Hyperion Data Collection:
Performance Assessment and Science Application

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***Abstract*--The EO-1 spacecraft, part of the New Millennium Program, hosts three advanced technologies, the Hyperion Imaging Spectrometer, the Advanced Land Imager (ALI), and the LEISA Atmospheric Corrector (LAC) payloads. EO-1 was launched November 21, 2000 into a sun synchronous orbit behind Landsat 7. Hyperion, which has a 7.6 km swath width, a 30 meter ground resolution and 220 spectral bands, is the focus of this paper. The calibrated spectral bands extend from 400 nm to 2400 nm in 10 nm bandwidths. The initial objectives for the TRW Hyperion team was to characterize the on-orbit performance as thoroughly as possible and to compare with pre-flight characterization test data. On-orbit characterization was followed by research activities carried out by the EO-1 Science Validation Team aimed at assessing the utility of space-based hyperspectral data. This paper provides an overview of the technical innovation and on-orbit characterization of the Hyperion instrument. This paper highlights data collects and analysis methodology of a set of standard and unique data collects that were defined to address specific issues. Sample science applications are also briefly discussed.**

1. INTRODUCTION

EO-1 is a member of the New Millennium Program (NMP), an initiative to demonstrate advanced technologies and designs that show promise for dramatically reducing the cost and improving the quality of instruments and spacecraft for future space missions. The primary EO-1 mission is to validate new instrument technologies in flight and to provide science data to the user community for utility assessments. The three primary instruments are the Advanced Land Imager (ALI) [1], the Hyperion hyperspectral imager [2] and the Linear etalon imaging spectrometer array (Leisa) Atmospheric Corrector (LAC) [3]. An overview of these three instruments is given in Table 1 along with characteristics of the Landsat Enhanced Thematic Mapper (ETM+). This paper focuses on the Hyperion instrument.

One of the first objectives for Hyperion was to characterize the radiometric performance of the imaging spectrometer and compare it against the performance established during pre-flight tests. A set of standard and unique data collects were defined to address specific radiometric, spectral and image quality calibration issues. This paper presents a sample of the data collects and analysis methodology that were used to characterize the on-orbit performance. An introduction to some of the sample applications is also provided.

The paper is organized to, first, present an overview of the Hyperion instrument. Subsequent sections provide a summary comparison of the pre-flight characterization and a description of the on-orbit characterization process. A description of methods used to address the radiometric, spectral and optical characterization of the instrument on-orbit is provided, followed by a brief discussion of some sample applications.

2. HYPERION SYSTEM DESCRIPTION

The Hyperion instrument provides high quality calibrated data that supports the evaluation of hyperspectral technology for Earth observing missions. Hyperion is a pushbroom imaging instrument. Each image taken in this configuration captures the spectrum for each of the 256 cross-track pixels that comprise the 7.6 km swath width which is perpendicular to the spacecraft velocity. Each pixel views a 30 m x 30 m region of the ground. The swath length of each image depends on the duration of the collect and is commanded by the spacecraft.

	MULTISPECTRAL		HYPERSPECTRAL	
	Landsat 7	EO-1	EO-1	
Parameters	ETM+	ALI	HYPERION	LAC
Spectral Range	0.4 - 2.4* µm	0.4 - 2.4 µm	0.4 - 2.5 µm	0.9 - 1.6 µm
Spatial Resolution	30 m	30 m	30 m	250 m
Swath Width	185 Km	37 Km	7.6 Km	185 Km
Spectral Resolution	Variable	Variable	10 nm	2-6 nm
Spectral Coverage	Discrete	Discrete	Continuous	Continuous
Pan Band Resolution	15 m	10 m	N/A	N/A
Number of Bands	7	10	220	256

TABLE I
SUMMARY OF PRIMARY EO-1 INSTRUMENT CHARACTERISTICS AND COMPARISON WITH LANDSAT 7

Hyperion has a single telescope and two spectrometers, one visible/near infrared (VNIR) spectrometer and one short-wave infrared (SWIR)) spectrometer. The Hyperion instrument consists of 3 physical units: Hyperion Sensor Assembly (HSA); Hyperion Electronics Assembly (HEA); and Cryocooler Electronics Assembly (CEA).

