Consistency of L4 TM absolute calibration with respect to the L5 TM sensor based on near-simultaneous image acquisition

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ABSTRACT

The Landsat archive provides more than 35 years of uninterrupted multispectral remotely sensed data of Earth observations. Since 1972, Landsat missions have carried different types of sensors, from the Return Beam Vidicon (RBV) camera to the Enhanced Thematic Mapper Plus (ETM+). However, the Thematic Mapper (TM) sensors on Landsat 4 (L4) and Landsat 5 (L5), launched in 1982 and 1984 respectively, are the backbone of an extensive archive.

Effective April 2, 2007, the radiometric calibration of L5 TM data processed and distributed by the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) was updated to use an improved lifetime gain model, based on the instrument's detector response to pseudo-invariant desert site data and cross-calibration with the L7 ETM+. However, no modifications were ever made to the radiometric calibration procedure of the Landsat 4 (L4) TM data. The L4 TM radiometric calibration procedure has continued to use the Internal Calibrator (IC) based calibration algorithms and the post calibration dynamic ranges, as previously defined.

To evaluate the "current" absolute accuracy of these two sensors, image pairs from the L5 TM and L4 TM sensors were compared. The number of coincident image pairs in the USGS EROS archive is limited, so the scene selection for the cross-calibration studies proved to be a challenge. Additionally, because of the lack of near-simultaneous images available over 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. The alternate sites were identified in Yuma, Iraq, Egypt, Libya, and Algeria. The cross-calibration approach involved comparing image statistics derived from large common areas observed eight days apart by the two sensors. This paper summarizes the average percent differences in reflectance estimates obtained between the two sensors. The work presented in this paper is a first step in understanding the current performance of L4 TM absolute calibration and potentially serves as a platform to revise and improve the radiometric calibration procedures implemented for the processing of L4 TM data.

Keywords: Landsat, TM, calibration, characterization, spectral bands, detectors, gain, bias, lookup table, IC, RSR, reflectance

1. INTRODUCTION

Landsat 4 was launched on July 16, 1982, as the fourth satellite in an already 10-year-old series of Earth observing missions to capture moderate-resolution imagery used to study the Earth's surface. Landsat 5 followed shortly after, on March 1, 1984, and continues its mission today. Both satellites were launched into a 705-km orbit with a 16-day repeat cycle. They were positioned with an eight-day offset between the two. Both

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carried identical instruments: the Multispectral Scanner (MSS) and the Thematic Mapper (TM). This paper will focus on the L4 and L5 TM instruments.

The TM is a seven-band, moderate-resolution whiskbroom scanner. The Relative Spectral Response (RSR) profiles between corresponding L5 TM and L4 TM spectral bands are shown in Figure 1. Silicon photodiode detectors for Bands 1–4 are located at the primary focal plane. The cold focal plane, which is maintained at 91 K by radiative cooling, contains the InSb detectors for Bands 5 and 7, as well as the HgCdTe Band 6 detectors. The visible and near infrared (VNIR) and shortwave infrared (SWIR) bands have a spatial resolution of 30 m and the thermal infrared (TIR) band has a spatial resolution of 120 m.

