

## **Hyperion: A 0.4 $\mu\text{m}$ - 2.5 $\mu\text{m}$ Hyperspectral Imager for the NASA Earth Observing-1 Mission**

Paul Lee, Steve Carman, C. K. Chan, Marty Flannery, Mark Folkman, Kelly Iverson,  
Pete Jarecke, Lushalan Liao, Kien Luong, Jim McCuskey, Jay Pearlman, Kent  
Rasmussen, Carol Segal, Delores Viola, Wendy Watson, Don Wolpert  
TRW Space and Technology Division, Redondo Beach, CA 90278

Vicky Gauthier, Andy Mastandrea, Gerry Perron, Gerry Szarek  
SSG, Inc., 65 Jonspin Road, Wilmington, MA 01887

### ABSTRACT

A hyperspectral imaging payload has been developed for the NASA New Millennium Program (NMP) Earth Observing-1 satellite (EO-1) which provides 30 meter resolution, 7.5 km swath, earth images in 220 continuous 10 nm spectral bands from 0.4  $\mu\text{m}$  to 2.5  $\mu\text{m}$ . The instrument includes an internal and a solar calibration sub-system. The Hyperion imaging payload was developed for the EO-1 satellite in 12 months and is scheduled to be launched in June 2000. This paper describes the Hyperion design, development and performance.

### 1. INTRODUCTION

In 1996, NASA started the New Millennium Program (NMP), designed to identify, develop, and flight-validate key instrument and spacecraft technologies that can enable new or more cost-effective approach to extend and improve upon the Landsat images of the Earth's continents. The first of these New Millennium Program Earth-Observing missions is Earth Observing-1 (EO-1) an advanced, land imaging mission that will demonstrate new instruments and spacecraft systems. EO-1 is scheduled to launch from Vandenberg Air Force Base, Calif., in mid 2000.

EO-1 will fly in formation with Landsat 7 collecting and comparing land imagery under the same atmospheric conditions to fully validate the EO-1 advanced imaging instruments. The three remote sensing instruments on the EO-1 are the Advanced Land Imager (ALI), the Hyperion hyperspectral imaging spectrometer, and the Linear Imaging Spectrometer Array (LEISA) Atmospheric Corrector (AC). ALI will lay the technology groundwork for future land imaging instruments following the current Landsat 7 imager, the ETM+. The Hyperion is a science grade instrument providing a new class of Earth observation data from space with 220 spectral channels leading to improved surface spectral characterization. The LEISA AC instrument will test an atmospheric corrector that can increase the accuracy of surface reflectance estimates. A comparison of the instrument characteristics, including under-flight instruments, is given in Table 1.0.

The ALI Instrument was developed by MIT/LL, the Hyperion instrument was developed by TRW, Inc. and the LEISA AC instrument was developed by Goddard's Applied Engineering and Technology Directorate (AETD). All three instruments are under the project management of NASA's Goddard Space Flight Center, Greenbelt, MD.

Report Documentation Page		
<b>Report Date</b> 00012001	<b>Report Type</b> N/A	<b>Dates Covered (from... to)</b> -
<b>Title and Subtitle</b> Hyperion: A 0.4 $\mu\text{m}$ - 2.5 $\mu\text{m}$ Hyperspectral Imager for the NASA Earth Observing-1 Mission	<b>Contract Number</b>	
	<b>Grant Number</b>	
	<b>Program Element Number</b>	
<b>Author(s)</b> Lee, Paul; Carman, Steve; Chan, C. K.; Flannery, Marty; Folkman, Mark; Iverson, Kelly; Jarecke, Pete; Liao, Lushalan; Luong, Kien; McCuskey, Jim; Pearlman, Jay; Rasmussen, Kent; Segal, Carol; Viola, Delores; Watson, Wendy; Wolpert, Don; Gauthier, Vicky; Mastandrea, Andy; Perron, Gerry Szarek, Gerry	<b>Project Number</b>	
	<b>Task Number</b>	
	<b>Work Unit Number</b>	
<b>Performing Organization Name(s) and Address(es)</b> TRW Space and Technology Division, Redondo Beach, CA 90278	<b>Performing Organization Report Number</b>	
<b>Sponsoring/Monitoring Agency Name(s) and Address(es)</b> Director, CECOM RDEC Night Vision and Electronic Sensors Directorate, Security Team 10221 Burbeck Road Ft. Belvoir, VA 22060-5806	<b>Sponsor/Monitor's Acronym(s)</b>	
	<b>Sponsor/Monitor's Report Number(s)</b>	
<b>Distribution/Availability Statement</b> Approved for public release, distribution unlimited		
<b>Supplementary Notes</b> The original document contains color images.		
<b>Abstract</b>		
<b>Subject Terms</b>		
<b>Report Classification</b> unclassified	<b>Classification of this page</b> unclassified	
<b>Classification of Abstract</b> unclassified	<b>Limitation of Abstract</b> UNLIMITED	
<b>Number of Pages</b> 10		