The HSA shown in Fig. 1 includes subsystems for the telescope, internal calibration lamps, the two grating spectrometers and the supporting focal plane electronics and cryocooling system. The Hyperion telescope (fore-optics) is a three-mirror-anastigmat design. The telescope images the Earth onto a slit that defines the instantaneous field-of-view which is 0.624° wide (i.e., 7.6 Km swath width from a 705 Km altitude) by 42.55 µ radians (30 meters) in the satellite velocity direction. The HEA contains the interface and control electronics for the instrument. The CEA controls cryocooler operation. These units are placed on the deck of the spacecraft with the viewing direction along the major axes of the spacecraft.

The VNIR spectrometer uses a 70 (spectral) by 256 (spatial) pixel array, which provides a 10 nm spectral bandwidth over a range of 400-1000 nm. The SWIR spectrometer uses HgCdTe detectors in an array of 172 (spectral) x 256 (spatial) channels. Similar to the VNIR, the SWIR spectral bandwidth is 10 nm. The calibrated spectral channels range from 400 to 2400 nm with a spectral resolution of 10nm. The HgCdTe detectors, cooled by an advanced TRW cryocooler, are maintained at 118 K.

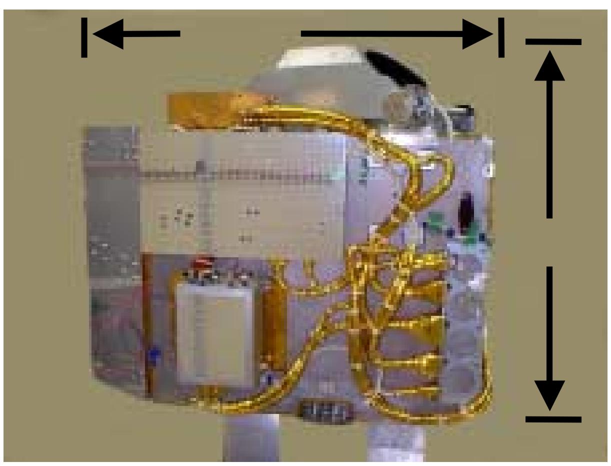

Fig. 1. Hyperion Sensor Assembly includes the telescope, the two grating spectrometers and the supporting focal plane electronics and cryocooler. Dimensions in inches

3. Hyperion Performance and Characterization

Pre-launch, the instrument was extensively characterized to provide a performance baseline for the collection of radiometric data for use by the Hyperion science team as described by Liao [4] and Jarecke [5].

Following launch, the on-orbit instrument performance was characterized and compared with pre-launch measurements. The characterization was carried out over a four-month period. A variety of sites were specified in order to perform the on-orbit characterization. These include targets such as:

1.) Radiometric ground truth sites
2.) Lunar, and Solar Collects
3.) Atmospheric Limb and studied mineralogical sites
4.) Bridge scenes, ice shelf
5.) Well documented agricultural sites
6.) High Contrast scenes

Sites were targeted for use in measuring specific instrument parameters such as, in corresponding order:

1.) Absolute calibration
2.) Repeatability, stability
3.) Spectral calibration
4.) MTF
5.) VNIR – SWIR alignment
6.) Artifact correction verification and detection

Table II presents the results from the final comparison. The on-orbit measured performance agreed with the pre-flight measurements. The following sections describe details of the radiometric, spectral and optical characterization that were the basis for the numbers presented in Table II. The pre-flight and on-orbit comparison took into consideration the accuracy of each characterization technique. There were some characteristics, such as the spectral bandwidth, for which on-orbit characterization was not attempted.