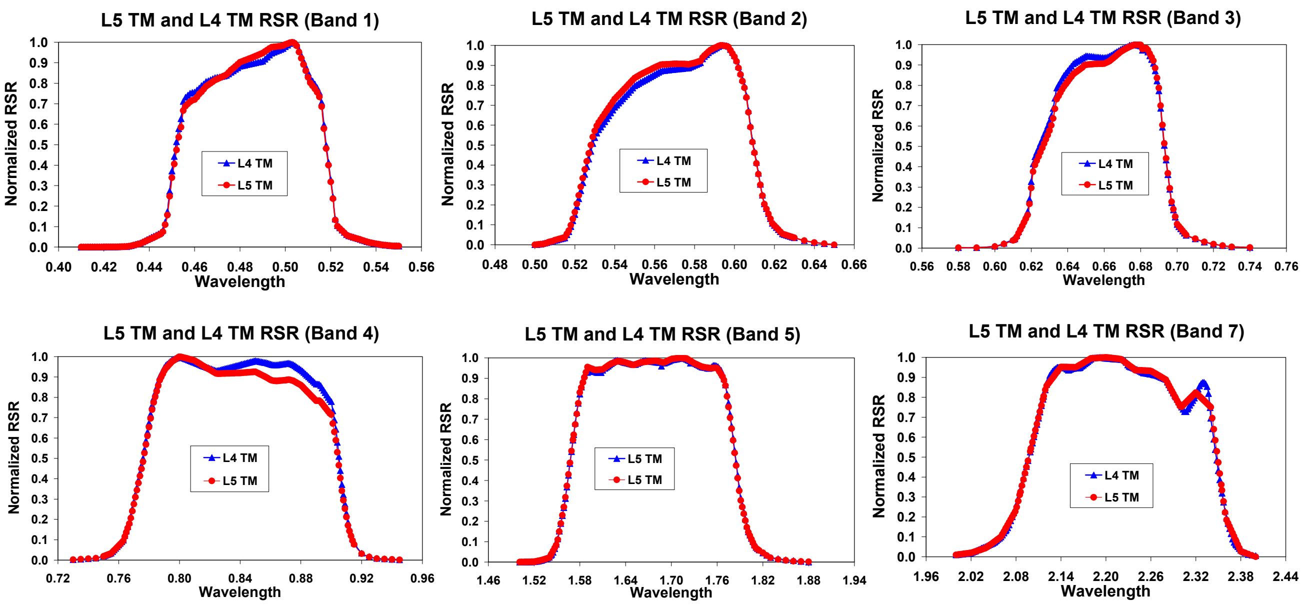


Fig 1. Relative Spectral Response (RSR) profiles of L5 TM and L4 TM

L4 developed two serious problems within the first year after launch. First, two solar panels failed, curtailing some operations due to lower power. Second, both direct downlink transmitters failed, allowing no TM data transmission until the Tracking and Data Relay Satellite System (TDRSS) became operational. With the launch of L5, the L5 TM became the primary imager. Neither TM instrument had a data recorder on board, as the ETM+ does now, so when the TDRSS transmitter failed on L5 in 1987, it was no longer possible to downlink data to the United States that was collected outside the U.S. acquisition circle. L4 TM was turned back on to acquire the international data, as its TDRSS transmitter was functional. The L4 transmitter eventually failed in 1993. L5 continues to acquire data, still only capable of downlinking data within the U.S. acquisition circle to the U.S. archive, though international ground stations do receive data acquired over their own reception circles[1].

2. REVISED L5 TM RADIOMETRIC CALIBRATION PROCEDURE

Historically, the L4 and L5 TM calibration procedure in the National Land Archive Production System (NLAPS) used the instrument's response to the Internal Calibrator (IC) on a scene-by-scene basis to determine gains and offsets. The L5 TM calibration was updated in 2003[2] and further revised in 2007[3]. The calibration approach implemented on May 5, 2003, for the reflective bands (1–5, 7) is based on a lifetime radiometric calibration curve that is derived from the instrument's IC, cross-calibration with the ETM+, and vicarious measurements[1, 4]. The calibration approach implemented on April 2, 2007, is based on the instrument's response to pseudo invariant desert sites and cross-calibration with the L7 ETM+[3].

The lifetime gain models used to generate the band average gain over the lifetime of the mission are stored in day-specific lookup tables. These numbers are referred to as LUT gains in this paper. Further, the LUT model implemented in 2003 is referred to as LUT03, and the LUT model implemented in 2007 is referred to as LUT07. In the same sense, the gains calculated using IC responses are referred to as IC gains. A comparison of pre-launch, vicarious, IC, LUT03, and LUT07 gains over the lifetime of the instrument is shown in Figure 2. The LUT gains can be accessed online through the USGS Landsat Project Web site[5]. No modifications were made to the calibration of L4 TM image data. The NLAPS system uses the IC based calibration algorithms procedures to generate L4 TM data through USGS EROS.

