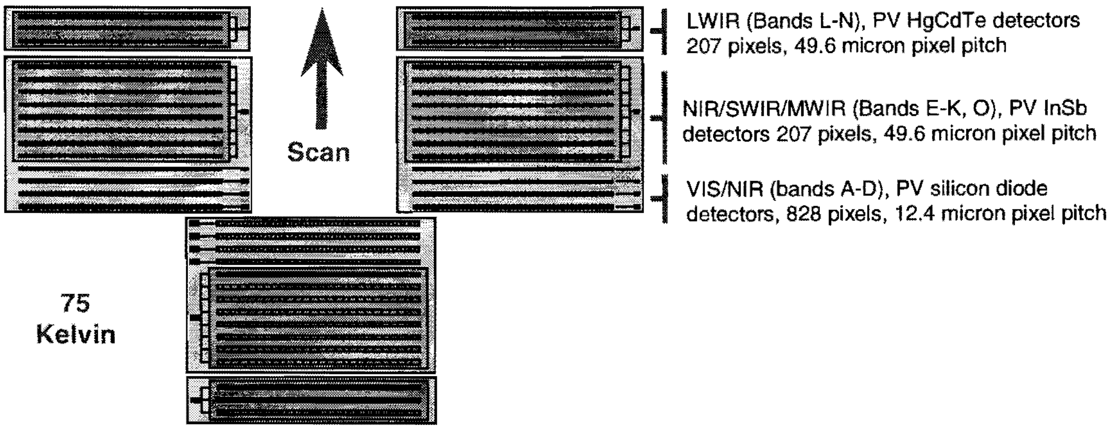

Figure 11. Physical layout of focal plane arrays on six Sensor Chip Assemblies.

The SCA's, including the PIN diodes, are designed to operate at 75 K. This single focal plane design alleviates the need for a beam splitter to separate visible and infrared spectral components.

While we would have preferred to use a single large SCA as depicted in the concept diagram of Figure 3, we were forced to use three smaller assemblies due to difficulties in manufacturing long arrays. This requires the ground software to combine data from corresponding arrays on each of the three chip assemblies to synthesize a single logical array.

Interference filters mounted in a bezel over the SCAs, shown in the bottom photograph of Figure 12, precisely select wavelength bands. The motherboards with sensor chip assemblies and filter bezel are mounted in an optically baffled and cold shielded housing. The FPA is mounted into the OA with its window placed just ahead of the telescope's exit pupil. The cold shield aperture is aligned precisely with the telescope's exit

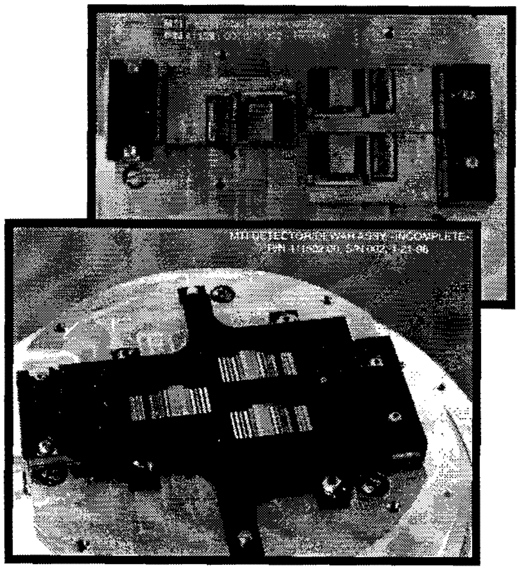

Figure 12. Flight Sensor Chip Assemblies and filter bezel with interference filters mounted.

pupil, prohibiting thermal emissions from the OA structure from directly illuminating focal plane detectors. The barium fluoride window passes the broad range of wavelengths detected by MTI. The FPA housing mates to a vacuum housing surrounding the cryogenic cooler cold head by way of a flexible bellows. This housing allows the volume surrounding the cold head, focal plane, and cold shield to be evacuated, and hence cooled to 75 K, with the remainder of the OA and payload at ambient laboratory temperature and pressure. This greatly simplifies the task of testing and aligning the infrared portions of the focal plane compared with a system in which the entire payload must be placed in a vacuum chamber before the infrared detectors can be cooled.

