Absolute calibration accuracy of L4 TM and L5 TM sensor image pairs

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ABSTRACT

The Landsat suite of satellites has collected the longest continuous archive of multispectral data of any land-observing space program. From the Landsat program's inception in 1972 to the present, the Earth science user community has benefited from a historical record of remotely sensed data. However, little attention has been paid to ensuring that the data are calibrated and comparable from mission to mission. Launched in 1982 and 1984 respectively, the Landsat 4 (L4) and Landsat 5 (L5) Thematic Mappers (TM) are the backbone of an extensive archive of moderate resolution Earth imagery. To evaluate the "current" absolute accuracy of these two sensors, image pairs from the L5 TM and L4 TM sensors were compared. The approach involves comparing image statistics derived from large common areas observed eight days apart by the two sensors. The average percent differences in reflectance estimates obtained from the L4 TM agree with those from the L5 TM to within 15 percent. Additional work to characterize the absolute differences between the two sensors over the entire mission is in progress.

Keywords: Landsat, TM, ETM+, calibration, characterization, spectral bands, detectors, gain, bias, look-up-table, IC, RSR, reflectance

1. INTRODUCTION

The Landsat program has surpassed three decades of imaging the earth's surface. The launch of Landsat 4 on July 16, 1982 and Landsat 5 on March 1, 1984 marked a significant advance in remote sensing with the addition of a more sophisticated sensor, an increased acquisition capability, faster transmission of data, and more rapid data processing at a highly automated data processing facility. L4 and L5 continued to use the Multi-Spectral Scanner (MSS) instrument from the previous missions, and replaced the Return Beam Vidicon (RBV) cameras with the Thematic Mapper (TM), which could measure data in six spectral bands with a spatial resolution of 30 m. The TM also employed a thermal band with a spatial resolution of 120 m. Eventually, TM data became the primary data source from these satellites due to the enhanced spatial and spectral resolution of the TM instruments, the decommissioning of Landsat's 1-3, and failures in the MSS instruments and/or the transmitter systems resulting in the loss of MSS data[1].

1.1 Brief Instrument Overview

The L4/5 TM incorporated advancements in spectral, radiometric, and geometric capabilities relative to the MSS flown on previous Landsats. The TM bands 1-5 and 7 have 16 detectors with center wavelengths of approximately 0.49, 0.56, 0.66, 0.83, 1.67, and 2.24 μm, respectively[1]. The detectors for bands 1-4 are located at the Primary Focal Plane (PFP) where the temperature is not controlled but normally varies between 292 and 300 K. The detectors for bands 5, 6, and 7 are located at the Cold Focal Plane (CFP). Because of their relatively long wavelengths, high noise signals can result from the internal thermal excitation of the detector materials. To minimize this noise and allow adequate detection of scene energy, the CFP

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temperature is maintained between 95 and 105 K by a radiative cooler. The L5 TM bands were designed to mimic the standard L4 TM spectral bands 1, 2, 3, 4, 5, 6, and 7. The wavelength coverage, detector composition, and Ground Sample Distance (GSD) are summarized in Table 1. The Relative Spectral Response (RSR) profiles between corresponding L7 Enhanced Thematic Mapper Plus (ETM+), L5 TM, and L4 TM spectral bands are shown in Fig. 1.

Table 1. L4/5 TM spectral coverage and ground sample distance[2]

Band	Type	L5 TM Spectral Range (um)		Detectors	GSD (m)
1	Si Photodiode	Blue-Green	0.45 - 0.52	16	30
2	Si Photodiode	Green	0.52 - 0.60	16	30
3	Si Photodiode	Red	0.63 - 0.69	16	30
4	Si Photodiode	Near-IR	0.76 - 0.90	16	30
5	InSb	Mid-IR1	1.55 - 1.75	16	30
6	HgCdTe	Thermal-IR	10.4 - 12.5	4	120
7	InSb	Mid-IR2	2.08 - 2.35	16	30

1.2 Internal Calibrator

The Internal Calibrator (IC) is incorporated as an on-board radiometric calibration system for the TM. Onboard calibration of the MSS and TM uses lamps to calibrate the reflective bands and a blackbody source to calibrate the thermal band. The calibrator is synchronized with the scan mirror in such a way that it brings the calibration sources sequentially in view of the detectors during each scan mirror turnaround (when no scene data are being taken). The IC used by the TM (except band 6) consists of three independent lamps. These lamps were calibrated prior to launch and provide calibration light pulses. Each lamp has a different attenuating filter, which allows for different brightness levels for each lamp. A total of eight brightness levels can be produced with the three-lamp combination. The light source from the IC is channeled through prisms and optical fibers to the end of an oscillating calibration shutter arm. Detector responses are recorded on the left and right edges of the raw TM image. The IC lamps cycle through the eight combinations of lamp states in the order 000, 100, 110, 010, 011, 111, 101, and 001, where each digit represents a single lamp state with “1” indicating the lamp is on[2].