Characteristic	**Pre-launch Cal**	**On-orbit Cal**
Ground Sample Distance (GSD,m)	29.88	30.38
Swath (km)	7.5	7.75
No. of Spectral Channels	220	200 (L1 data)
VNIR SNR (550-700nm)	144-161	140-190
SWIR SNR (~1225nm)	110	96
SWIR SNR (~2125nm)	40	38
VNIR X-trk Spec. Err	2.8nm@655nm	*
SWIR X-trk Spec. Err	0.6nm@1700nm	0.58
Spatial Co-Reg: VNIR	18%@Pix#126	*
Spatial Co-Reg: SWIR	21%@Pix#131	*
Abs.Radiometry(1Sigma)	<6%	3.4%
VNIR MTF@630nm	0.22-0.28	0.23-0.27
SWIR MTF@1650nm	0.25-0.27	0.28
VNIR Bandwidth	10.19-10.21	*
SWIR Bandwidth	10.08-10.09	*

*similar to pre-launch values within measurement error.

TABLE II
Summary of On-orbit and Pre-flight Characteristics

4. Hyperion Radiometric Characterization

The on-orbit radiometric characterization incorporated the use of vicarious calibration sites, lunar calibration collects and solar calibration collects. Each collect offers unique opportunities to study the instrument.

Vicarious Calibration

Vicarious calibration provides a unique opportunity to investigate the characteristics of the instrument from a direction that is user-oriented. The process involves extensive ground truth and coordination with spacecraft mission operations to coordinate the time of data collection of the spacecraft with the ground truth measurements. The result is a direct comparison of the top of atmosphere (TOA) radiance measurements made by the instrument with the top of atmosphere prediction based on the independently measured ground spectral reflectance measurements and propagation through a modeled atmosphere. The primary vicarious site incorporated into the Hyperion performance characterization was Lake Frome, South Australia, in coordination with Australian Commonwealth Science and Industrial Research Organization (CSIRO), [6],[7],[8].

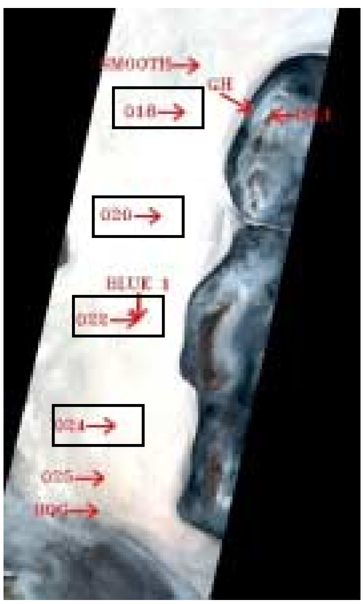

Fig. 2 Hyperion image of Lake Frome Calibration Site.

Lake Frome is located in the north east of South Australia and is a large, normally dry salt lake (playa). Fig. 2 shows the Hyperion RGB representation of the playa with the ground truth sites indicated. The sites encased in the boxes were used in the analysis. The radiometric comparison is provided in fig 3. The ratio of the Lake Frome ground truth-estimated TOA to the Hyperion-measured TOA radiance is provided. The variation in the VNIR was consistent with the variation determined using the lunar calibration collect, which will be discussed next. The variation in the SWIR has higher uncertainty since the ground collect was not coincident with the overpass date and the moisture content in the salt playa is suspected to have changed.

The accuracy of the comparison is dependent on the atmospheric correction model, including the solar irradiance profile used, and the stability / precision of the instruments used during the ground truth as well as the timing of the collect relative to the overpass. An unanticipated but critical value of the Lake Frome campaign was that the ground control points were used to confirm the spatial relationship between the independent VNIR and SWIR images.