The photographs of Figures 13 show the fully assembled flight FPA and its various components.

Cryogenic Cooler

The pulse-tube cryogenic cooler, built by TRW, is shown in Figure 14A. It maintains the FPA SCAs at 75 K and the FPA cold shield at 117 K. The unit produces 3 watts of cooling capacity at 65 K (at its cold tip), with an efficiency of 52 watts/watt. An opposing cylinder design and control electronics provide both active vibration and temperature control.

Figure 14B shows the cooler mounted to the payload. Thermal connection is made through the flexible cold strap shown in Figure 14C, which is connected to the back of the FPA via the three threaded holes shown in Figure 14D. The bellows shown between the cooler and back of the FPA in Figure 14B permits the volume surrounding the cooler and focal plane to be evacuated, while maintaining a soft interface. The combination of the bellows and flexible cold strap isolates the FPA from any movement between the payload structure (where the cooler is hard mounted) and the OA (where the FPA is hard mounted). It also reduces any residual vibration that might be transmitted to the FPA from the cooler on orbit.

Built-in Calibration

The radiometric accuracy goals DOE has established for MTI, over wavelengths ranging from 0.45 to 10.70 µm, are fundamental to the mission objective, and to date, have only been achieved in the laboratory. This dictates new, innovative, state-of-the-art calibration methods. To meet this challenge, MTI's calibration strategy is based on accurately calibrating the sensor prior to launch and then maintaining calibration on orbit.[4]

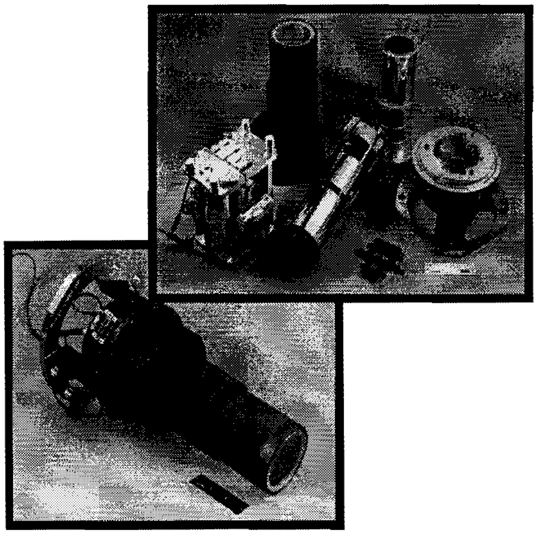

Figure 13. Flight Focal plane assembly and internal components.

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[4] A more detailed description of MTI calibration has been published by Paul G. Weber, et.al., "Multispectral Imaging," SPIE Conference on Imaging and Spectrometry IV, San Diego, CA, July 21, 1998.