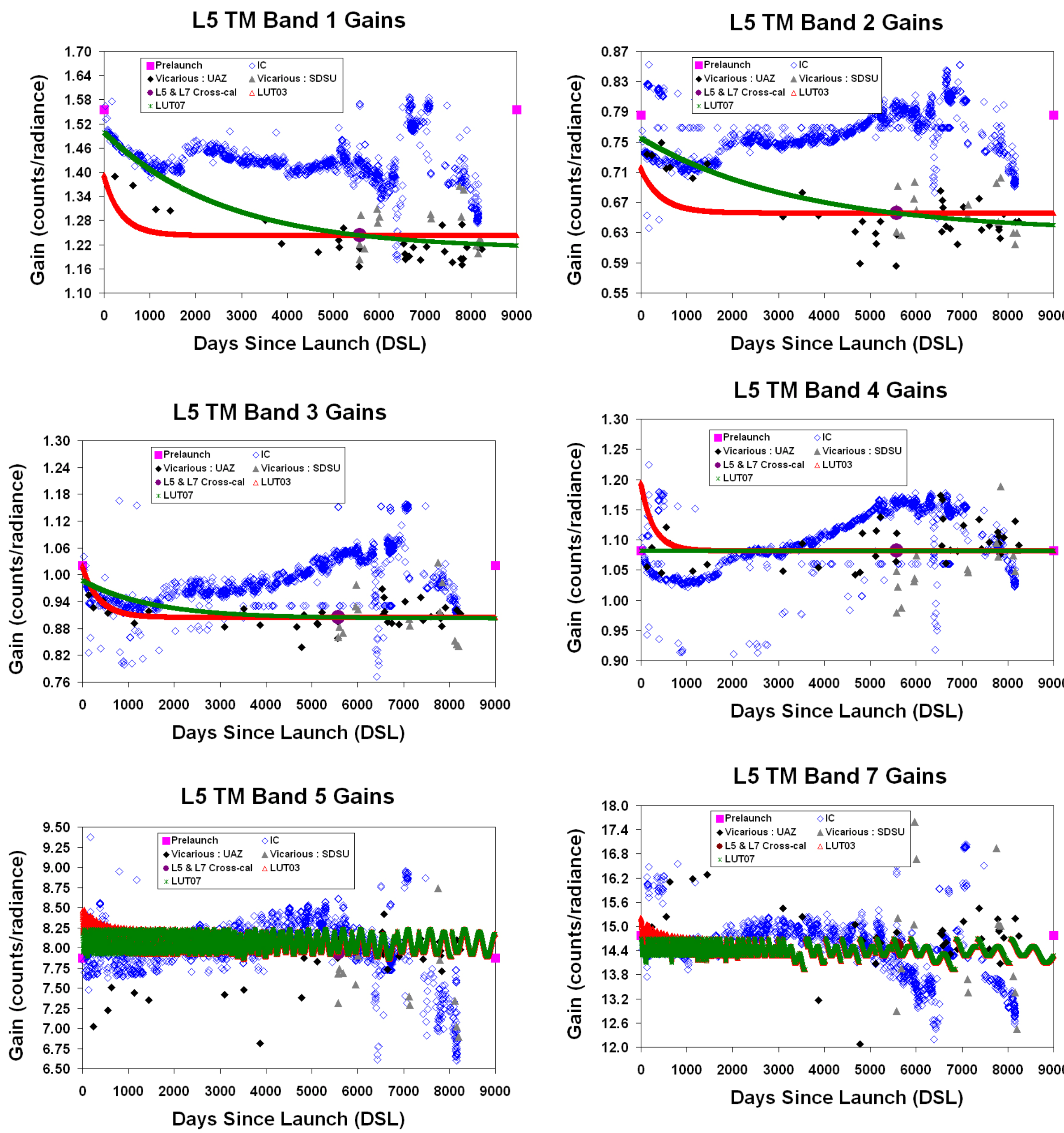


Fig 2. Comparison of L5 TM Radiometric Calibration Methods

3. CALIBRATION BASED ON IMAGE STATISTICS

This section provides the comparisons of the reflectance measurements obtained from the L4 TM data processed using IC, and L5 TM data processed using LUT07. The L5 TM and the L4 TM scenes compared in the study were 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 LUT07 calibration curve.

3.1 Test site descriptions

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 the following five areas - Yuma, Iraq, Egypt, Libya, and Algeria. Table 1 lists the L4 and L5 TM scenes that were selected for the cross-calibration study along with their scene ID numbers, locations, paths, rows, dates of acquisition, Day-of-Year (DOY), the sun elevation and azimuth angles and archive sources.

Table 1. L5 TM and L4 TM IMAGE PAIRS

Scene ID	TM	Date	Location	Path	Row	DOY	Solar Elevation	Solar Azimuth	Agency
LT5166039009024210	L5	1990-08-30	Iraq	166	39	242	53.19	118.11	USGS
LT4166039009025010	L4	1990-09-07				250	53.21	124.74	USGS
LT5038038009014510	L5	1990-05-25	Yuma	38	38	145	60.36	103.30	USGS
LT4038038009013710	L4	1990-05-17				137	61.80	108.79	USGS
LT5179041008729310	L5	1987-10-20	Egypt	179	41	293	44.34	141.43	USGS
LT4179041008730110	L4	1987-10-28				301	41.21	141.93	USGS
LT5179041008730910	L5	1987-11-05				309	39.89	145.87	ESA
LT4179041008731710	L4	1987-11-13				317	37.17	145.44	USGS
LT5179041008732510	L5	1987-11-21				325	35.99	148.14	ESA
LT5192039008813110	L5	1988-05-10	Algeria	192	39	131	61.09	109.21	ESA
LT4192039008813910	L4	1988-05-18				139	61.51	104.76	USGS
LT5192039008814710	L5	1988-05-26				147	62.62	102.59	ESA
LT5182042008833310	L5	1988-11-28	Libya	182	42	333	35.73	148.23	ESA
LT4182042008834110	L4	1988-12-06				341	34.66	148.51	USGS
LT5182042008834910	L5	1988-12-14				349	33.31	147.75	ESA

3.2 Data Processing System

Level 1R (L1R) scenes from the TM sensors were used for this study. L1R is a radiometrically corrected product (with 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 and L5 TM data were processed at USGS EROS through NLAPS.

The data received from the European Space Agency (ESA) were in the Committee on Earth Observation Satellites (CEOS) format. The data were received as Level 0 raw products (L0Rp). Since the NLAPS could not process the CEOS format, the L1R processing was accomplished manually. Line-by-line bias subtraction was performed, then the LUT07 gains were applied to convert the data to units of absolute radiance.

The L4 TM data were processed using the IC calibration procedure, which is based on linear regression through the detector responses to all lamp states[4] collected during a scene acquisition time. The L5 TM data were processed using the LUT07 gain model calibration procedure[3].

3.3 Conversion from Radiance to Reflectance

The image data from both sensors were 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. Further, the data were converted to reflectance scale before any analyses were performed[2].

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, reflectance compensates for different values of the exoatmospheric solar irradiances arising from spectral band differences[2].

3.4 Regions of Interest (ROI)

Regions of Interest (ROI) were selected within each respective TM scene to understand the improvement in accuracy relative to one another. The analysis approach[6, 7, 8] used image statistics derived from large areas in common between the L4 TM and L5 TM image pairs. An image pair represents an acquisition of an observed area by each of the TM sensors acquired eight days apart.

Each image pair is about 400x400 pixels. Bright and dark regions were selected to obtain maximum coverage over each sensor’s dynamic range. Large homogeneous regions common to the two image pairs were selected using cross-correlation techniques. Figure 3 shows the selected regions for the five test sites. To check the sensitivity of the regions to image geometry, the regions were shifted horizontally right and left and vertically up and down by one sample. The mean for each region was calculated at each shifted location, and the standard deviation (SD) of these means was computed. The coefficient of variation (CV) is SD/Mean < 0.01 percent for all the regions.