Parameters	Landsat 7	EO-1	EO-1		A/C Underflight	
	ETM+	Multispectral	HYPERION	AC	AVIRIS	TRWIS III
Spectral Range	0.4 - 2.4* $\mu\text{m}$	0.4 - 2.4 $\mu\text{m}$	0.4 - 2.5 $\mu\text{m}$	0.9 - 1.6 $\mu\text{m}$	0.4 - 2.5 $\mu\text{m}$	0.4 - 2.5 $\mu\text{m}$
Spatial Resolution	30 m	30 m	30 m	250 m	20 m	1-8 m
Swath Width	185 Km	36 Km	7.5 Km	185 Km	11 Km	0.3 - 2.0 Km
Spectral Resolution	Variable	Variable	10 nm	6 nm	12 nm	6 nm
Spectral Coverage	Discrete	Discrete	Continuous	Continuous	Continuous	Continuous
Pan Band Resolution	15 m	10 m	N/A	N/A	N/A	N/A
Total Number of Bands	7	10	220	256	224	384

Table 1.0. EO-1 Instruments, ETM<sup>+</sup>, AVIRIS and TRWIS III Parameters Comparison

## 2.INSTRUMENT DEVELOPMENT

### 2.1 EO-1 Program

The EO-1 satellite will fly "in formation" with the Landsat 7 satellite in a sun-synchronous, 705 km orbit with a 10:01 am descending node. EO-1 will be in an orbit that covers the same ground track as Landsat 7, approximately one-minute behind Figure 2.1. The objective is to obtain images of the same ground area at nearly the same time, so that they may be directly compared.

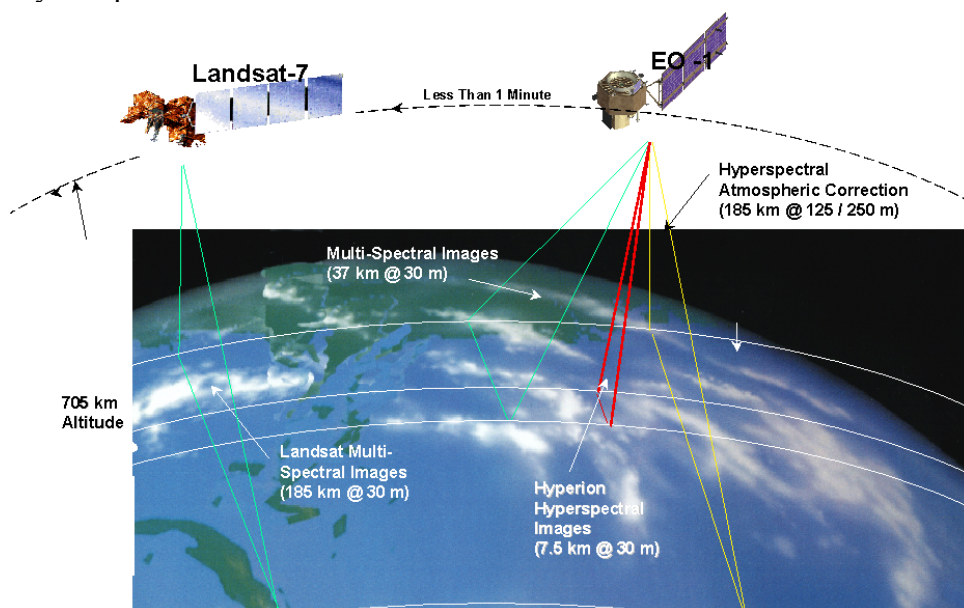


Figure 2.1 - EO-1 instruments and Landsat 7 cover the same ground track to support direct comparison of images

## 2.2 Hyperion Development

The Hyperion instrument was built by TRW, Inc. The optical structure was designed, fabricated, and assembled by SSG, Inc., the SWIR focal plane array was produced by Boeing, the VNIR focal plane array was built by Loral, and the gratings were fabricated by JPL. The Hyperion project had a fast-track schedule and used inventory remaining from the Lewis HSI instrument and leverages the experience gained in assembling and testing that instrument to accomplish instrument delivery in thirteen months. As with the HSI, the focus of the instrument is to provide high quality calibrated data that can support evaluation of hyperspectral technology for Earth observing missions.