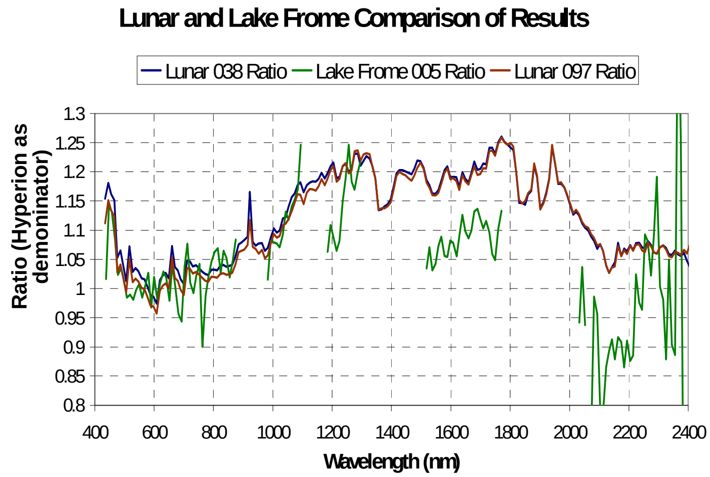

Fig. 3 Hyperion Comparison with reference for Lake Frome and Lunar Calibration Studies.

Lunar Calibration:

The Lunar calibration collect was found to be one of the most studied on-orbit collects. The moon is viewed directly by the instrument. There is no atmosphere that needs to be estimated. A model of the lunar irradiance is required and depends on the spacecraft position, as well as the relative positions of the earth, moon and sun. The process of modeling of the lunar irradiance is described by Keiffer [9] and involves using spacecraft telemetry and a number of lunar model coefficients. Fig. 3 shows the ratio of the lunar irradiance to the instrument measured irradiance. The results here are consistent with Ref 9 for day 38. The difference between day 38 and day 97 reported in Ref 9, and not seen here, was due to an inconsistency in the processing level of day 97 provided for the analysis used in Ref 9.

Note that the Lake Frome results match the Lunar results from 400 nm to 1100 nm. It is important to recognize that these two pathways are extremely different. The excellent agreement from the 400 nm to the 1100 nm range is a testament to the quality of each of the activities.

The lunar collect provides the opportunity for repeatability analysis. EO-1 obtains Lunar Calibration collects once per month, alternating between Hyperion and ALI centered pointing. Fig. 4 shows a subset of the lunar images collected. Note that the entire Hyperion swath is presented. The spacecraft pointing was commanded to slightly different angles during the early portion of the mission causing the location of the moon within the Hyperion swath to vary. The use of the lunar collects for repeatability assessment is described in-conjunction with the solar calibration collects discussed in the next section.

The lunar collect, being a bright target with limb regions and a deep space background, enables detailed study of additional instrument characteristics. For example, the lunar collect is also used to verify proper dark subtraction, proper artifact correction, identify artifacts, and measure image quality parameters.

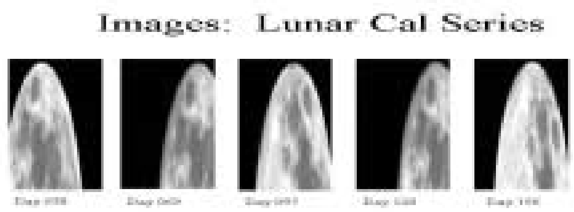

Fig. 4 Series of Lunar Calibration Images used to assess Hyperion repeatability.

Solar Calibration

The Hyperion instrument does not view the sun directly. In order to view the sun, the spacecraft performs a yaw maneuver such that sunlight reflects off the solar calibration panel into the instrument aperture. This requires the cover to be commanded to a partially open position, and requires a specific spacecraft rotation. The solar calibration collect is unique in that it provides a uniform cross-track reference that is very stable.

The solar calibration collect was used for absolute comparison and to update the pre-flight calibration file by correcting for pixel-to-pixel variations [10]. The solar calibration taken on Feb 16 was used for this purpose. This is the only difference between the pre-flight and on-orbit calibration file.

EO-1 continues to collect Hyperion solar calibration images once per two weeks. These collects are used in conjunction with the lunar calibration collects to monitor the instrument stability. Fig. 5 and 6, respectively, show the repeatability of two wavelengths in the VNIR and two wavelengths in the SWIR relative to the collect closest to day 097, and relative to VNIR band 40. The series of lunar and solar calibration collects are used to measure the continued repeatability of the VNIR and SWIR. The VNIR repeatability is better than 1 %. The repeatability of the SWIR is better than 3 % with some of the variation indicated by the solar calibration trends possibly due to the variations in the data collect. The reflectance of the cover surface is sensitive to pointing angle of the spacecraft.