1.3 L4 TM Missing Data from 1983-1987

L4 was launched in July 1982. Both the primary and redundant X-Band transmitters, which were needed to communicate TM data to Earth prior to launch of the Tracking and Data Relay Satellite System (TDRSS), did not work as expected. The primary unit failed on September 22, 1982, and the redundant unit failed on February 15, 1983. The only remaining L4 TM capable transmitters were the Ku band TDRS links. The first TDRS satellite was launched in April 1983, but due to a rocket malfunction it did not reach the geosynchronous orbit initially. Using the on-board thrusters, TDRS-1 did finally achieve geosynchronous orbit in the summer of 1983. Several test acquisitions of L4 TM data downlink were performed in August 1983, but routine acquisitions of L4 TM were not performed. L5 was launched in March, 1984. A few "tandem" acquisitions were performed with L4 and L5 over Tennessee on March 15-16, 1984. While L5 became the main satellite for the Landsat program, L4 may have been used for infrequent International acquisitions. The failure of the Ku band on L5 occurred in February, 1987, which restarted the usage of L4 in May, 1987. As a result of these system failures, there is a paucity of L4 data from the spring of 1983 to the spring of 1987. L4 served the Landsat fleet for the next six years, primarily collecting land areas out of view of the United States ground station.

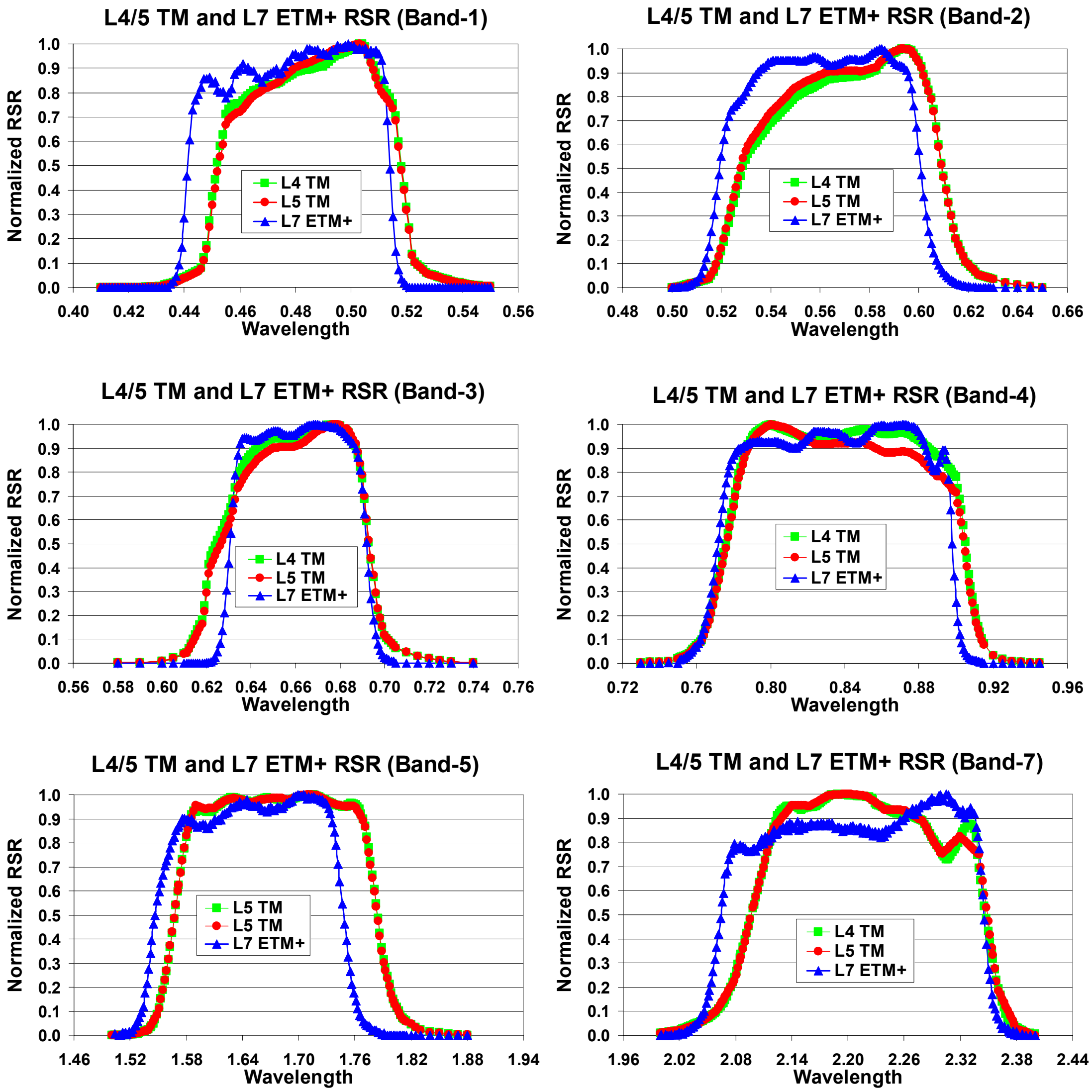

Figure 1. Relative Spectral Response (RSR) profiles of L7 ETM+ and L4/5 TM

2. REVISED L5 TM RADIOMETRIC CALIBRATION PROCEDURE

Over the lifetime of TM, there have been three U.S. data product generation systems. The initial processing system for TM was the TM Image Processing System (TIPS). It was used by the National Oceanic and Atmospheric Administration (NOAA), and later, the Earth Observation Satellite Company (EOSAT) adopted TIPS when it assumed operational control of the Landsat Program. EOSAT updated its processing system to the Enhanced Image Processing System (EIPS) in October, 1991. At the same time, the USGS began its own TM archive, and eventually began processing TM data with the National Landsat Archive Production System (NLAPS).

