Vicarious Radiometric Calibration of EO-1 Sensors by Reference to High-Reflectance Ground Targets

Stuart F. Biggar, Kurtis J. Thome, and Wit Wisniewski

***Abstract*—The Remote Sensing Group at the University of Arizona has been using ground targets for the in-flight vicarious calibration of airborne and satellite sensors since the early 1980s. Targets such as Railroad Valley Playa in north central Nevada and White Sands Missile Range in New Mexico have proven to be useful for this work. This paper presents the results from multiple vicarious calibration experiments at a variety of sites for two of the Earth Observing 1 (EO-1) optical sensors. The Advanced Land Imager (ALI) and Hyperion sensors operate in the visible and shortwave infrared portions of the spectrum. The ground sample distance of about 30 m works well for vicarious calibration and allows an easy comparison to legacy sensors such as the Enhanced Thematic Mapper Plus (ETM+) which has the same 30-m ground sample distance. The approach used in this work is to measure the surface reflectance and atmospheric properties during the sensor image acquisition. These data are used as input to a radiative transfer code which computes the top of atmosphere spectral radiance. This predicted radiance is compared to the radiance from the image of the site. Results show that the preflight calibrations of ALI and Hyperion are probably not consistent with in-flight performance of the instruments. New calibration coefficients adopted in December 2001 improve the comparison to the vicarious predictions.**

***Index Terms*—Absolute-radiometric calibration, Advanced Land Imager (ALI), Hyperion, vicarious calibration.**

I. Introduction

THE EARTH Observing 1 satellite was launched on November 21, 2000 into an orbit trailing Landsat-7 by about 1 min and preceding Terra by about 40 min. It carries three experimental optical imaging sensors along with other experiments such as an electronically steered antenna in place of a mechanically steered high-gain antenna and a pulsed plasma thruster to be used for attitude control. The satellite is also capable of autonomous formation flying with Landsat-7. The optical imaging sensors forming the satellite payload are the Advanced Land Imager (ALI), Hyperion, and the Linear Etalon Imaging Spectrometer Array (LEISA) Atmospheric Corrector (LAC). This paper will describe the vicarious calibration of the ALI and Hyperion Instruments by reference to high-reflectance ground targets. Papers detailing the ALI and Hyperion sensors can be found elsewhere in this special issue.

The ALI is a completely new design as compared to the scanning ETM+ instrument. It uses a 15° field-of-view (FOV) telescope and filtered linear arrays. As ALI is a proof of concept, only one fifth of the focal plane was populated by detector and filter assemblies. Therefore, the swath width is about 37 km, while the 30-m ground sample distance is the same as the earlier Thematic Mapper (TM) sensors. There are nine spectral bands and one 10-m ground sample distance pan band. The telescope is a reflective triplet with a 15° cross-track FOV and a 1.26° along-track FOV. There is also a flat folding mirror between the last powered element and the focal plane. The design uses a reflective stop at the second mirror, a flat focal plane, and is telecentric in image space. The four mirrors are silicon carbide which has good mechanical properties for use in space but is difficult to polish to a low scatter surface.

Only a 3° FOV segment at one edge of the focal plane is populated by sensor chip assemblies (SCAs). Each SCA has 320 spectral and 960 pan detectors with strip interference filters over each linear array of detectors. The linear array allows for long integration time as compared to the scan mirror (pushbroom in place of whisk broom scan) in TM and ETM+ which allows for a much improved SNR. The pan and first six spectral bands use silicon detector arrays and the three SWIR bands are made of mercury-cadmium-telluride (HgCdTe) arrays. The focal plane assembly is passively cooled by a radiative cooler to about 220 K.

The ALI instrument has an on-board radiometric calibration capability. A variable aperture in the instrument aperture cover allows sunlight to illuminate a Spectralon diffuser which can be deployed in front of the secondary mirror. There is also an on-board lamp source which illuminates the focal plane. As the EO-1 satellite is agile, the ALI sensor can also be pointed at the moon at a consistent phase to determine a radiometric calibration. The goals are 5% absolute and 2% relative radiometric calibration during the mission. Preflight calibration radiometric response was estimated to be within $\pm 3.5\%$ [1].