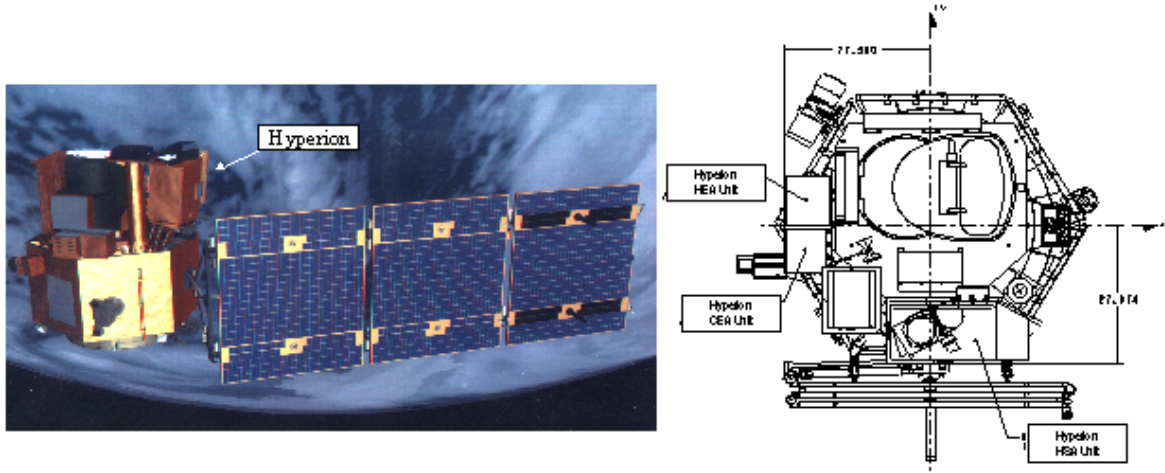


Figure 2.2 Locations of the Hyperion HSA, HEA and CEA components on the EO-1 Spacecraft

## 3. HYPERION DESIGN DESCRIPTION

### 3.1 Instrument Overview

The Hyperion is a push-broom instrument with a single telescope and two spectrometers, one visible/near infrared (VNIR) spectrometer and one short-wave infrared (SWIR) spectrometer. The VNIR spectrometer focal Plane Array (FPA) operates at 10°C and the SWIR spectrometer FPA is actively cooled to 110K with a pulse tube cryocooler. The unit calibration includes internal calibration lamps in addition to solar and moons calibration capabilities. Hyperion will produce hyperspectral images of the earth's surface with 30-meter spatial resolution over a 7.5km swath and 220 contiguous spectral channels from 0.4  $\mu\text{m}$  to 2.5  $\mu\text{m}$  in wavelength. Spectral bandwidth of each channel is 10 nm.

The Hyperion instrument consists of 3 physical units (Figure 3.1), (1) the Hyperion Sensor Assembly (HSA), (2) the Hyperion Electronics Assembly (HEA), and (3) the Cryocooler Electronics Assembly (CEA).

### 3.2 Hyperion Sensor Assembly (HSA)

The Hyperion Sensor Assembly (HSA) includes the telescope, the two grating spectrometers and the supporting focal plane electronics and cooling system. The optical system is shown in Figure 3.2.