Historically, the L4/5 TM calibration procedure in NLAPS (adapted from TIPS) used the instrument's response to the IC on a scene-by-scene basis to determine gains and offsets. Effective May 5, 2003, revised L5 TM radiometric calibration procedures and post-calibration dynamic ranges (LMAX, LMIN) were implemented into the NLAPS system for all of the data processed and distributed by USGS Earth Resources Observation and

Science (EROS) [3]. The modified approach discontinued use of the IC for the reflective bands (with the exception of the thermal band) and implemented instead a time-dependent calibration Look-up Table (LUT). Note that products generated before May 5, 2003 (calibrated with the IC-based gain and converted to radiance using the older LMINs and LMAXs), will not provide the same radiances as those processed since May 5, 2003 (calibrated with the LUT gain and converted to radiance with the new LMINs and LMAXs). No modifications were made to the calibration of L4 TM image data. The NLAPS system will continue to use the IC-based calibration algorithms until an improved characterization and calibration procedure of the L4 TM is developed.

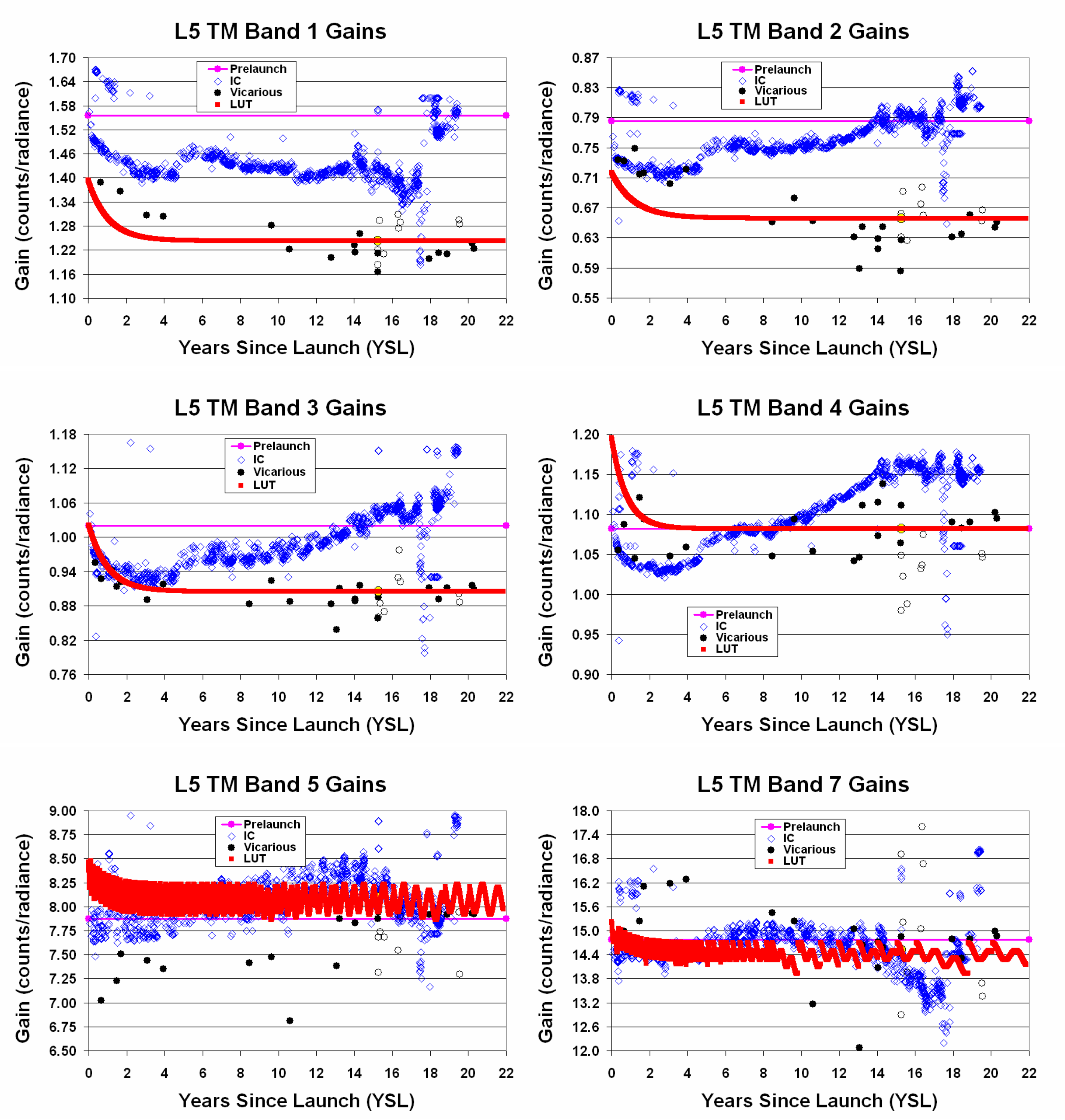

Figure 2. Comparison of L5 TM Radiometric Calibration Methods

2.1 Comparison of L4/5 TM Radiometric Calibration Methods

The new calibration procedure for L5 TM is based on a lifetime radiometric calibration model for the instrument's reflective bands (1-5 and 7), and is derived, in part, from the IC response without the related degradation effects, and is tied to the cross-calibration with the L7 ETM+[5]. The final lifetime gain model for L5 TM has been scaled to the cross-calibration estimates with the L7 ETM+. These gains are generated over the lifetime of the mission and stored in day-specific LUTs. These are referred to as LUT gains in this paper. In the same sense, the gains calculated using IC responses are referred to as IC gains. A comparison of pre-launch, vicarious, and IC versus the LUT gains over the lifetime of the instrument is shown in Fig. 2 and 3.