The Hyperion sensor is a pushbroom hyperspectral sensor covering the range from 400–2500 nm with 220 spectral bands. The nominal ground sample distance is 30 m with a narrow image swath of about 7.5 km. This swath mostly overlaps the populated portion of the ALI sensor swath. Hyperion has two grating spectrometers covering a wavelength range of 400–1000 nm with a silicon CCD and the 900–2500-nm range with an HgCdTe detector array. A single telescope and slit are used with a dichroic filter to split the signal to the two spectrometers. The SWIR focal plane is cooled to about 110 K by a cryocooler in order to improve the SNR and to enhance stability.

Hyperion has common in-flight radiometric calibration systems for the two spectrometers. Two independent strings of two

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incandescent lamps produce a reference signal which can be compared to both solar and lunar calibrations. The solar calibrator is a diffuse white paint applied to the back side of the instrument aperture cover. The cover is set to a 37° angle, and the spacecraft is oriented to illuminate the diffuser surface with a direct solar beam. The EO-1 satellite can also be oriented such that Hyperion can view the moon for lunar calibrations.

II. Vicarious Calibration

The Remote Sensing Group (RSG) of the Optical Sciences Center has done in-flight radiometric calibrations of various spacecraft and aircraft optical sensors since the early 1980s. Example satellite sensors include the Thematic Mapper and Enhanced Thematic Mapper Plus on the Landsat series and the Systeme Pour l'Observation de la Terre (SPOT) series of sensors. Aircraft sensors have included the Airborne Visible/Infrared Imaging Spectroradiometer and the Moderate Resolution Imaging Spectroradiometer/Advanced Spaceborne Thermal Emission and Reflection Radiometer (MODIS/ASTER) Airborne Simulator. This work is normally done at field sites that are characterized by high probability of clear skies, low aerosol loading, flat level terrain, uniform, high surface reflectance, and near lambertian reflectance characteristics for view angles slightly off nadir [2]–[5]. Example sites include the alkali flats at the White Sands Missile Range in New Mexico and dry lake beds such as Ivanpah playa near the California/Nevada border and Railroad Valley and Lunar Lake in central Nevada. We have also used a uniform, weathered, asphalt parking lot surface at the Pima County (Arizona) Fairgrounds, as it is close to our laboratory and hence allows more frequent experiments. Accurate radiometric calibration of a sensor allows for atmospheric correction of data and retrieval of surface reflectance. Calibration also allows for a correction of instrument drift over time and for comparison of datasets from different sensors.

The radiometric calibration depends on measurements of the reflectance of the bright surface and characterization of the atmospheric path from the sun to the surface and then to the sensor. The in-situ measurements are used to determine the spectral directional reflectance of the surface and the spectral optical depth components causing scattering in the atmosphere (aerosols and molecules) [6]. These data are used as inputs to a Gauss–Seidel radiative transfer code which computes the radiance field at an angular grid at various heights in the atmosphere [7]. The Gauss–Seidel code also computes the effect of ozone absorption based on a nominal vertical profile and an estimate of the total column ozone amount derived from the optical depth measurements. The sites used are fairly large and homogeneous to minimize the effects of surface nonuniformity and the adjacency effect. The code, however, does not compensate for three-dimensional or surface reflectance changes. The radiative transfer code is run for multiple monochromatic wavelengths covering the wavelength range of the sensor. For this work, the range of 350–2500 nm is computed at a spacing of 1 nm. The output of the code is a normalized radiance for one unit of solar irradiance incident on the top of the atmosphere. To convert to absolute radiance, a solar model must be applied. For this work, the solar irradiance model chosen is the MODTRAN4 Chance database. This particular spectrum was chosen, as it is used for ETM+ and allows consistent comparisons with ETM+. The higher resolution MODTRAN data are averaged over a 1-nm interval before being used to convert the normalized radiance values from the radiative transfer code. A band-averaged radiance is then computed given the spectral response of each sensor spectral band. For ALI, the measured preflight spectral response curves published by Lincoln Laboratory were used. For Hyperion, the gaussian shape, width, and center wavelength published by TRW were used. This band-averaged radiance is then corrected for absorption by gases such as water vapor and oxygen using MODTRAN [8].