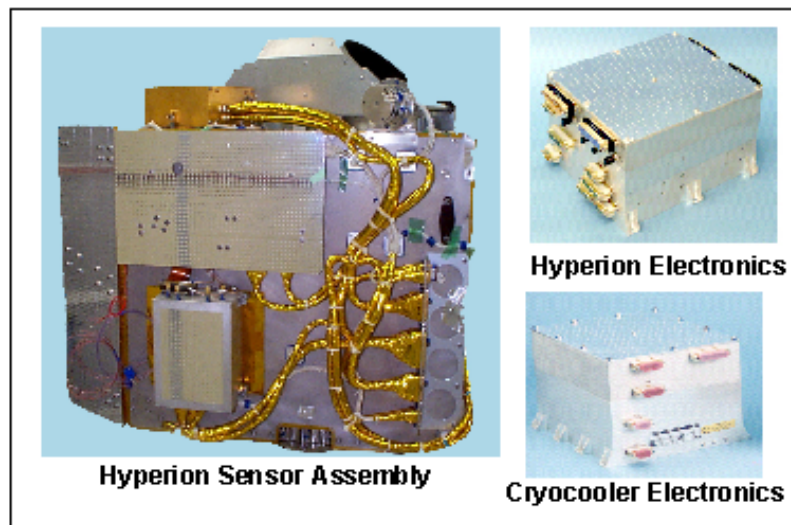


Figure 3.1 - Picture of Hyperion HSA, HEA and CEA

The HSA consists of an enclosure providing thermal control for the Opto-mechanical Subsystem (OMS) on which are mounted the VNIR and the SWIR FPAs. The thermal control of the HSA enclosure is provided by heaters, thermostats, radiators, and thermal straps. The HSA enclosure is the mounting interface between the HSA and the spacecraft, has a motorized aperture cover, and also provides support for the pulse tube cryocooler, the VNIR and the SWIR Analog Signal Processors (ASP), and the in-flight calibration source (IFCS). The SWIR FPA is cooled, via a thermal strap, by a cryocooler supported by a radiator, and the VNIR FPA is cooled via another thermal strap by a radiator. The ASP electronics boxes provide timing control for the FPAs, clocks out and transmits the FPA data to the HEA. The IFCS consists of a redundant set of lamps to illuminate the backside of the aperture cover, which is a diffused white screen. In addition, with the aperture cover partially open, solar illumination of the diffused white screen provides a second method for on-orbit radiometric calibration.

### 3.2.1 Hyperion Opto-Mechanical Structure (OMS)

The Hyperion OMS is designed and manufactured by SSG, Inc. The OMS consists of an optical metering structure (the optical bench) which supports the fore-optics, the VNIR spectrometer and the SWIR spectrometer. The OMS and imaging spectrometers are pinned and bolted together, permitting alignment of the two sections to take place independently. All of the mirrors in the system are constructed from coated aluminum and the structure holding the optical elements is also constructed from aluminum so that the mirrors and housing all expand and contract at the same rates. This results in an athermal design over a limited temperature range. In operation the housing will be maintained at  $20^{\circ} \pm 2^{\circ}\text{C}$  for precision imaging and alignment.

### 3.2.2 Fore-optics

The Hyperion fore-optics is a reflective telescope design.. The fore-optics image the Earth onto a slit that defines the instantaneous field-of-view of  $0.624^{\circ}$  wide (i.e., 7.5 Km swath width from a 703 Km altitude) by  $42.55 \mu$  radians (30 meters) in the satellite velocity direction. A dichroic filter behind the slit reflects the image spectrum from 400 to 1,000 nm to one spectrometer and transmits the spectral information from 900 to 2,500 nm to the other

spectrometer. The overlap with the VNIR from 900 to 1000 nm will allow cross calibration between the two spectrometers. All of the fore-optics and spectrometer optics are aluminum.

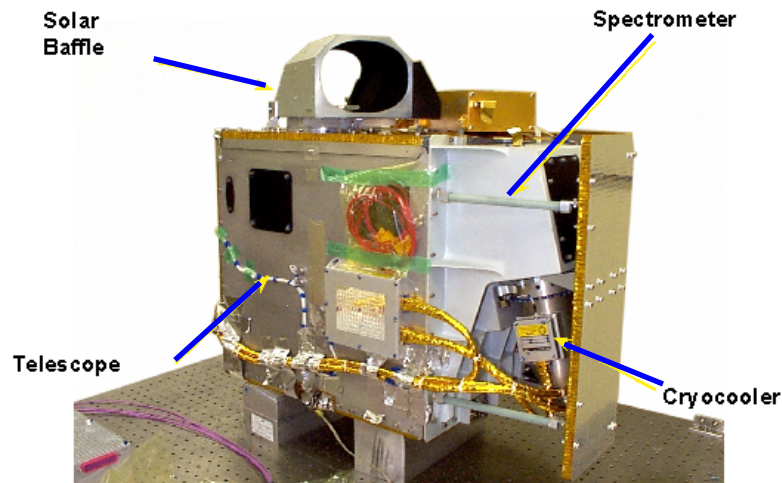


Figure 3.2 - Detailed view of the Hyperion Sensor Assembly (HSA)