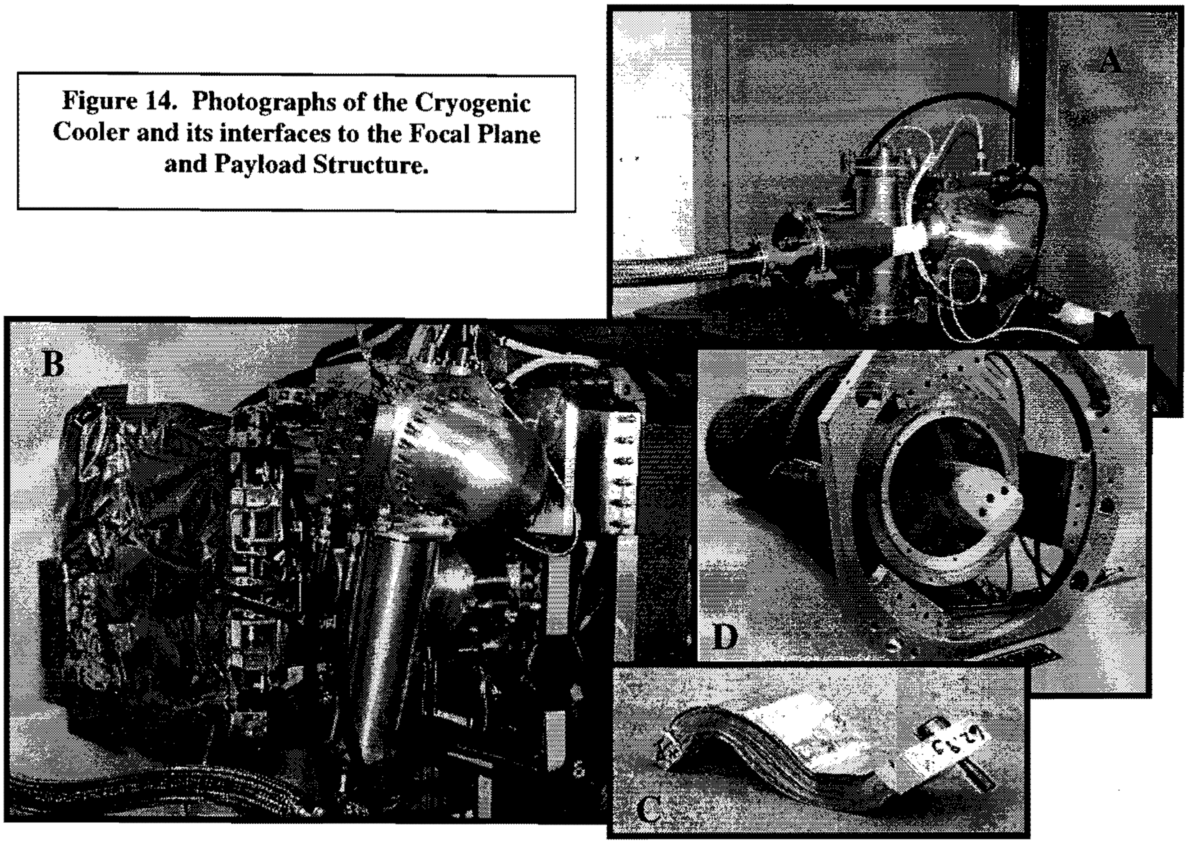

Figure 14. Photographs of the Cryogenic Cooler and its interfaces to the Focal Plane and Payload Structure.

To minimize uncertainties due to thermal effects, the thermal subsystem monitors and controls both focal plane and OA temperatures. The focal plane is actively maintained at 75 K by controlling cooler stroke and heat pipe conductance. OA temperature is maintained at a near uniform 275 K by heater tapes in 42 zones using 90 temperature monitors.

The built-in calibration system employs NIST-traceable sources, the sun and cold space to maintain long-term calibration. The basic strategy is to use the MTI sensor itself as a transfer radiometer between the ground-based calibration system and the onboard calibration sources.

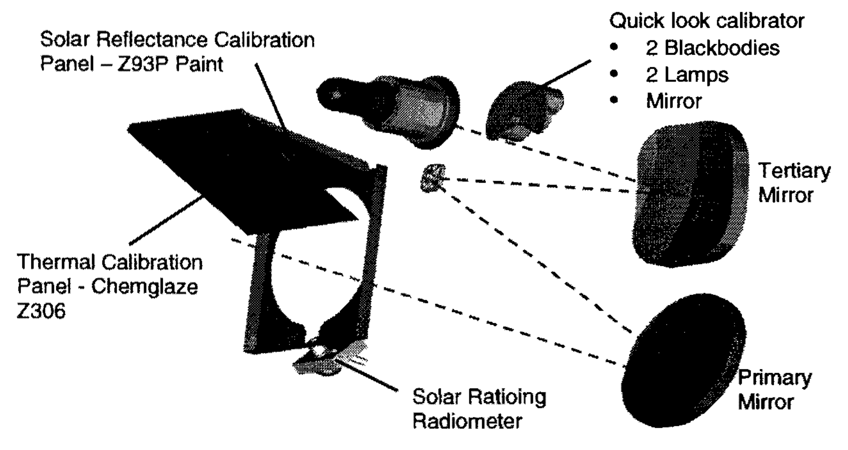

Figure 15. Optics and built-in calibration.