An area of the ground covering multiple pixels in usually measured for high spatial resolution sensors (e.g., we usually measure a site equivalent to 16×4 30-m pixels for the Landsat TM) [9]. We mark several corners of the site with large blue tarpaulins such that we can find the corner markers in the sensor image. This allows us to accurately identify the site we measured in the image independent of pixel geolocation, so we can find the average digital count in the image for the measured area of the ground. Finally, the calibration coefficient for each spectral band is found by dividing the digital counts by the band-averaged spectral radiance. This methodology assumes that appropriate gains and offsets are already applied to eliminate pixel-to-pixel nonuniformities.

RSG started collecting ground data for calibration of ALI and Hyperion in late December of 2000. Since December 29, 2000, the RSG has collected data at Ivanpah Playa, CA, Railroad Valley, NV, White Sands Missile Range, NM, Pima County Fairgrounds near Tucson, AZ, and Barreal Blanco (a playa), Argentina. These sites have significantly different reflectance characteristics but the aerosol loading of the atmosphere at all these sites is, in general, fairly low. RSG had the opportunity to travel to Argentina in January 2001 to take data for a radiometric calibration of ALI and Hyperion early in the life of the sensors. A comprehensive measurement campaign for southern hemisphere sites was organized for early in the mission to increase the probability of a successful early mission collection (fewer clouds in the southern hemisphere summer), to increase the signal in order to maximize the SNR of the imagery (especially for Hyperion in the SWIR region), and to increase the probability of a successful evaluation of the new sensors, as the spacecraft has little redundancy and was designed for only a one year mission.

As EO-1 was scheduled to acquire an image of Barreal Blanco on January 22, 2001, we traveled to the site on January 20 in order to find a uniform part of the lake bed. On January 21 we set up a site for our reflectance measurements, including a site appropriate for the ASTER sensor on the Terra platform as well as ETM+ on Landsat-7 and ALI and Hyperion on EO-1. On January 21 we also made reflectance measurements to evaluate site heterogeneity and temporal variability. The data collection for the EO-1 sensor southern hemisphere vicarious calibration was done on January 22, 2001. An automated ten-band solar radiometer was set up near the reflectance site for atmospheric measurements. The barometric pressure and ambient air temperature were measured with a small portable electronic barometer and recorded by hand. The solar

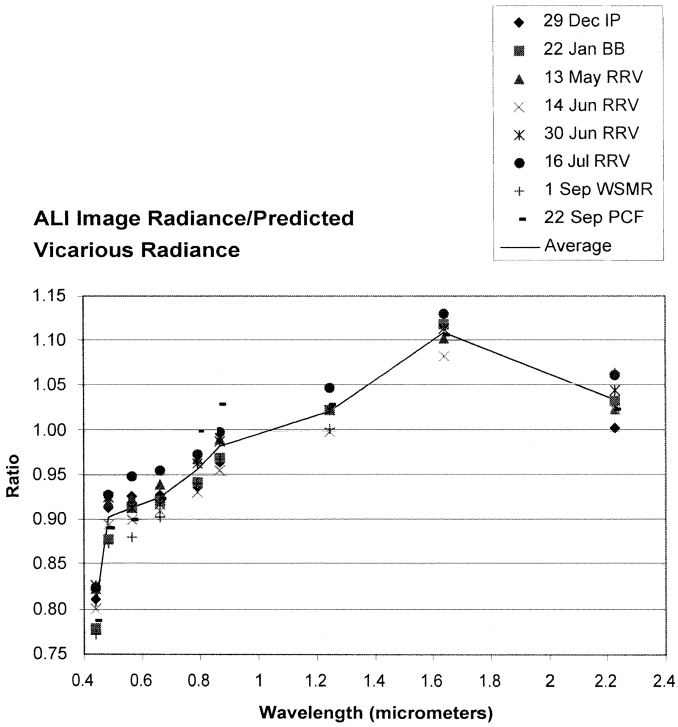

Fig. 1. ALI image radiance/predicted vicarious radiance using preflight calibration.