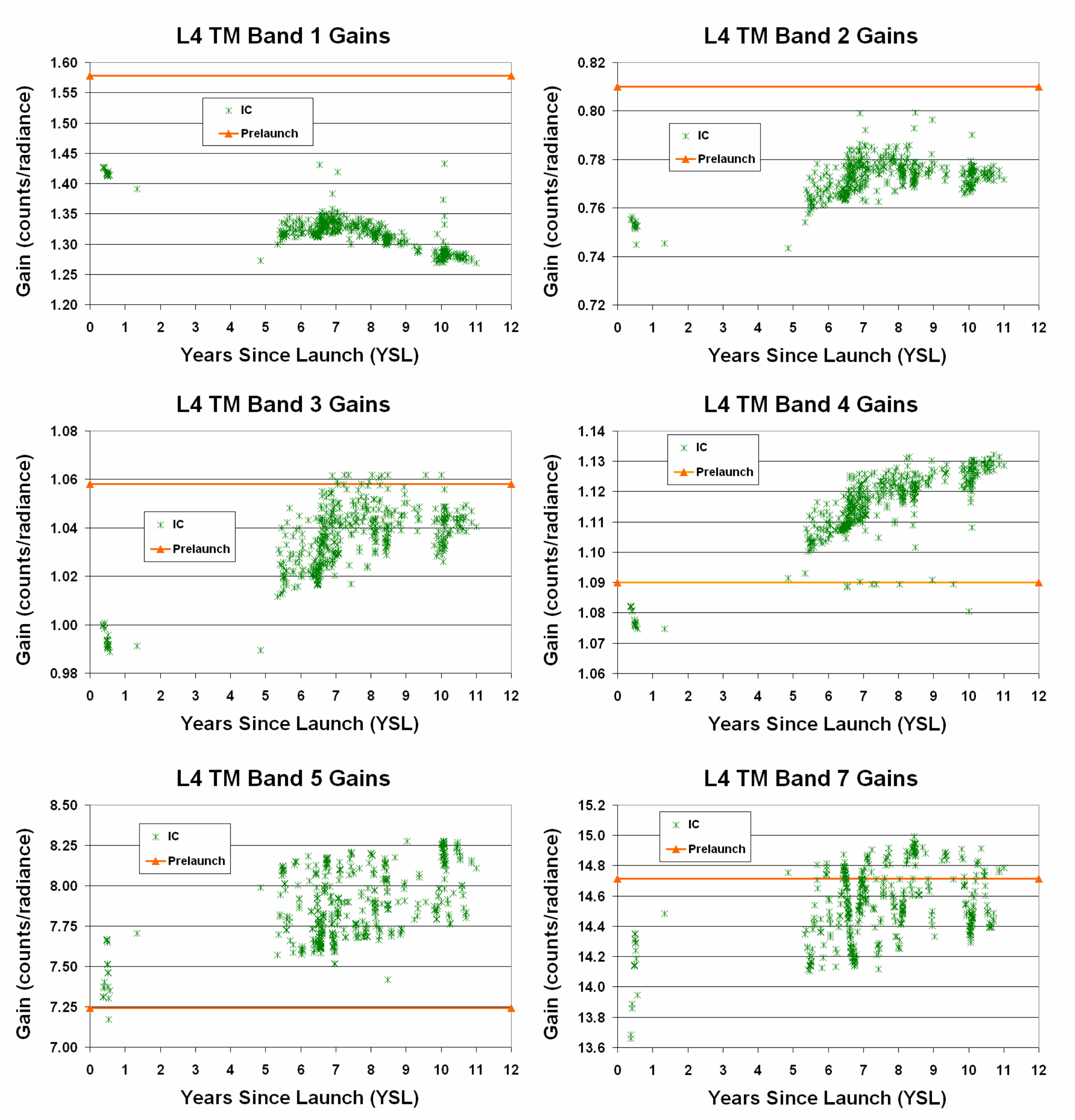

Figure 3. Comparison of L4 TM Radiometric Calibration Methods

2.2 Improvement In Absolute Calibration Accuracy of L5 With L7

This section provides the comparisons of the reflectance measurements obtained from the L5 TM and L7 ETM+ scenes. The goal of this analysis was to show the improvement in consistency of the L5 data compared to L7 data achieved by implementation of the LUT approach in the L5 data product generation system. Since the work is published and documented elsewhere, only the key results are summarized here for completeness[3, 5, and 6]. Three image pairs acquired in June, 1999 (L5/7 tandem orbit) were used in this analysis: Railroad Valley Playa in Nevada (RVPN) having Worldwide Reference System (WRS) path/row 40/33; Niobrara, Nebraska, having WRS path/row 31/30; and Washington, D. C. (DC) having WRS path/row 15/33. Fig. 4 clearly indicates a significant improvement in the consistency of L5 data compared to L7 data achieved using the LUT approach as opposed to the historical IC calibration procedure. The average percentage difference in band 2 reduces from about 15.6 percent (L7 ETM+ and L5 TM IC) to 1.8percent (L7 ETM+ and L5 TM LUT).