Once all area ROIs were selected, image statistics were computed to obtain their minimum, maximum, mean, and standard deviation values on a band-by-band basis. L4 has two inoperable detectors: one in Band 2 (detector 4) and one in Band 5 (detector 3). These detectors were excluded from the analyses. To be consistent with L4 TM, the same L5 TM detectors were also excluded from the analyses.

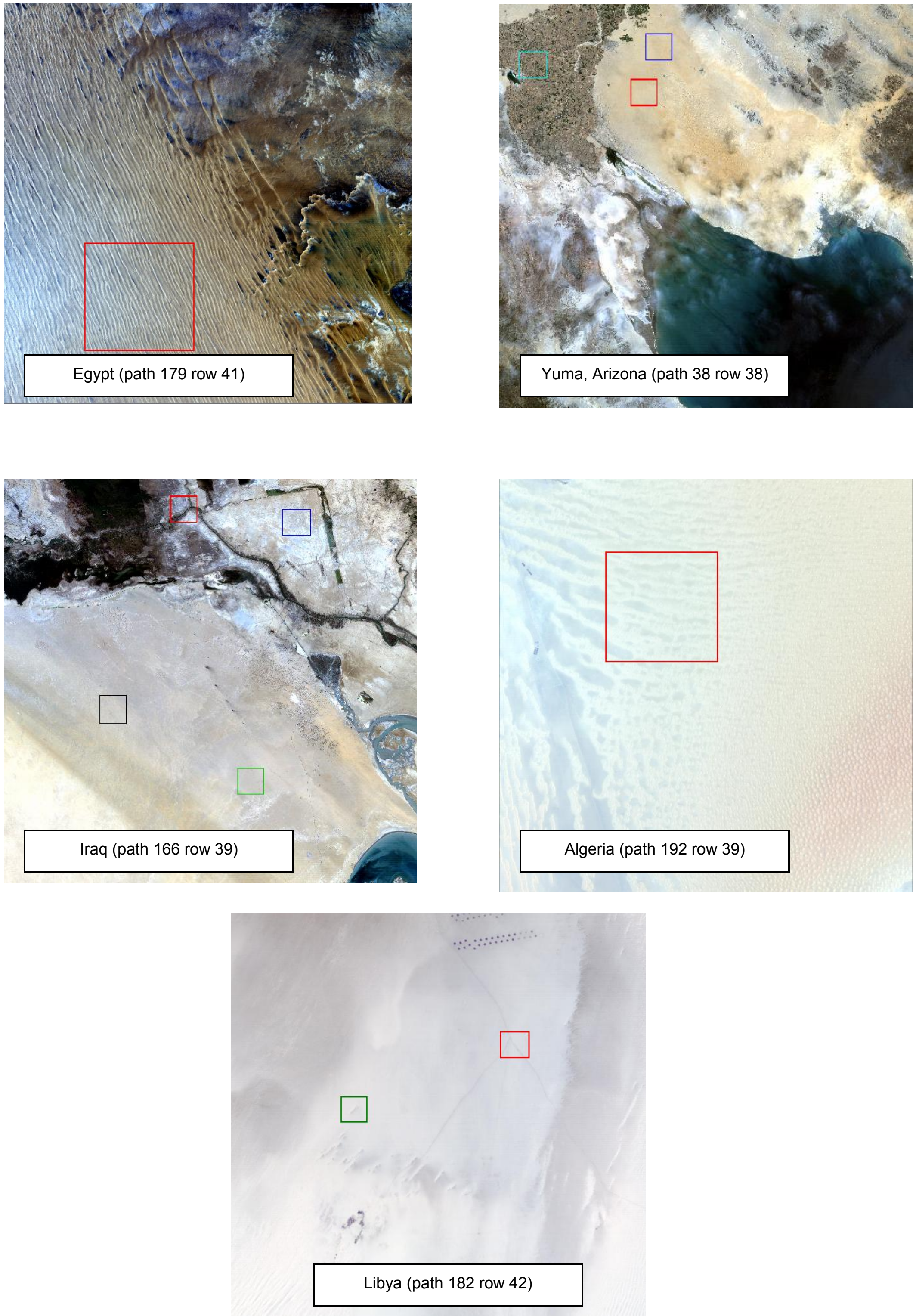


Fig 3. Areas in common between the L5 TM and the L4 TM image pairs.

4. ABSOLUTE CALIBRATION ACCURACY OF L4 TM WITH L5 TM

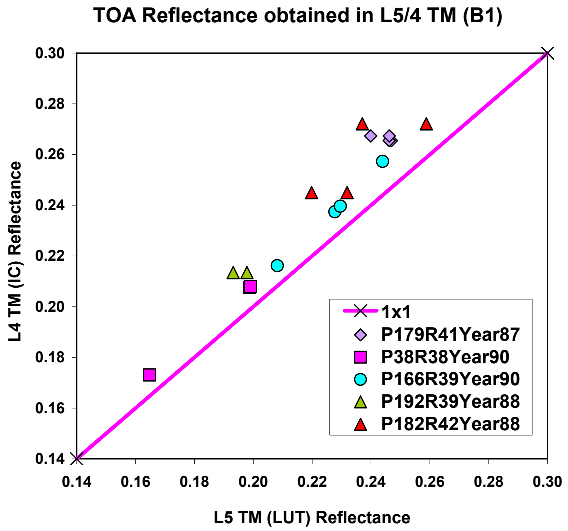
The results of reflectance comparison for solar reflective bands 1 to 7 are presented in Figure 4. The plots compare the reflectance extracted from L4 TM IC and L5 TM LUT07 processed data. Each data point on these plots represents an ensemble average of all pixels in a defined region for a given day and spectral band. The one-to-one line represents the idealized perfect agreement between the reflectances obtained from both sensors for a particular band.