Radiometric Calibration Summary:

This section highlights the three main radiometric calibration collects. The results indicate the VNIR is within 5 % of expectation and perhaps the calibration file should be updated based on the consistent lunar and Lake Frome findings. The comparisons show a larger ratio in the SWIR, however, the lunar and Lake Frome results are not consistent above 1100 nm. Consistent results in the SWIR are required before recommendations can be made. Although not presented, cross-comparisons with Landsat ETM + support the VNIR findings, and show even more differences in the SWIR.

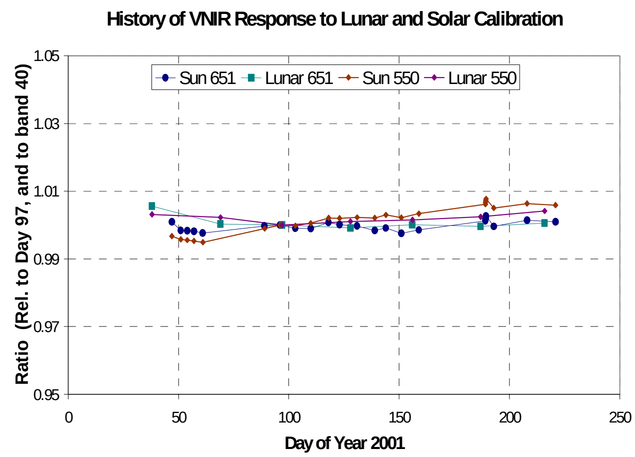

Fig. 5 VNIR Repeatability Assessment

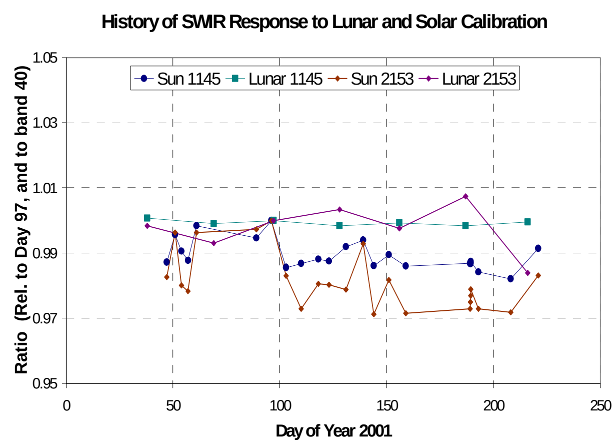

Fig. 6 SWIR Repeatability Assessment

5. Hyperion Spectral Characterization

One of the key performance parameters is the spectral calibration. The spectral calibration is defined by a center wavelength and bandwidth at full width half maximum of a modeled Gaussian spectral response function. The spectral calibration is defined for each spectral channel for each row of pixels along the spatial dimension.

The observational data required to perform this verification must contain clearly defined spectral features that can be identified and traced to a reference spectrum. We attempted to use features in ground scenes but difficulties arose in removing the spectral continuum. The variable spectral reflection of the earth's surface added uncertainty to the process.

A data collection of earth's atmospheric limb provided a more tractable data source. The atmospheric limb is a solar calibration collect scheduled such that the instrument views the sun through different tangent heights of the atmosphere Fig 7. Recall that Hyperion views the reflectance of the sun off the solar panel diffuser. The result is a collect that is uniform across the field of view and contains spectral features, which can be matched with solar lines, atmospheric lines and absorption lines associated with the solar diffuser.