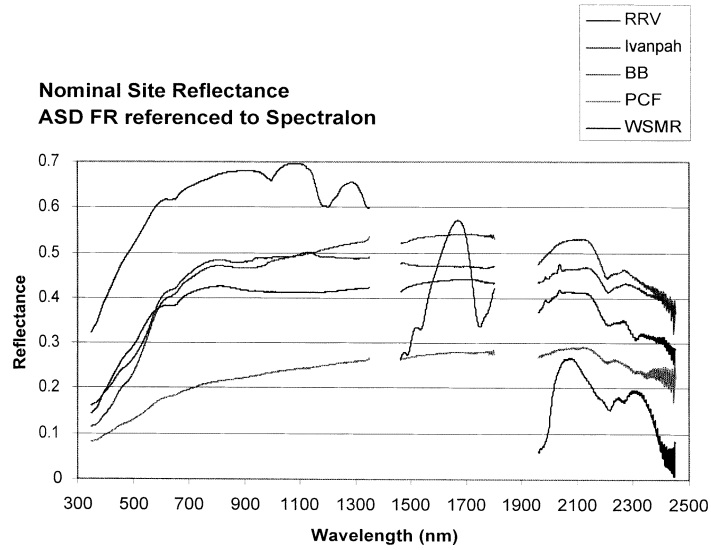

Fig. 2. Nominal site reflectance of vicarious field sites.

radiometer collected data from about 30 min after sunrise until after all ground reflectance measurements were completed. We collected ground reflectance data with an ASD FieldSpec FR portable spectrometer (ASD FR). The spectrometer is used in a relative mode where we collect data from a sunlit Spectralon reference panel and ratio measurements of the dry lake bed to those from the Spectralon. The Spectralon panel directional reflectance factor is calibrated in our laboratory before the field experiment. We use data covering the range of 350–2500 nm, giving us a measured ground reflectance, which is one boundary condition for the radiative transfer computation.

We have made similar ground-based measurements many times since launch at sites other than Barreal Blanco. High-quality image data from the EO-1 sensors were acquired for some of these collections. The first ground experiment done by the RSG was on December 29, 2000, at Ivanpah Playa. Over the course of the mission, data were acquired from ALI more often than for Hyperion. The results from eight different calibration experiments for ALI are shown in Fig. 1. The data points shown are the average image radiance over the measured ground site taken from the Level 1 Hierarchical Data Format (HDF) file divided by the predicted, band-averaged, vicarious radiance determined during each experiment. The Level 1 data are corrected for detector-to-detector and SCA nonuniformities and the preflight calibration was applied. All the ALI data presented here were collected from SCA4 except for the one set from Pima County fairground which was collected from SCA2. The Pima County data were taken as an evaluation of the stray light correction proposed by the instrument vendor. The stray light problem will have some effect on the vicarious calibration; the effect is probably small due to the relatively homogeneous surface reflectance of the calibration sites.

III. Results

In Fig. 1, IP is Ivanpah Playa, CA, BB is Barreal Blanco, Argentina, RRV is Railroad Valley, NV, WSMR is White Sands Missile Range, and PCF is Pima County Fairgrounds, Tucson, AZ. Ivanpah, Barreal Blanco and Railroad Valley are dry lake beds, while White Sands is gypsum sand and Pima County Fairgrounds is weathered asphalt (a large parking lot). Our vicarious calibration data for ALI shows a large change in the calibration of ALI in the shortest band (designated 1P) and smaller but still significant changes in some other bands. The standard deviation of the ratios in Fig. 1 is less than 3% for each band. This standard deviation is a measure of the spread in our results and shows the level of repeatability in our measurements. The uncertainty in our results in the visible near-infrared (VNIR) is estimated at 5% based on earlier work with other sensors [3].

ALI has an on-board solar calibrator and can also view the moon. Data from solar and lunar calibrations are, in general, consistent with our vicarious results according to the instrument vendor [10]. In most cases, the data compare to within the expected uncertainties of the various methods. The largest difference, which we cannot explain at this time, is in band 5 at about 1.64 μm. Of interest is the consistency of the ground calibrations even though the data were taken during different times of the year (significant difference in solar elevation) and at sites with significantly different surface reflectance characteristics. For example, the reflectance at White Sands is as much as three times larger than that of Pima County Fairgrounds in the visible and White Sands is less than one half the reflectance of Ivanpah in the shortwave infrared (SWIR). Fig. 2 shows the typical measured spectral reflectance for the various sites. There are two gaps in the reflectance curves. The first gap around 1380 nm is due to water vapor absorption. The second gap near 1800 nm is due to a combination of high atmospheric absorption and low SNR in the field spectrometer where there is a change in detector and grating. The unreliable data in these regions has been excluded from the figure.