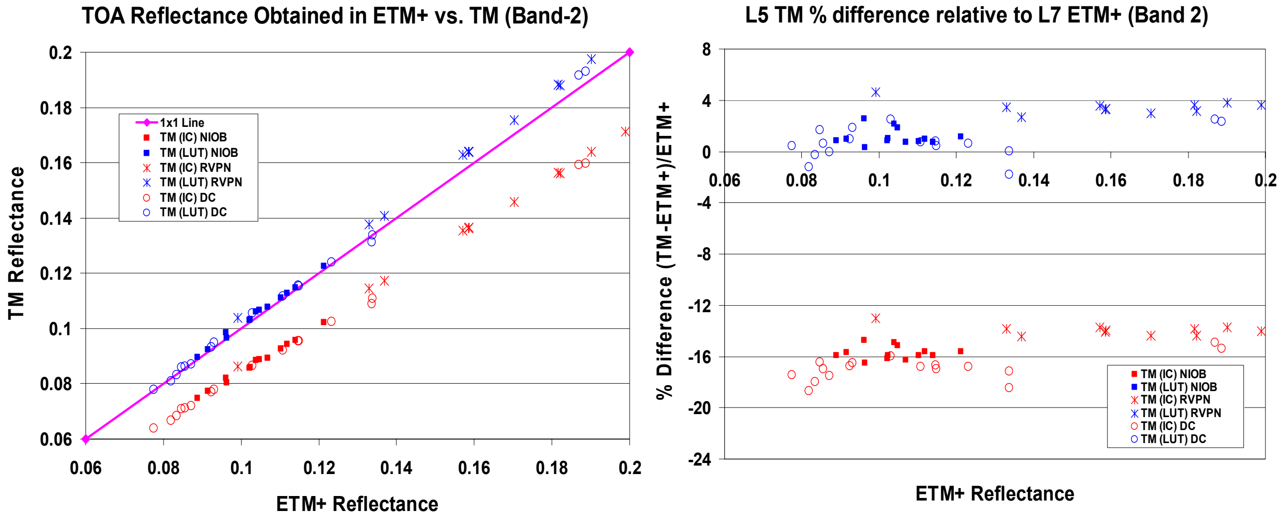

Figure 4. Comparison of reflectance measurements from large ground regions common to band 2 of both L7 ETM+ and L5 TM sensors

3. CALIBRATION BASED ON IMAGE STATISTICS

Data continuity within the Landsat Program requires consistency in interpretation of image data acquired by all Landsat sensors, especially among the TM and ETM+ sensors. This section provides the comparisons of the reflectance measurements obtained from the L4 TM and L5 TM scenes acquired eight days apart. The goal of this analysis is to show the current status of the L4 TM IC absolute calibration accuracy relative to the L5 TM LUT processing.

3.1 Test site descriptions

The test sites used for sensor calibration of the solar reflective bands are primarily located in desert regions. These regions are used for several reasons. First, these sites exhibit high surface reflectance, which improves the signal to noise ratio (SNR) and decreases uncertainties in the calibration. Second, the low probability of cloud coverage improves the chances of the sensor imaging the test site at the time of overpass. In addition, the low aerosol loading typical of these regions decreases uncertainties due to the atmospheric characterization[4].

Due to the limited number of co-incident image pairs in the USGS EROS archive, the scene selection for the cross-calibration studies proved to be a challenge. Due to the lack of near-simultaneous images available over the well characterized and traditionally used calibration sites, alternate sites that have high reflectance, large dynamic range, high spatial uniformity, high sun elevation, and minimal cloud cover were investigated. As a result the final scenes selected for the current work were over Kuwait and Iraq (Path 166, Row 39) and Yuma, Arizona (Path 38, Row 38).

3.2 Landsat orbit and image pairs

L4 and L5 satellites operate in a sun-synchronous orbit with a repeat cycle of 16 days, completing 233 orbits per cycle on the WRS. The sun-synchronous orbit means that all acquisitions over a given area occur at the same time of the day. The equatorial crossing time during descending passes (descending passes are on the sunlit side of the Earth and ascending passes are always on the dark side of the orbit) is, for all Landsat missions, between 9:30 and 10:00 a.m. local time. The sensors always scan the ground at or close to satellite nadir. L5 used to orbit eight days behind L4 or vice-versa. Therefore, a given area on the ground was imaged by L4 or L5 every eight days. Currently L5 and L7 have an 8 day revisit as well.

To perform cross-calibration between these two sensors, cloud-free scenes were selected over the Iraq and Yuma test sites. Two image pairs acquired eight days apart in 1990 were used in this analysis. Table 2 lists the L4/5 TM scenes that were selected for the cross-calibration study along with the scene ID number, location, path, row, date of acquisition, Day-Of-Year (DOY), and the sun elevation angle for the scenes. It should be noted that these pairs were obtained four months apart and on opposite sides of the Earth.