### 3.2.3 - Imaging Spectrometers

The two grating imaging spectrometers shared a common set of fore-optics and slit. The imaging spectrometers used the NASA JPL 3-reflector Offner design with convex gratings. The convex gratings are designed and manufactured by NASA JPL. The spectrometers are designed, manufactured, aligned, and integrated with the fore-optics by SSG, Inc. The two grating imaging spectrometers relay the slit image of the Earth to two focal planes at a magnification of 1.38 :1. The focal plane dimension parallel to the slit axis provides the cross-track spatial image of the Earth through the slit while the axis perpendicular to the slit provides the spectral information on each cross-track pixel.

### 3.2.4 Focal Plane Arrays (FPA)

The two dimensional focal planes in the two spectrometers are designed for 223.4 Hz framing rates equivalent to the time that it takes the satellite to move forward one slit width. Each image taken in this “push broom” configuration captures the spectrum of the slit image. As the satellite progresses in its forward direction successive frames of data are gathered. Stacked on top of one another, they represent successive spectral Earth images along the satellite track. These so called “image cubes” can be taken for as long as a recorder has data storage space available.

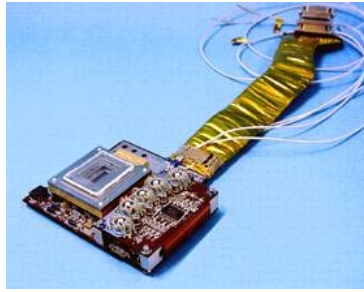
### 3.2.5 SWIR FPA

The HgCdTe shortwave infrared (SWIR) FPA (Figure 3.2.4) was developed specifically for hyperspectral imaging applications on TRW internal funds. This 2-D FPA has 256 x 256 pixels of 60  $\mu\text{m}$  pitch and a custom pixel readout integrated circuit that is highly linear at low photon flux levels. For the Hyperion instrument, only a 160 pixel (spectral) x 250 pixel (spatial) section of the FPA was used. The spectral bandwidth for each pixel is 10 nm. As a result, the spectral range of the instrument extends from 400 nm to 2,500 nm

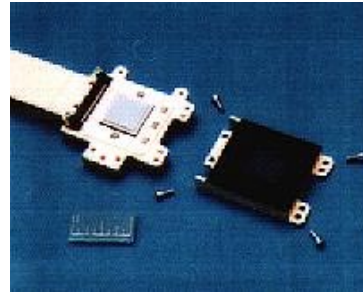


### 3.2.6 VNIR FPA

The visible/near-infrared (VNIR) FPA (Figure 3.2.4) was a custom development for the SSTI HSI instrument. This VNIR FPA is a MPP 2-D frame transfer CCD with 384 x 768 pixels of 20  $\mu\text{m}$  pitch. The FPA pixels are divided equally into 4 quadrants each with a frame transfer buffer, serial readout summing well and pre-amplifier. For Hyperion a 3 x 3 pixels aggregation is performed during the readout resulting in a 60  $\mu\text{m}$  pixel pitch. The Hyperion VNIR spectrometer uses only a 60 (spectral) x 250 (spatial) pixel section of the VNIR FPA to provide a 10 nm spectral bandwidth over a range of 400-1000 nm.



VNIR FPA Assembly



SWIR FPA Assembly

Figure 3.2.4 - Picture of the Hyperion 384 x 768 pixels frame transfer VNIR FPA and the HgCdTe 256 x 256 pixels SWIR FPA

### 3.3 Hyperion Electronics Assembly (HEA)

The HEA is separate from the HSA, and is mounted on the nadir deck with direct thermal contact. The HEA consists of electronics (1) to convert spacecraft 28VDC power to instrument power; (2) to support spacecraft command and telemetry via the 1773 data bus; (3) to collect and digitize the instrument state of health data; (4) to collect and digitize the VNIR and SWIR science data from the corresponding ASPs; (5) to support science data transmission to the spacecraft over two 32-wire RS-422 data buses; and (6) to support command and telemetry functions for the CEA.