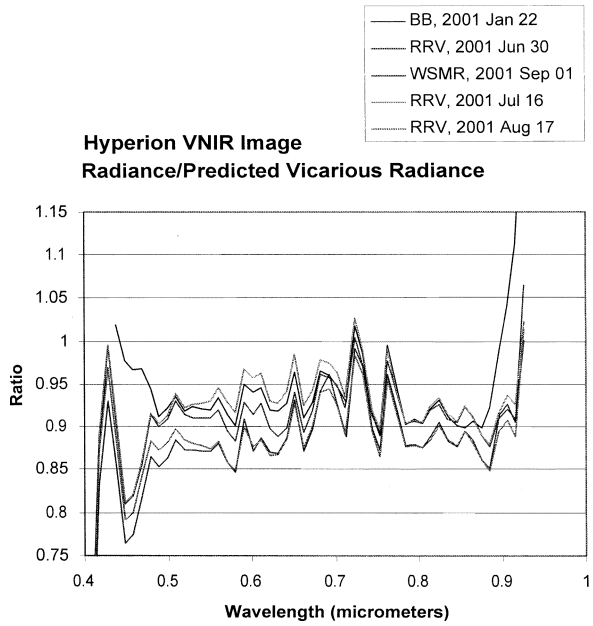

Fig. 3. Hyperion VNIR image radiance/predicted vicarious radiance with preflight calibration coefficients.

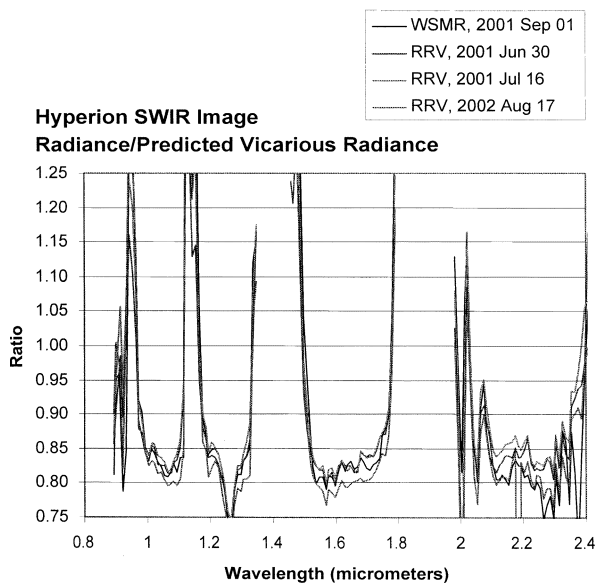

Fig. 4. Hyperion SWIR image radiance/predicted vicarious radiance with preflight calibration coefficients.

Hyperion data were available for only some of the dates used for ALI. In some cases the ground site was not imaged due to the narrow swath width of Hyperion combined with pointing uncertainties, especially early in the mission, and in other cases the SWIR section was not at the correct operating temperature so the SWIR data were not usable. Figs. 3 and 4 show comparisons of the calibrated data from the Level 1 HDF data to predictions in the same format as presented for ALI in Fig. 1. Data are shown for January 22, 2001, at Barreal Blanco in the VNIR but not the SWIR, as the SWIR focal plane was not at normal operating temperature. Hyperion data are available at approximately 10-nm intervals so the data are shown as curves rather than as points.

The Hyperion data shown are for the wavelengths as contained in the Level 1 data and have been corrected for the spectral smile as measured preflight [11]. Other investigators have found a probable shift in wavelength calibration from that reported preflight.[1] Our vicarious calibration results have not been corrected for this additional spectral shift. Any uncorrected spectral shifts would cause differences around strong absorption features. Therefore, details of the following curves are probably not accurate in some details but the curves are certainly indicative of a difference in performance in-flight as compared to preflight. In the VNIR section of Hyperion between 0.448 and 0.915 μm, our data shows an average shift of about 9% with a standard deviation of about 4%. At longer wavelengths in the VNIR section of Hyperion, water vapor absorption reduces the signal and uncertainties in our correction for water vapor cause poor results. In the SWIR region of the spectrum not effected by strong absorption (four parts), there is an average shift of between 12% and 20%. Therefore, based on results from other investigators and, to some extent, these results, it appears that there is a calibration shift of about 8% in the VNIR and about 18% in the SWIR from preflight in regions free of substantial absorption. The regions around 1.4 and 1.8 μm are not shown in Fig. 4, as absorption makes the measurement of ground reflectance inaccurate and the signal measured by Hyperion is very low giving a relatively poor SNR.