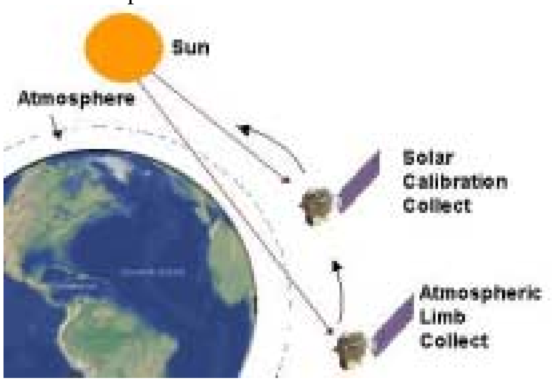

Fig. 7 Atmospheric Limb Collect Pictoral

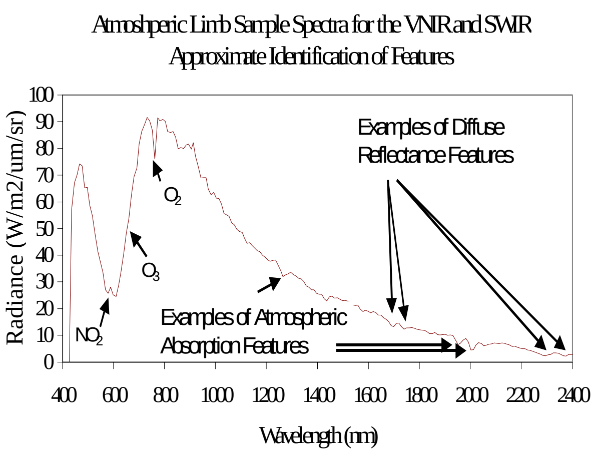

Fig. 8 Sample Atmospheric Limb Hyperion Spectra

The process enabled the center wavelength and variation of the center wavelength across the field of view to be characterized on-orbit [11]. There remain some uncertainties in the spectral location of features associated with the atmosphere. The most accurate spectral features were associated with the properties of the solar diffuser, the oxygen line and a Fraunhoffer line.

Although periodic repeats of the atmospheric limb collect are planned, the Hyperion spectral calibration is expected to be constant since the Hyperion instrument spectrometer is temperature controlled.

The application of the spectral calibration file in the SWIR was confirmed by the analysis of the minerals in the Mt Fitton, South Australia test site [12]. In this case, details of the SWIR spectrum were used to identify subtle differences in the SWIR spectra enabling the classification presented in Fig. 9.

However, the results confirm that the Hyperion pre-flight spectral calibration derived on the ground is valid for on-orbit operations. The more precise spectral calibration that was derived pre-flight was released for on-orbit operations.

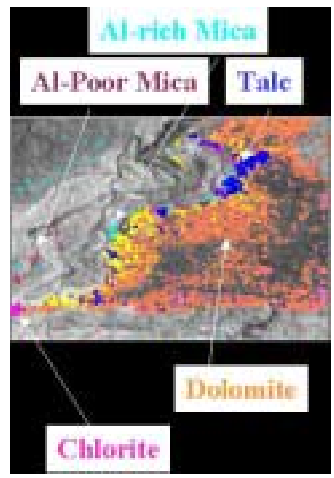

Fig. 9 Mt Fitton Mineral Classification based on SWIR spectra

6. HYPERION OPTICAL CHARACTERIZATION

Part of the on-orbit characterization involves measuring the spatial resolution for an imaging system. The Modulation Transfer Function (MTF) was calculated for the VNIR and SWIR from both edge and bridge objects. Bridge scenes produced excellent correlation with the pre-flight measurements while the edge scenes offered challenges for continued algorithm development [13]. Based on the average difference between the pre-flight and on-orbit MTF measurements there has not been significant change in the Hyperion optical performance due to the launch or operational environment.

Fig. 10 and 11 below show samples of data used for the MTF analysis. The image is of the Mid-Bay Bridge near Eglin AFB in Destin, Florida. The Hyperion image was acquired on December 24, 2000 and was used to measure cross-track MTF. The left picture is a close-up of the bridge from band 30 which has a center wavelength of 0.650 µm. The right image is a color composite from three Hyperion bands (Red = Band 28, Green = Band 21, Blue = Band 16).