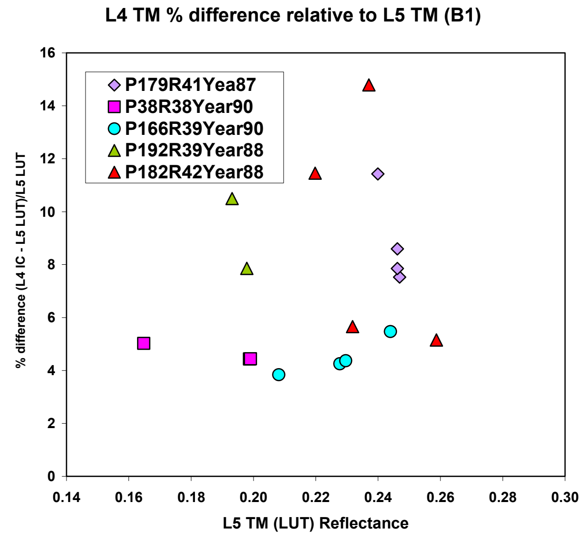
The ratios in the reflectances obtained from the data processed using the L4 TM IC and the L5 TM LUT calibration approaches are summarized in Figure 5. These time-series plots are planned to be extended, to monitor the stability and consistency between these sensors.

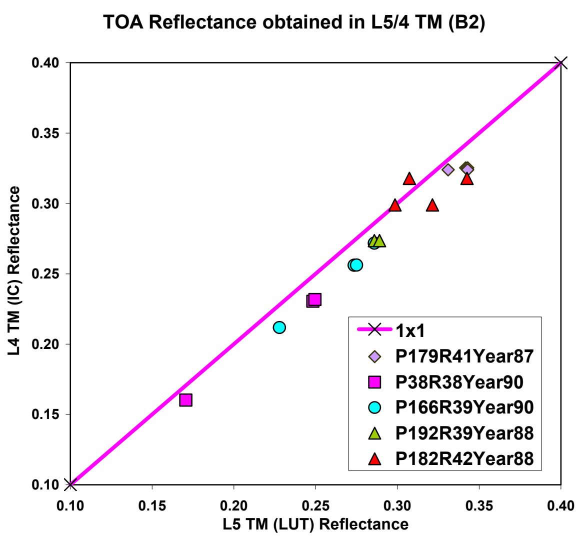
There were two ROIs selected for the (P182R42) from the image-pair (DOY-333, 341, 349). In all the bands it can be observed that there are two clustered sets of points. These differences were not caused due to the choice of ROI between the triplet image pairs, but due of the atmospheric changes between the sites from acquisitions (DOY-333 and 341) that were eight days apart.

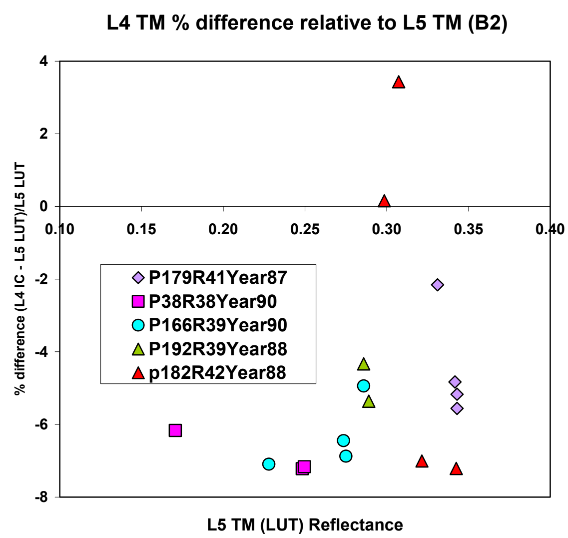
The average percent difference in reflectances obtained from the L4 TM IC relative to the L5 TM LUT are summarized in Table 3. In Band 1, the average percentage difference is 7.21; in Band 2, 5.36; in Band 3, 6.00; in Band 4, 3.33; in Band 5, 2.86; and in Band 7, 2.17. Note that agreement between L4 TM IC and L5 TM LUT is increasing with the wavelength, except for Band 3. It is missing values in Band 5 because of saturation problem. The root mean squared error (RMSE) values give another statistical measure of the magnitude of the variation between the measurements. Figure 6 summarizes the average percent differences for all the solar reflective bands. It can be observed from the figure that the average percent differences reflectance estimated get lower with increasing wavelength.