Table 2. L5 TM and L4 TM image pairs

Scene ID	TM	Date (YYYY-MM-DD)	Location	Path	Row	DOY (Day Of Year)	Solar Elevation angle in degrees
LT5166039009024210	L5	1990-08-30	Iraq	166	39	242	53.19
LT4166039009025010	L4	1990-09-07	Iraq	166	39	250	53.21
LT5038038009014510	L5	1990-05-25	Yuma	38	38	145	60.36
LT4038038009013710	L4	1990-05-17	Yuma	38	38	137	61.80

3.3 Geometric matching

A feature simultaneously observed by both sensors is represented by slightly different numbers of image pixels because of the differences in viewing geometry and sensor scanning times. This makes it very difficult to establish sufficient geometric control to facilitate radiometric comparisons on a point-by-point and/or detector-by-detector basis. Therefore, the analysis approach made use of image statistics derived from large areas in common between the image pairs (a pair represents an acquisition of an observed area by each of the TM sensors acquired eight days apart). These large areas were carefully selected using distinct features common to both of the images. In each image pair, the common regions, approximate 5 to 50 km^2 in area, were defined. Bright and dark regions were selected to obtain maximum coverage over each sensor's dynamic range. To avoid registration problems, TM image pairs can be geometrically co-registered, but that involves resampling. For this particular study, it was necessary to avoid the corrupting of pixel values by resampling in order to obtain the highest possible radiometric accuracy. Radiometric effects due to residual image misregistration were avoided by using the large areas common to both the TM image pairs.

3.4 Data processing system

Level 1R (L1R) scenes from the TM sensors were used for this study. L1R is a radiometrically corrected product (but no geometric corrections applied); radiometric artifacts such as detector striping are removed during radiometric correction. During L1R product generation, the image pixels are converted to units of absolute radiance using 32-bit floating-point calculations. The absolute radiances are then scaled to calibrated digital numbers before output to the distribution media. The L4/5 TM data were processed at USGS EROS, through NLAPS. The L4 TM calibration procedure used the IC calibration, based on linear regression through the detector responses to all lamp states collected during a scene acquisition time. The L5 TM calibration procedure used the LUT gain model calibration procedure.

3.5 Regions of interest

Regions of Interest (ROI) were selected within each respective TM scene to understand the improvement in accuracy relative to one another. Areas common to the two images in a pair were selected to exclude clouds and cloud shadows. Fig. 5 shows the selected regions that were common to the L4 and L5 TM images for the RVPN test site. Once all area ROIs were selected, image statistics were computed to obtain minimum, maximum, mean, and standard deviation target values on a band-by-band basis. The mean target statistics from both sensors were then converted to absolute units of radiance, which is the fundamental step in putting image data from multiple sensors and platforms onto a common radiometric scale.

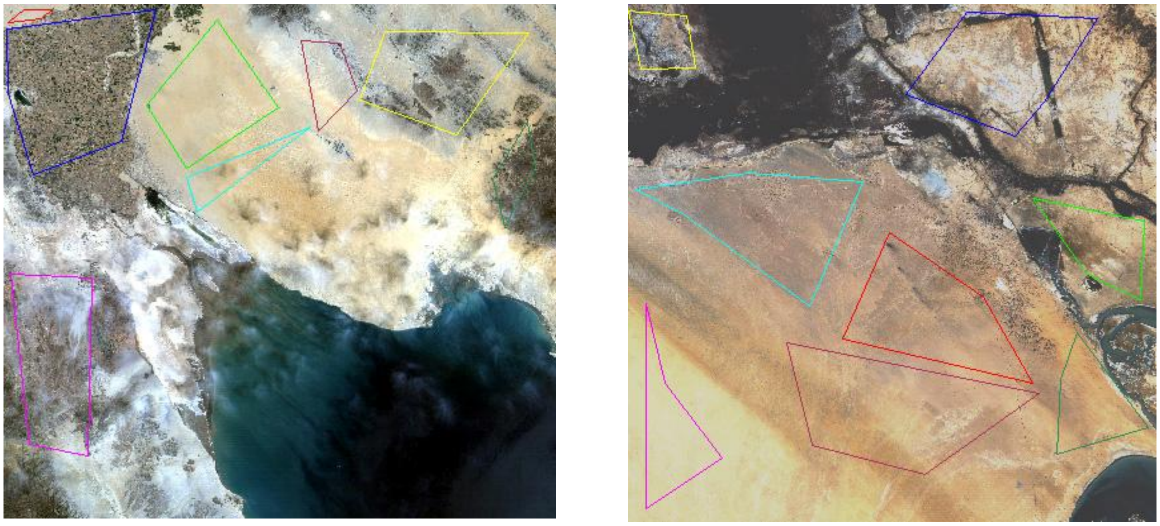

Figure 5. Areas in common between the L5 TM and the L4 TM image pairs. The left hand side image is over Yuma, Arizona (path 38 row 38) and the right hand side is over Kuwait and Iraq (path 166 row 39)

For relatively "clear" Landsat scenes, a reduction in scene-to-scene variability can be achieved through normalization for solar irradiance by converting the spectral radiance to a planetary or exoatmospheric reflectance. When comparing images from different sensors, there are two advantages to using reflectance instead of radiance. First, the cosine effect of different solar zenith angles due to the time difference between data acquisitions can be removed; and second, it compensates for different values of the exoatmospheric solar irradiances arising from spectral band differences.

4. ABSOLUTE CALIBRATION ACCURACY OF L4 TM WITH L5 TM

Results of reflectance comparison for spectral bands 1-3 and 4-7 are presented in Figures 6 and 7, respectively. The plots on the left side in each of these figures relate reflectances extracted from L4 TM L1R data to corresponding reflectances obtained from L5 TM LUT data. Each data point on these plots represents an ensemble average of all pixels in a defined region for a given day and spectral band. The one-to-one line represents the idealized perfect agreement between the reflectances obtained from both sensors for a particular band. The plots on the right side represent average percentage differences in observation using the L4 TM IC relative to L5 TM LUT data.