Table I shows the average difference between ALI preflight and vicarious results along with similar results for ETM+ for matching bands [12], [13]. This comparison shows that the vicarious method predicts the radiometric performance of ETM+ to within 5% and, since the data for both sensors were contemporaneous, that there is some systematic difference in the ALI calibration as compared to ETM+. Based on vicarious data, lunar observations, and solar calibrator data, the calibration coefficients for both ALI and Hyperion have been changed by the respective instrument teams. The results from this work were considered by the instrument teams hence any comparison of our work and the revised data is not completely independent. If these new coefficients are used in the processing of the ALI datasets we used for vicarious calibrations, the comparison between instrument and vicarious calibration radiances is much improved as shown in Table II. The data are plotted as Fig. 5 with the standard deviation shown as error bars. Only the band at about 1.64 μm shows more than a 5% difference between the mean of our vicarious predictions and the new calibration. There appears to be a bias in our results as compared to the instrument calibration. The reason for this bias is not understood at this time. Also, our data are not sufficiently repeatable to predict a trend in the calibration over the period evaluated in this work. More datasets taken at Railroad Valley later in the mission may allow trends to be determined.

IV. Conclusion

The radiometric performance of ALI and Hyperion appears to be stable to within the uncertainty of our vicarious calibration method over the period spanned by our vicarious measurements. Multiple calibrations of ALI give repeatable results to within 3%

[1]EO-1 Science Validation Team meeting, April 23, 2002.

TABLE I
ALI AND ETM+ VICARIOUS CALIBRATION RESULTS USING PREFLIGHT CALIBRATION VALUES

ALI Wavelength in μm (band)	ALI Average Ratio (preflight/vicarious)	ALI Standard Deviation (in %)	ETM+ Ratio (preflight/vicarious)	ETM+ Standard Deviation (in %)
0.442 (1P)	0.803	2.7	-	-
0.485 (1)	0.903	2.3	0.956	1.3
0.567 (2)	0.913	2.3	0.972	3.8
0.660 (3)	0.925	1.8	0.975	1.8
0.790 (4)	0.957	2.5	0.995	1.2
0.866 (4P)	0.983	2.5	-	-
1.244 (5P)	1.021	1.7	-	-
1.640 (5)	1.110	1.3	0.975	1.0
2.226 (7)	1.035	2.1	0.983	1.5

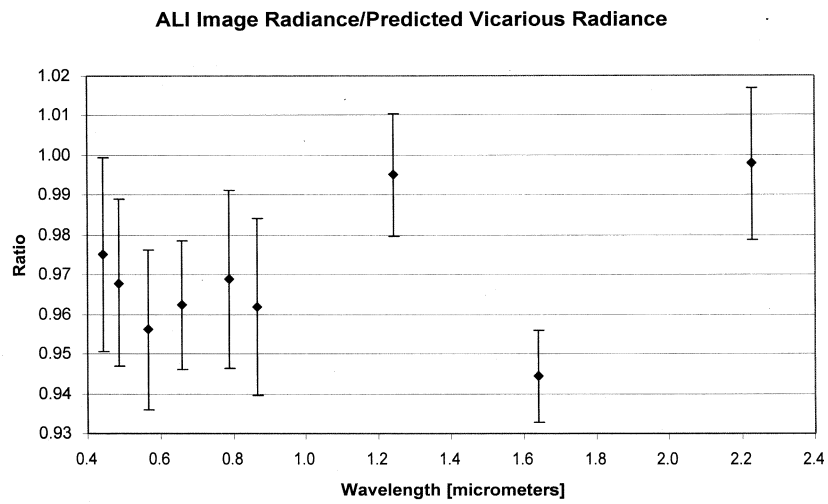

Fig. 5. ALI image radiance/predicted vicarious radiance with December 2001 calibration coefficients.