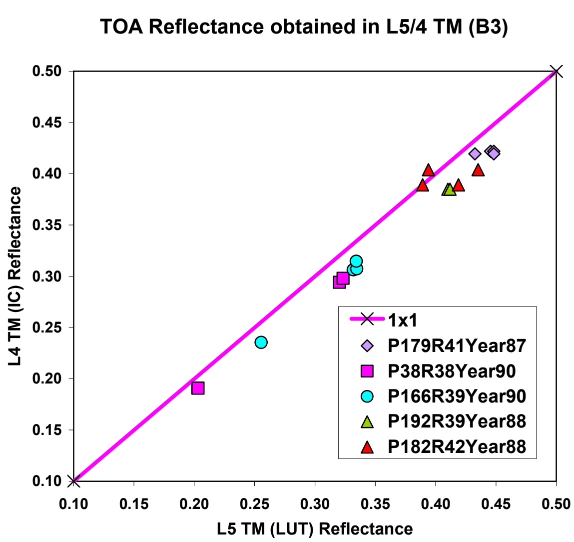
The table and the plots show consistency in the results among the five sites. Because the imaging of scene pairs was performed eight days apart, the potential changes in ground and atmospheric conditions may affect the comparison. The larger differences observed in the low reflectance range are probably caused by low Signal-to-Noise Ratio (SNR) in that portion of the instruments' responsivities. No spectral band adjustments were performed due to the similarity in the TM spectral responses. The average percent differences in reflectance estimates obtained from the L4 TM agree with those from the L5 TM to within 8 percent.

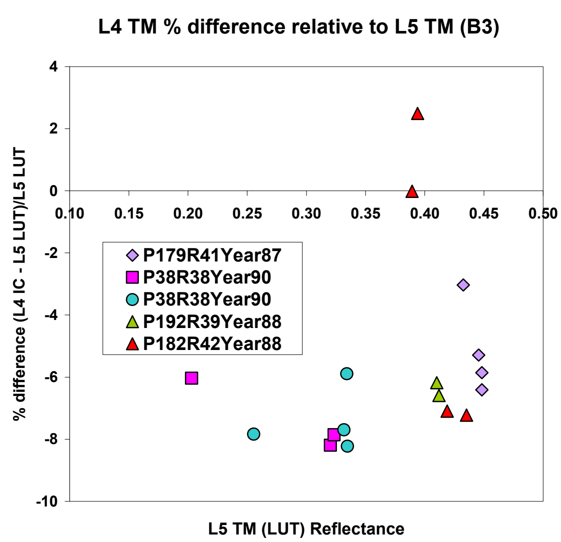

TOA Reflectance obtained in L5/4 TM (B1)
L4 TM (IC) Reflectance
L5 TM (LUT) Reflectance
1x1
P179R41Year87
P38R38Year90
P166R39Year90
P192R39Year88
P182R42Year88


L4 TM % difference relative to L5 TM (B1)
% difference (L4 IC - L5 LUT)/L5 LUT
L5 TM (LUT) Reflectance
P179R41Yea87
P38R38Year90
P166R39Year90
P192R39Year88
P182R42Year88


TOA Reflectance obtained in L5/4 TM (B2)
L4 TM (IC) Reflectance
L5 TM (LUT) Reflectance
1x1
P179R41Year87
P38R38Year90
P166R39Year90
P192R39Year88
P182R42Year88


L4 TM % difference relative to L5 TM (B2)
% difference (L4 IC - L5 LUT)/L5 LUT
L5 TM (LUT) Reflectance
P179R41Year87
P38R38Year90
P166R39Year90
P192R39Year88
p182R42Year88


TOA Reflectance obtained in L5/4 TM (B3)
L4 TM (IC) Reflectance
L5 TM (LUT) Reflectance
1x1
P179R41Year87
P38R38Year90
P166R39Year90
P192R39Year88
P182R42Year88


L4 TM % difference relative to L5 TM (B3)
% difference (L4 IC - L5 LUT)/L5 LUT
L5 TM (LUT) Reflectance
P179R41Year87
P38R38Year90
P38R38Year90
P192R39Year88
P182R42Year88