To measure the MTF the Line Spread Function (LSF) is sampled at a higher resolution than the GSD. This is accomplished by analyzing an object at a slight angle to the spacecraft direction and interlacing the consecutive frames. In this bridge scene the angle is too small to use consecutive frames so every 5th frame is used in the interlaced LSF. The interlaced LSF is then processed with a Fourier transform and adjusted by the bridge width to determine the MTF. The MTF at Nyquist measured using this scene agreed with the pre-flight measured value of 0.42.

In addition to measuring the spatial resolution of the imaging system, the ground sample distance and the VNIR to SWIR spatial relationship were measured on orbit.

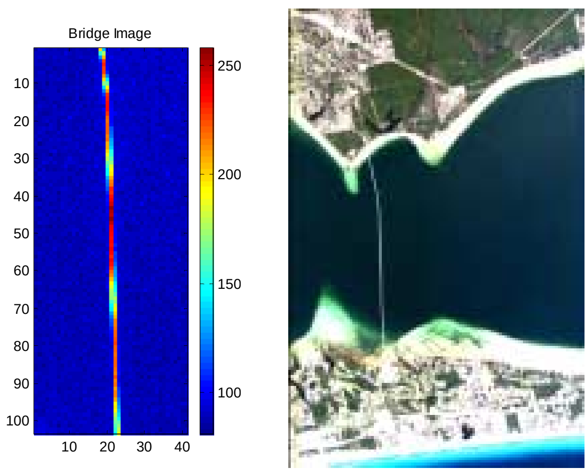

Fig. 10 Mid-Bay Bridge near Eglin AFB in Destin, Florida

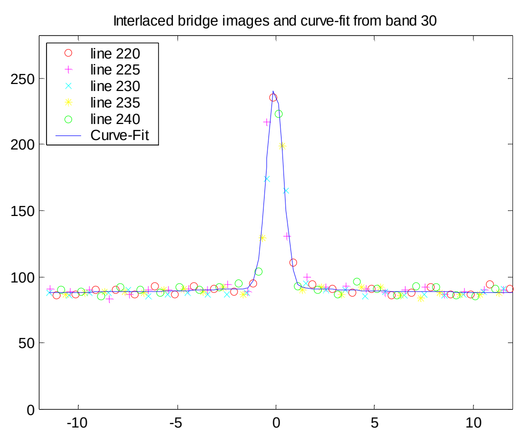

Fig. 11 Line Response Function for Mid-Bay Bridge

7. Hyperion Applications

The EO-1 Science Validation Team was selected by NASA with the task of evaluating the added science benefit from hyperspectral data. The scientists' range of interests includes studying the

1. geology
2. agricultural monitoring
3. volcanic temperature measurement
4. study of reef and coral bay health
5. glaciological applications

To support these activities there are also members studying areas that support the data quality such as atmospheric removal and vicarious calibration. Further information about the EO-1 validation program can be found through the http://eo1.gsfc.nasa.gov website.

Different instrument performance criteria are more important to different science applications. For example, for the geological studies, emphasis is placed on the furthest portion of the SWIR spectrum, which typically has a low signal. In comparison, the studies of the volcano plumes involve investigation of the temperature that has a signal so great that it will saturate the furthest portion of the SWIR spectra. Other applications, such as the agricultural and oceanographic studies may focus more attention on the VNIR bands with the oceanographic studies more concerned about the lowest portion of the instruments dynamic range.

8. Conclusions

The EO-1 Hyperion Instrument accomplished a very successful mission, meeting all the goals for on-orbit radiometric performance and performance characterization. As such, it will provide hyperspectral imagery with excellent radiometric quality to the science community for further use in establishing the value of this technology in remote sensing of the earth's environment.

Acknowledgements

The success of the EO-1 Hyperion program was driven by the TRW team that supported the design, test, and analysis of the instrument, during pre-flight and on-orbit operations. Significant support from the NASA operations team and science validation community is greatly appreciated. The authors would like to particularly express appreciation for the support from the Commonwealth Science and Industrial Research Organization (CSIRO), Australia led by David Jupp and the lunar calibration support led by Hugh Keiffer, United States Geological Survey (USGS) for technical contributions during initial on-orbit and continued on-orbit scientific analysis.

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