Once this transfer function has been established, on-orbit operations will employ the onboard calibration hardware to continually verify it. Built-in calibration components are shown in Figure 15. Two sources are built into the aperture door. As shown in Figure 16, the door is double hinged to allow two different surfaces to fill the telescope field of view, providing end-to-end calibration of the imaging system. When the door is closed (it is kept closed except when imaging), it presents the dark surface (coated with Chemglaze Z306) to the system. This is a temperature-controlled blackbody radiator for full-aperture calibration of the infrared channels.

Still referring to Figure 16, the other side of the double hinged door is painted white (Z93P paint). With the door partially opened to 45 degrees and the second hinge extended, the satellite can be oriented to reflect sunlight, flooding the aperture with a diffused source for calibrating the visible through SWIR channels. Referring back to Figures 6 and 15, a solar ratioing radiometer near the aperture opposite the door hinge is used to monitor the door's reflectance.

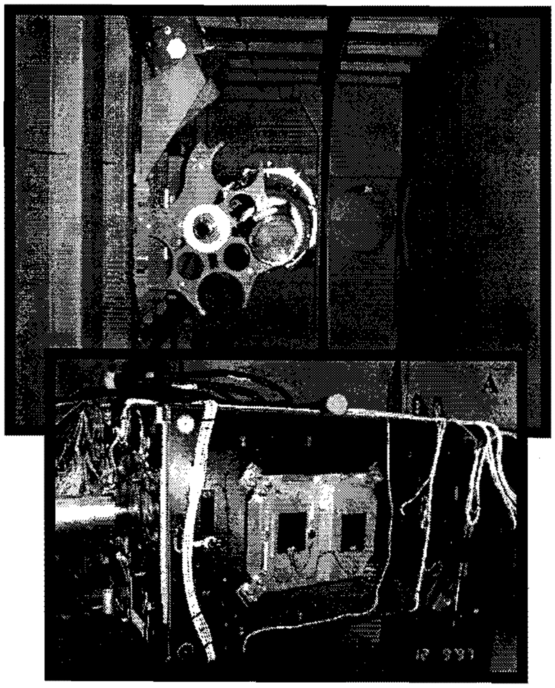

Figure 17. Calibration Wheel Assembly.
The rectangular object shown mounted in the side of the Optical Assembly in the bottom photograph is the Calibration Wheel Assembly. The top photograph is an internal view of the assembly (taken prior to installing the sources), looking back from the tertiary mirror toward the Focal Plane Assembly.

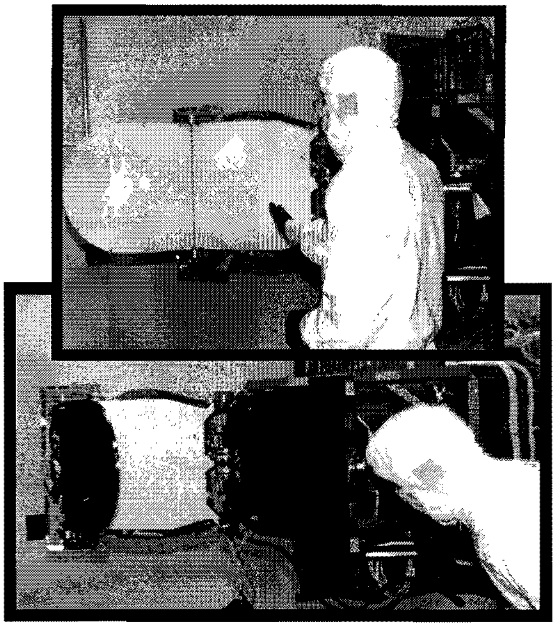

Figure 16. Double hinged Door.
The double hinged floods the instrument with black body radiation or diffused sunlight for full aperture calibration.