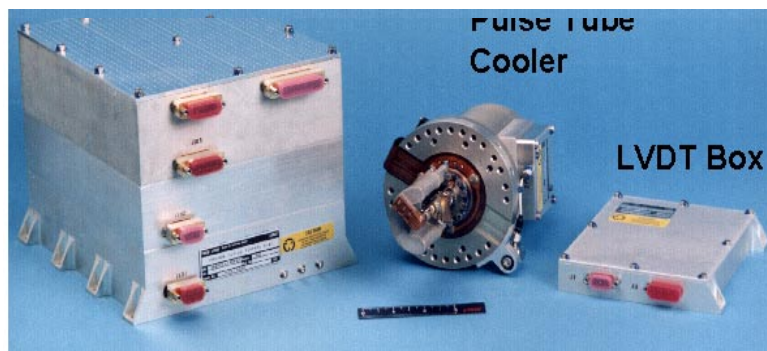


Figure 3.4 -The three components of the Pulse Tube Cryocooler support operation of the SWIR FPA at 115K.

### 3.4 Hyperion Cryocooler Electronics Assembly (CEA)

The CEA is also separate from the HSA, and is mounted on the payload platform with direct thermal contact. The CEA consists of electronics (1) to convert spacecraft 28VDC power to instrument power; (2) to support spacecraft command and telemetry via the HEA using a RS-422 data bus; and (3) to collect performance data from the pulse tube cooler and provide feedback control for optimal operation of the cryocooler.

### 3.5 Hyperion Radiometric Calibration

The Hyperion radiometric calibration approach employs a set of redundant internal calibration lamps, solar and lunar calibrations, and vicarious calibration to achieve the long-term absolute radiometric calibration goal of 6%. The internal lamps and solar calibration utilize a diffuse reflector on the backside of the optical cover to provide uniform illumination across the focal plane arrays; the direct viewing lunar calibration will be accomplished by scanning the instrument across the lunar surface, and vicarious calibration will use Hyperion images of well characterized ground targets.

A Hyperion calibration baseline was established during instrument integration and test using secondary standards transferred from primary standards, which reside at the TRW Radiometric Scale Facility. After integration of the instrument onto the EO-1 spacecraft, Hyperion performance was again verified and cross-checked against the ALI calibration. During the initial on-orbit checkout, the Hyperion internal calibration will be cross-referenced against both solar and lunar calibrations. A combination of internal, solar, lunar, and vicarious calibrations will provide continued monitoring of instrument performance during the life of the mission.

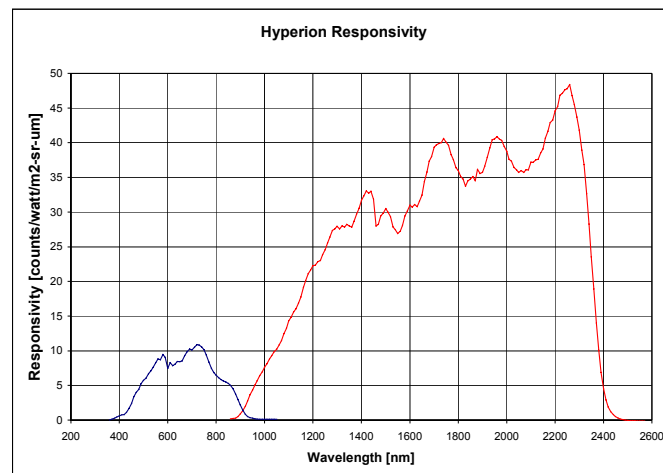


Figure 4.1 Measured Hyperion responsivity from 0.4 mm to 0.9mm (60 10nm channels on the VNIR FPA) and from 0.9 mm to 2.5 mm (160 10nm channels on the SWIR FPA).

## 4. HYPERION CHARACTERIZATION

The Hyperion instrument performance was characterized during instrument assembly and alignment, during the first and second thermal vacuum tests at TRW, and again after installation on the EO-1 spacecraft at GSFC. The Hyperion performance parameters measured include responsivity, signal-to-noise ratio (SNR), modulation transfer functions (MTF), cross-track spectral errors, spatial co-registration of spectral channels, VNIR and SWIR spectrometer co-



registration, linearity, Field of View (FOV) and Instantaneous Field of View (IFOV), polarization, etc. The following section will summarize results of a few of the more important performance parameters. Details of the Hyperion performance measurements were reported in Reference 2.