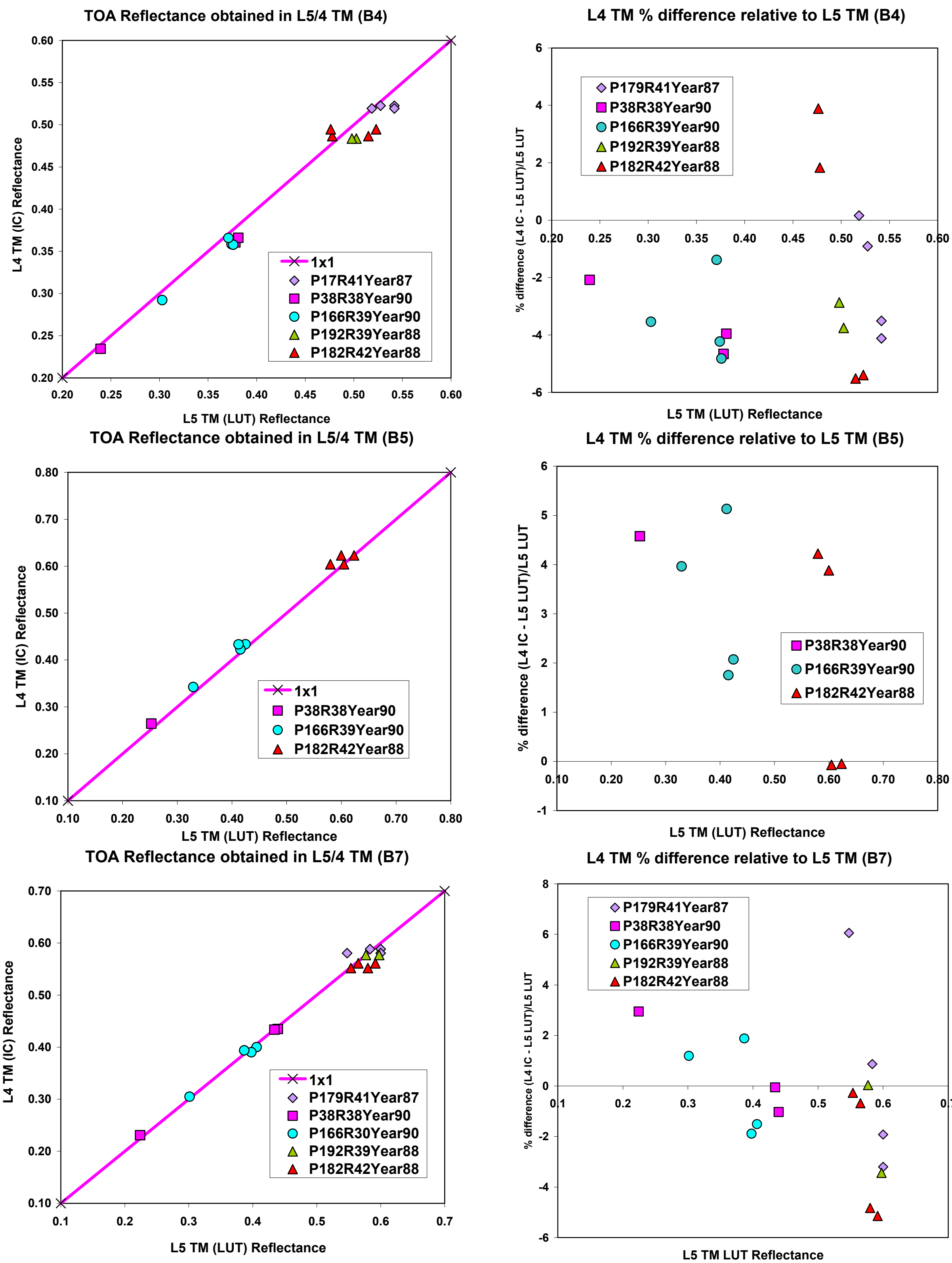


Fig 4. Comparison of reflectance measurements from large ground regions common to L4 TM and L5 TM sensors.