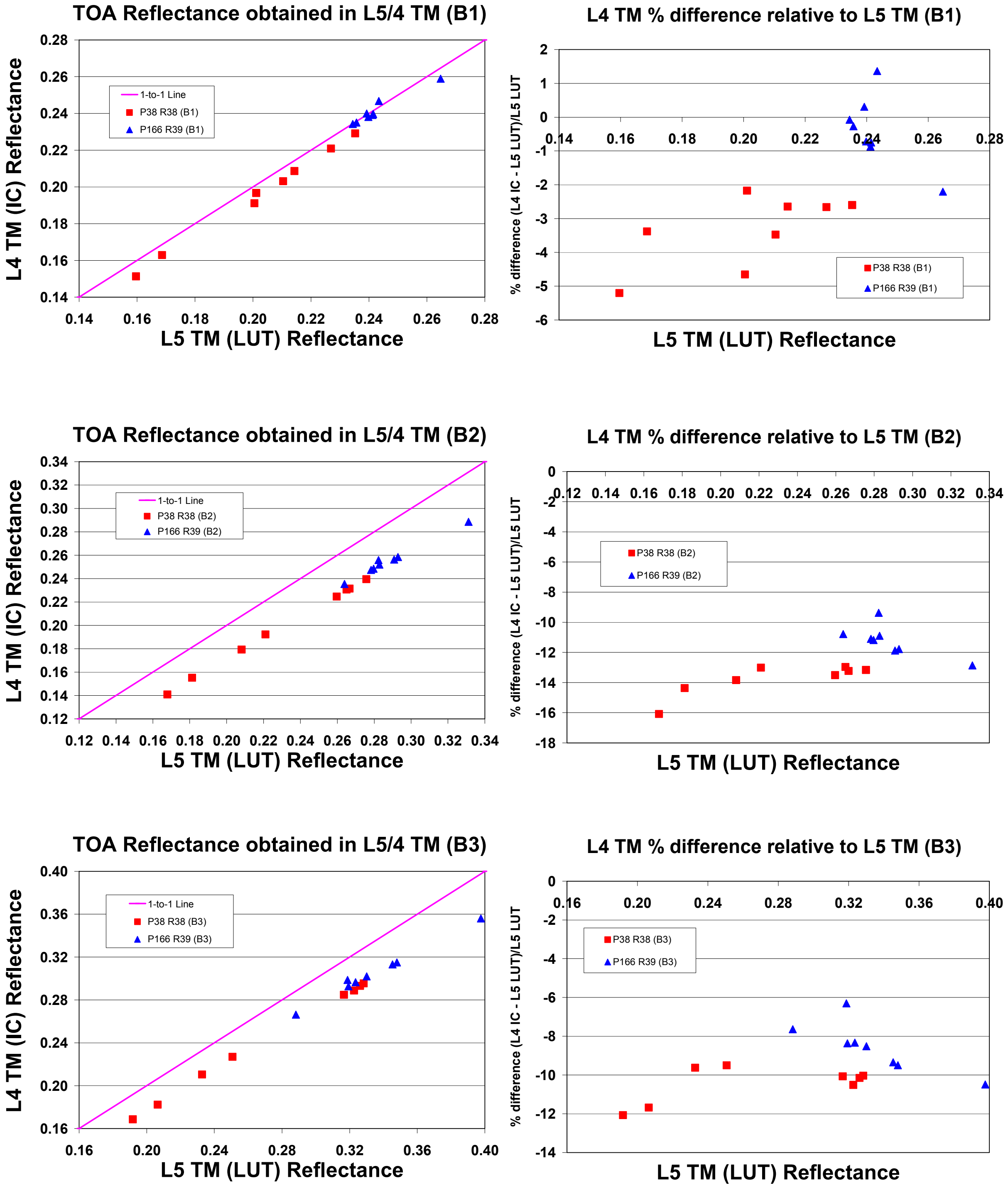

Figure 6. Comparison of reflectance measurements from large ground regions common to bands 1, 2, and 3 of both L4 TM and L5 TM sensors.