#### 4.1 Responsivity and Radiometric Calibration

The Hyperion is calibrated using primary standards and secondary standards from the TRW Radiometric Scale Facility. The primary standards include three Si high quantum efficiency trap detectors, NIST traceable FEL 1000 watts lamps, an electrically calibrated pyroelectric detector and a filter spectrometer. The end-to-end sensor calibration is accomplished with a 10-inch square Spectralon panel assembly which was illuminated by a 1000 watt FEL lamp and mounted on a vacuum chamber window outside the vacuum window. An error analysis of the transfer path is described in Reference 2 and 3. Figure 4.1 is a plot of the Hyperion responsivity obtained from the end-to-end instrument calibration.

#### 4.2 Signal-to-Noise Ratio (SNR)

The measured Hyperion SNR performances were shown in Figure 4.2 compared to the SNR estimates using a 30% Albedo Standard Scene at 45°-latitude north and with a 60° solar zenith-angle.

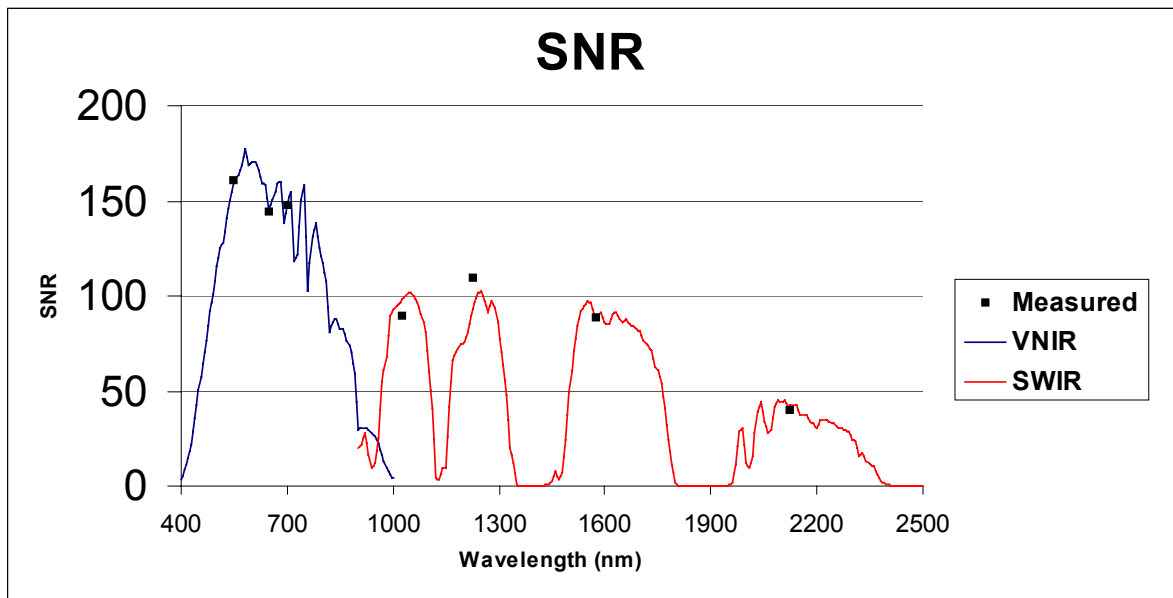


Figure 4.2. Hyperion VNIR and SWIR SNR measurements compared to estimates.

#### 4.3 - Modulation Transfer Function (MTF)

The Hyperion image quality characterized by the MTFs was measured in the cross-track direction using a standard knife-edge method and also by the direct mapping of a slit image. The results, shown in Table 4.3, were expressed as along-track MTF values by multiplying the cross-track MTFs by  $2/\pi$ , to account for the along track smear due to the spacecraft motion. The measurement repeatability is about 0.05.

#### 4.4 Spectral Errors and Spatial Co-registration

The cross-track spectral error measures the change in center wavelength along the FOV pixels. The measured Hyperion SWIR cross-track spectral error is less than 0.97 nm and this parameter is less than 3.3 nm for the VNIR worst case across the full FOV and over the entire spectral range of each spectrometer.