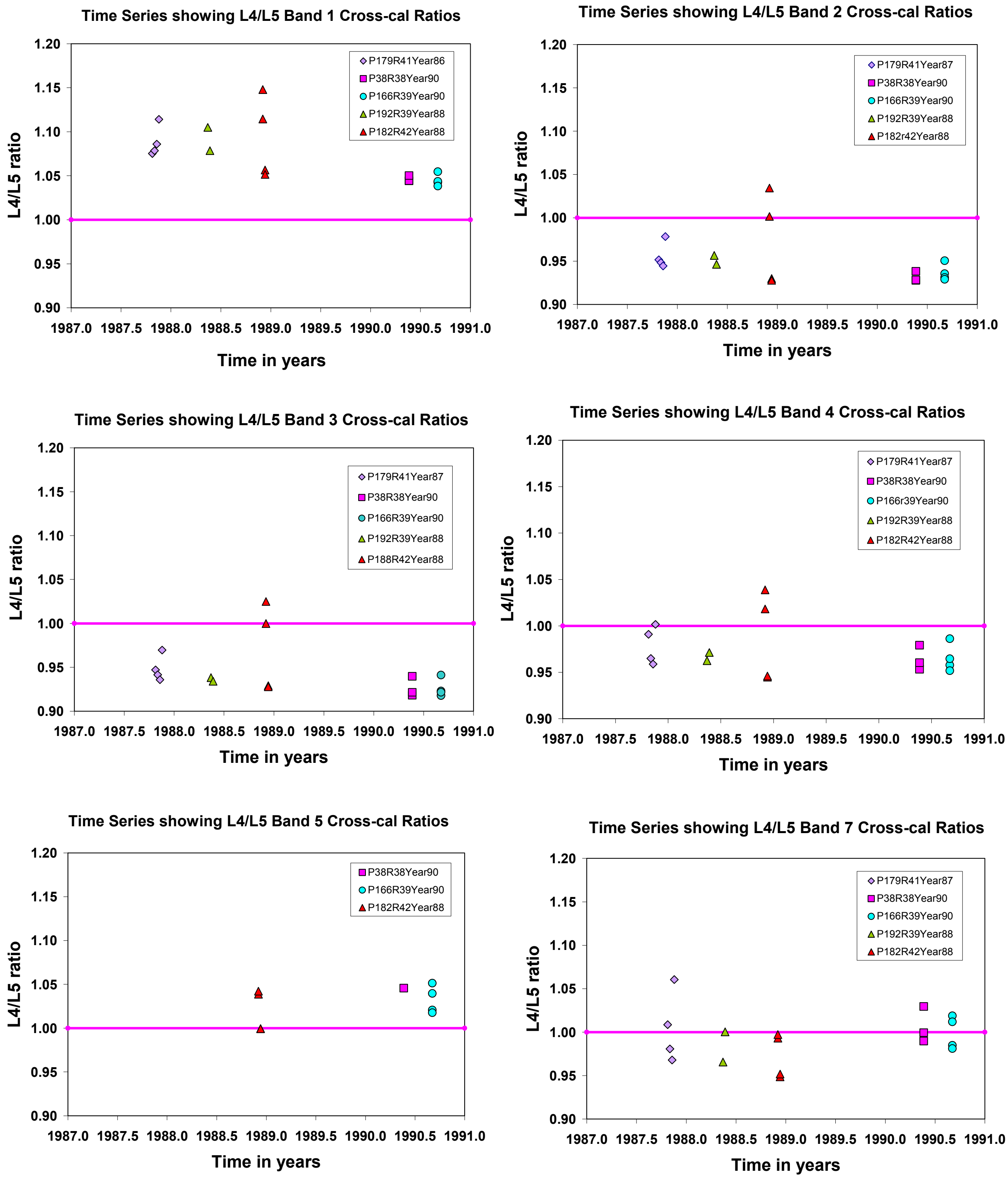


Fig 5. Time Series showing the L4/L5 cross-cal ratios for the solar reflective bands.

Table 3. L4 TM Root Mean Square Error (RMSE) with respect to L5 TM

Band	Average Percent Difference					
	P179R41	P38R38	P166R39	P192R39	P182R42	Combined
1	8.85	4.63	4.48	9.18	9.26	7.21
2	4.43	6.85	6.34	4.85	4.45	5.36
3	5.15	7.36	7.41	6.39	4.21	6.00
4	2.17	3.57	3.49	3.31	4.16	3.33
5		4.57	3.23		2.06	2.86
7	3.01	1.34	1.62	1.74	2.73	2.17

Band	Root Mean Square (RMS) of average percent difference					
	P179R41	P38R38	P166R39	P192R39	P182R42	Combined
1	8.98	4.64	4.52	9.27	10.10	7.86
2	4.63	6.87	6.40	4.87	5.31	5.69
3	5.31	7.42	7.47	6.39	5.21	6.38
4	2.74	3.73	3.73	3.34	4.42	3.66
5		4.57	3.51		2.87	3.39
7	3.58	1.80	1.64	2.43	3.55	2.81

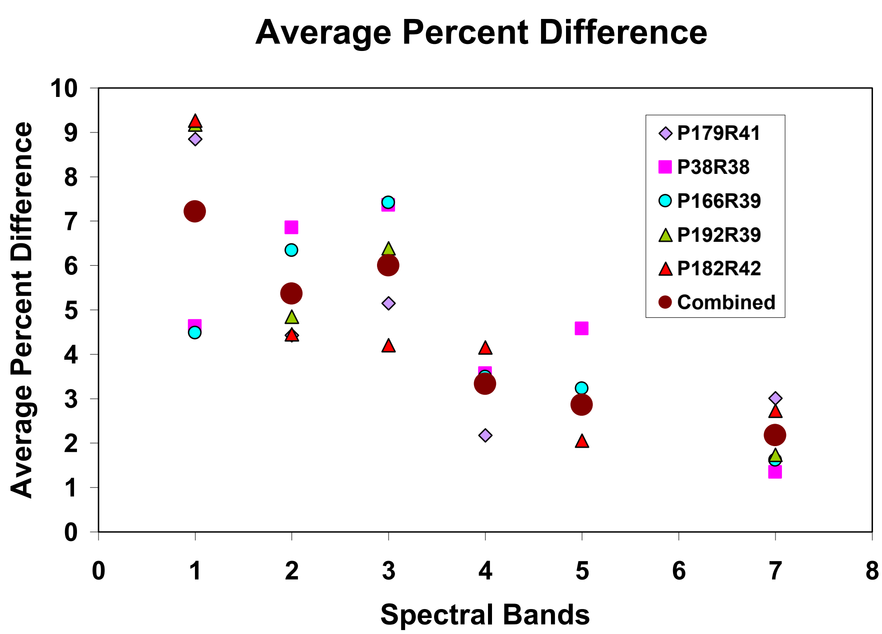


Fig 6. Summary of the average percent difference from reflectance measurements common to L4 TM and L5 TM sensors.

5. SUMMARY

The L4 TM distributed through the USGS EROS is processed using the IC method, whereas the L5 TM is processed using the revised LUT07 method. The revised LUT07 calibration procedure implemented on April 2, 2007, along with the revised post calibration dynamic ranges, provides the L5 TM data products that are more self-consistent and more consistent with L7 ETM+ data products. The study presented in the paper focuses on the evaluation of the "current" absolute accuracy of L4 TM sensors relative to L5 TM data. The cross-calibration was performed using image statistics based on large common areas observed by the two sensors that were acquired eight days apart. The average percent differences in reflectance estimates obtained from the L4 TM agree with those from the L5 TM to within 8 percent for Band 1, 6 percent for Bands 2 and 3, and 4 percent for Bands 4, 5, and 7. Based on the initial results, the L4 TM IC method seems to be consistent within 8 percent of the L5 LUT07 calibration approach.

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