TABLE II
ALI VICARIOUS CALIBRATION RESULTS WITH DECEMBER 2001 CALIBRATION APPLIED

Wavelength in micrometers (band)	Average Radiance Ratio (December 2001/vicarious)	Standard Deviation (in percent)
0.442 (1P)	0.975	2.5
0.485 (1)	0.968	2.2
0.567 (2)	0.956	2.1
0.660 (3)	0.962	1.7
0.790 (4)	0.969	2.3
0.866 (4P)	0.962	2.3
1.244 (5P)	0.995	1.6
1.640 (5)	0.944	1.2
2.226 (7)	0.998	1.9

one sigma over a period of about nine months. However, the preflight calibration appears to no longer predict the radiometric performance of either ALI or Hyperion. Vicarious calibration and cross-calibration results along with consistent results from other sources such as solar and lunar observations and aircraft sensor underflights have shown the need for a change in the calibration of both ALI and Hyperion. New calibration coefficients have been determined, and data processed since late December 2001 have been calibrated with the new coefficients. We suggest that users of ALI and Hyperion data ensure that the new calibration is applied if the user's product requires accurate radiometric calibration. ALI data processed with the new calibrations is consistent with vicarious calibrations for all spectral bands except for the band centered at 1.64 μm.

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REFERENCES

[1] J. A. Mendenhall, D. E. Lencioni, and J. B. Evans, "Earth Observing-1 Advanced Land Imager: Radiometric response calibration," Massachusetts Inst. Technol., Lincoln Lab., Project Rep. EO-1–3, 200.

[2] K. Thome, B. Markham, J. Barker, P. Slater, and S. Biggar, "Radiometric calibration of landsat," *Photogramm. Eng. Remote Sensing.*, vol. 63, pp. 853–858, 1997.

[3] P. N. Slater, S. F. Biggar, R. G. Holm, R. D. Jackson, Y. Mao, M. S. Moran, J. M. Palmer, and B. Yuan, "Reflectance- and radiance-based methods for the in-flight absolute calibration of multispectral sensors," *Remote Sens. Environ.*, vol. 22, pp. 11–37, 1987.

[4] S. F. Biggar, P. N. Slater, and D. I. Gellman, "Uncertainties in the in-flight calibration of sensors with reference to measured ground sites in the 0.4 to 1.1 μm range," *Remote Sens. Environ.*, vol. 48, pp. 242–252, 1994.

[5] P. N. Slater, S. F. Biggar, J. M. Palmer, and K. J. Thome, "Unified approach to pre- and in-flight satellite sensor absolute radiometric calibration," *Proc. SPIE*, vol. 2583, pp. 130–141, 1995.

[6] D. I. Gellman, S. F. Biggar, P. N. Slater, and C. J. Bruegge, "Calibrated intercepts for solar radiometers used in remote sensor calibration," *Proc. SPIE*, vol. 1493, pp. 19–24, 1991.

[7] B. M. Herman and S. R. Browning, "A numerical solution to the equation of radiative transfer," *J. Atmos. Sci.*, vol. 22, pp. 559–566, 1965.

[8] A. Berk, L. S. Bernstein, and D. C. Robertson, "MODTRAN: A moderate resolution model for LOWTRAN7," Phillips Lab., Geophysics Directorate, Hanscom, AFB, MA, Tech. Rep. GL-TR-90–0122, 1989.

[9] K. J. Thome, D. I. Gellman, R. J. Parada, S. F. Biggar, P. N. Slater, and M. S. Moran, "In-flight radiometric calibration of Landsat-5 thematic mapper from 1984 to present," *Proc. SPIE*, vol. 1938, 1993.

[10] J. A. Mendenhall, private communication.

[11] L. Liao, P. Jarecke, D. Gleichauf, and T. Hedman, "Performance characterization of the hyperion imaging spectrometer instrument," *Proc. SPIE*, vol. 4135, 2000.

[12] K. J. Thome, "Absolute radiometric calibration of Landsat-7 ETM+ using the reflectance-based method," *Remote Sens. Environ.*, vol. 78, pp. 27–38, 2001.

[13] B. L. Markham, J. L. Barker, W. C. Boncyk, E. Kaita, and D. L. Helder, "Landsat-7 Enhanced Thematic Mapper Plus in-flight radiometric calibration," in *Proc. IGARSS*, Lincoln, NE, 1996, pp. 1270–1272.

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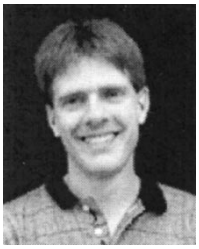

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