The spatial co-registration measures the change in position of a ground spot for all spectral channels. The measured Hyperion SWIR spatial co-registration of spectral channels is less than 0.28 pixel and for the VNIR channels is less than 0.25 pixel worst case across the full FOV and over the entire spectral range of each spectrometer. The spatial co-registration between the two Hyperion spectrometers is about one spatial pixel worst case across the full FOV. During spacecraft installation the Hyperion boresight is pinned to allow overlay of the ALI and AC footprint to allow direct cross comparison.

<b>Wavelength</b>	<b>-0.183°</b>	<b>Center FOV</b>	<b>+0.256°</b>
500 nm	0.29	0.27	0.22
630 nm	0.27	0.28	0.22
900 nm	0.24	0.26	0.22
1050 nm	0.28	0.30	0.28
1250 nm	0.28	0.30	0.27
1650 nm	0.27	0.27	0.25
2200 nm	0.28	0.27	0.23

Table 4.3 - Hyperion Along-track MTF Measurements at Three Cross-track FOVs

### 5. OPERATION

#### 5. Operations

The EO-1 satellite will fly in a sun-synchronous, 705km orbit with a 10:01 am descending node. Hyperion image data collections will be taken on approximately three orbits per day. With the EO-1 spacecraft capable of a 22-degree roll angle, targets on the Earth's surface can be imaged at various angles of observation for up to 5 times during the 16-day orbital re-visiting time. A Hyperion data collection event (DCE) includes a dark calibration before and after the imaging data collection, and a white and dark calibration following the second dark cal. Lunar calibration is performed about once per month; solar calibration is performed about once per week. The maximum Hyperion imaging time is approximately 3 minutes limited by the capacity of the onboard recorder. A standard Hyperion image, or cube, consists of 660 frames of data and takes about 3 seconds to collect.

Hyperion imaging and reference data is stored on the EO-1 WARP solid state recorder before being downlinked to ground station for processing. Level 0+ data processing at the Mission Operations Center (MOC) will restore Hyperion data to the correct frame order and integrate the separate VNIR and SWIR image cubes. Level 1 processing separates calibration data from image data, converts header data into physical units and performs radiometric calibration using the flight calibration data. All Level 1 processing for Hyperion will be performed at TRW's facilities in Redondo Beach, CA. Hyperion data will be available through the GSFC Science Validation Facility.

## 6. CONCLUSION

The Hyperion instrument will provide a new class of earth observation data for improved Earth surface characterization. Hyperion was delivered to GSFC for integration onto the EO-1 spacecraft in July, 1999, twelve months after the start of contract. Spacecraft integration was completed and end-to-end instrument testing is ongoing. The launch of EO-1 spacecraft is scheduled for July, 2000. Under NRA-99-OES-01, NASA and the U. S. Geological Survey (USGS) of the Department of the Interior (DOI) have jointly selected 31 proposals for scientific investigation to validate the NASA NMP Earth Observing-1 (EO-1) mission technologies and to assess EO-1 spectral imaging for science and application research.

## 7. ACKNOWLEDGEMENTS

The authors would like to thank the TRW Hyperion Team for their dedication that made possible the delivery of the Hyperion instrument in 12 months to meet the NASA challenge. We also thank NASA JPL for the manufacturing of a pair of high quality convex gratings. In addition, we would like to acknowledge the team work and support by the NASA GSFC Hyperion Project Team, the NASA GSFC EO-1 Program personnel, and the Swales EO-1 Spacecraft Team.

## 8. REFERENCES

1. P. Jarecke, L. Liao, "Radiometric Performance Characterization of the Hyperion Imaging Spectrometer Instrument", Conf. on Characterization and Radiometric Calibration for Remote Sensing, Utah, 1999
2. P. Jarecke, K. Yokoyama, "Radiometric Calibration of the Hyperion Imaging Spectrometer Instrument from Primary Standards to End-to-End Calibration", Conf. on Characterization and Radiometric Calibration for Remote Sensing, Utah, 1999
3. Jay Pearlman, Stephen Carman, Paul Lee, Lushalan Liao, Carol Segal, "Hyperion Imaging Spectrometer on the New Millennium Program Earth Orbiter-1 System", The 1999 International Symposium on Spectral Sensing Research (ISSSR99) and International Society for Photogrammetry and Remote Sensing (ISPRS) Commission 7, Working Group 1: Fundamental Physics and Modeling, October 31, 1999 - November 4, 1999, Tropicana Resort and Casino, Las Vegas, NV.