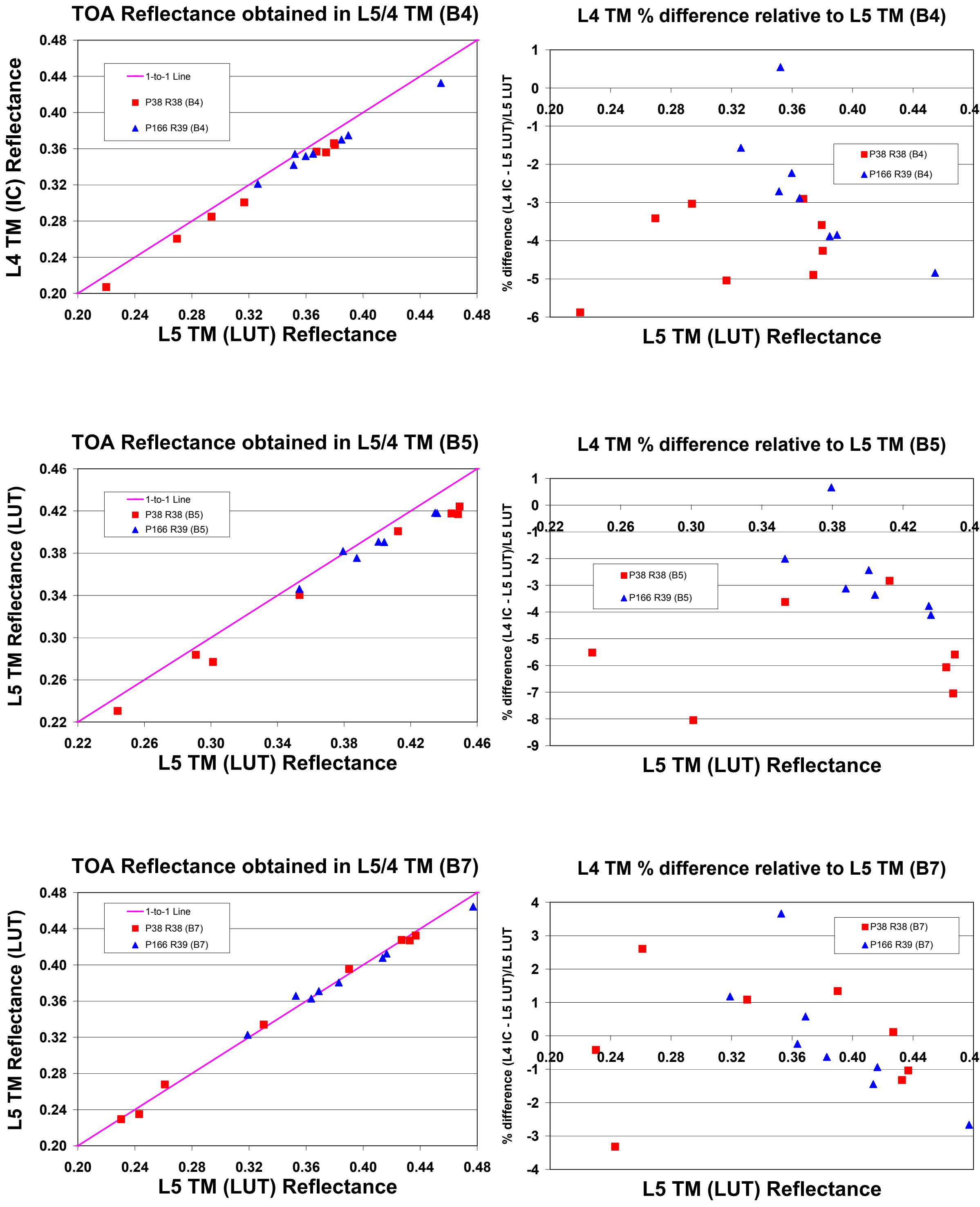

Figure 7. Comparison of reflectance measurements from large ground regions common to bands 4, 5, and 7 of both L4 TM and L5 TM sensors.

The average percent differences in reflectances obtained from the L4 TM IC relative to the L5 TM LUT are summarized in Table 3. In band 1, the average percentage difference is 2.08%; in band 2, 12.50%; in band 3, 9.51%; in band 4, 3.47%; in band 5, 4.25%; and in band 7, 1.41%. Similarly, the Root Mean Square Error (RMSE) values are summarized in Table 3. The RMSE values give another statistical measure of the magnitude of the variation between the measurements.

Table 3. Average percent difference and RMSE with respect to L5 TM

Average Percent difference			
Band	**P38R38**	**P166R39**	**Average**
1	3.35	0.82	2.08
2	13.77	11.23	12.50
3	10.46	8.56	9.51
4	4.13	2.81	3.47
5	5.15	3.34	4.25
7	1.41	1.42	1.41

Root Mean Square Error (RMSE)			
Band	**P38R38**	**P166R39**	**Average**
1	3.50	1.04	2.58
2	13.81	11.27	12.60
3	10.49	8.64	9.61
4	4.25	3.10	3.72
5	5.48	3.79	4.71
7	1.73	1.79	1.76

It is apparent from the table and the plots that there is a consistency in the results between the two sites. Because the imaging of scene pairs was performed eight days apart, the potential changes in ground and atmospheric conditions may affect the comparison. The larger differences observed in the low reflectance range are probably caused by low Signal-to-Noise Ratio (SNR) in that portion of the instruments' responsivities. In general, no spectral band adjustments were performed, so most of the remaining differences in all bands are attributed to the different relative spectral response profiles of the L4/5 TM spectral bands[7]. The average percent differences in reflectance estimates obtained from the L4 TM agree with those from the L5 TM to within fifteen percent. The bands 1, 4, 5, and 7 agree within five percent and bands 2 and 3 agree within 13 percent. Additional work to characterize the absolute differences between the two sensors over the entire mission is in progress.

5. SUMMARY

Data continuity within the Landsat Program requires the ability to consistently interpret image data acquired by the evolving imaging instruments. A critical step in this process is to put image data from subsequent generations of sensors onto a common radiometric scale. To evaluate the “current” absolute accuracy of L4 TM in this role, image pairs from the L5 TM and L4 TM sensors were compared. The cross-calibration was performed using image statistics based on large common areas observed by the two sensors that acquired data eight days apart. The average percent differences in reflectance estimates obtained from the L4 TM agree with those from the L5 TM to within 15 percent. Additional work to characterize the absolute differences between the two sensors over the entire mission is in progress.

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