Again referring to Figure 15, another set of calibration sources is mounted inside the telescope in a wheel assembly. These sources are used to obtain a quick look at drift and 1/f effects just prior to and following imaging. The assembly mounts into the side of the telescope as shown in Figure 17A (the rectangular assembly) and can be seen near the bottom of the cutaway of Figure 6, just in front of the FPA housing. Figure 17B, taken prior to installing the sources, is a view looking back from the tertiary mirror toward the FPA mount with the calibration wheel shown in the optical path. Beginning at about the 10 o'clock position, the very large cutout in the wheel is positioned in front of the focal plane when the system is imaging. Moving clockwise, the large semicircle cutout at the top of the wheel (12 o'clock), contains a narcissus mirror, which is viewed by the focal plane when the system is not imaging to minimize the thermal load on the cryogenic cooler and to provide a cold reference. Moving clockwise to the next position (about 3 o'clock), the back of a folding mirror can be seen. This mirror reflects two visible calibration sources, located at the far upper left of the OA into the FPA. Moving clockwise to the two semicircle cutouts at about 5 and 8 o'clock, these large semicircle cutouts contain blackbodies for 2-point thermal calibration checks. The three small holes in the wheel are light-weighting.

Readout and Control Electronics

The various optical and mechanical imaging and calibration components and mechanisms are controlled and readout by five electronic packages.

- **Focal Plane Readout**–controls focal plane readout, digitizes analog image data and passes it to the payload recorder interface
- **Payload Recorder Interface**–compresses and formats mission data in real-time and writes it into a solid state recorder (Mass Storage Unit)
- **Mass Storage Unit** (built by Odetics)–stores mission and housekeeping on orbit between ground station passes
- **Telescope Calibration and Control Assembly**–controls the optical assembly telescope and built-in calibration mechanisms and sources
- **Cooler Control Electronics Assembly** (built by TRW)–controls the cryogenic cooler

Summary

In summary, MTI is a comprehensive R&D project, executed by an integrated multilaboratory team of DOE scientists, engineers and analysts, with major support from other government agencies, academia and private industry. It is a complex project that includes up-front modeling and analysis, system design, fabrication, assembly and testing, on-orbit operations, experimentation and data analysis. The project will bring together and advance a number of state-of-the-art, but relatively mature, technologies and methodologies in anticipation of an early and rich R&D payoff.

Although MTI is specifically aimed at advancing technologies and collecting data needed to build more capable operational systems for monitoring WMD treaties and other agreements, the technology is rich with other important national security and civilian applications. Non-DOE experimenters in over forty government organizations will investigate these applications and currently participant through the MTI Users Group.

This introduction has emphasized MTI's advanced imaging and calibration system design, which is unique among current and planned space-based systems.

Acknowledgments

The design described in this report represents the work of a dedicated integrated project team at Sandia, Los Alamos and other organizations, who deserve the real credit. The authors are especially indebted to teams at Santa Barbara Research Center, Raytheon Optical Systems, and TRW, who designed and built the Focal Plane Assembly, Optical Assembly and Cryogenic Cooler and to the Air Force Research Laboratory for technical and administrative assistance in procuring the cooler. We thank Ball Aerospace for important contributions to system engineering. We are also indebted to the Air Force Space Test Program office and to many other military and DOD agencies, instrumental in securing and funding MTI's launch. Next, we thank our colleagues at the Savannah River Technology Center and other DOE laboratories for their research in the late 1980s that laid the groundwork for the project. Our final acknowledgment goes to our DOE sponsor and his management team for vision and leadership that has made this project possible.