Improvement in absolute calibration accuracy of Landsat-5 TM with Landsat-7 ETM+ data

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ABSTRACT

The ability to detect and quantify changes in the Earth's environment depends on satellites sensors that can provide calibrated, consistent measurements of Earth's surface features through time. A critical step in this process is to put image data from subsequent generations of sensors onto a common radiometric scale. To evaluate Landsat-5 (L5) Thematic Mapper's (TM) utility in this role, image pairs from the L5 TM and Landsat-7 (L7) Enhanced Thematic Mapper Plus (ETM+) sensors were compared. This approach involves comparison of surface observations based on image statistics from large common areas observed eight days apart by the two sensors. The results indicate a significant improvement in the consistency of L5 TM data with respect to L7 ETM+ data, achieved using a revised Look-Up-Table (LUT) procedure as opposed to the historical Internal Calibrator (IC) procedure previously used in the L5 TM product generation system. The average percent difference in reflectance estimates obtained from the L5 TM agree with those from the L7 ETM+ in the Visible and Near Infrared (VNIR) bands to within four percent and in the Short Wave Infrared (SWIR) bands to within six percent.

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

1. INTRODUCTION

1.1 Landsat-5 Thematic Mapper

The Landsat-5 (L5) Thematic Mapper (TM) is an Earth-imaging sensor that was launched on March 1, 1984. It incorporated advancements in spectral, radiometric, and geometric capabilities relative to the Multispectral Scanner (MSS) flown on previous Landsats. Onboard are two imaging sensors, the MSS and the TM. L5 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 result from the internal thermal excitation of the detector materials. To minimize this noise and allow adequate detection of scene energy, the CFP temperature is maintained between 95 and 105 K by a radiative cooler.

The Internal Calibrator (IC) is incorporated as an on-board radiometric calibration system for the L5 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

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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 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].

1.2 Landsat-7 Enhanced Thematic Mapper Plus

The Enhanced Thematic Mapper Plus (ETM+) sensor was launched on April 15, 1999, on the Landsat-7 (L7) platform; it is based on the TM sensors onboard the Landsat-4 (L4) and L5 satellites. Changes on the ETM+ sensor include a new panchromatic band, an increase in the spatial resolution of the thermal band to 60 m, and the addition of the two calibration devices to help improve the radiometric calibration. The ETM+ bands were designed to mimic the standard 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 ETM+ and L5 TM spectral bands are shown in Fig. 1.

L7 ETM+ has three on-board calibration devices, a Full Aperture Solar Calibrator (FASC), which is a white painted diffuser panel; a Partial Aperture Solar Calibrator (PASC), which is a set of optics that allows the ETM+ to image the sun through small holes; and an Internal Calibrator (IC), which consists of two lamps, a black body, a shutter, and optics to transfer the energy from the calibration sources to the focal plane[3]. One of the requirements of the L7 mission is to achieve radiometric calibration accuracy of the ETM+ data within an uncertainty of less than 5% in at-sensor radiance. This requirement is more stringent than past requirements for the Landsat Program.

An additional significant improvement in the L7 system is the incorporation of an Image Assessment System (IAS), as part of the ground processing system. The IAS is located at the U.S. Geological Survey (USGS) National Center for Earth Resources Observation and Science (EROS) in Sioux Falls, South Dakota. The NASA Goddard Space Flight Center (GSFC) Landsat Project Science Office (LPSO) works with the IAS in analyzing the calibration information and updating the algorithms used within the IAS. The IAS is responsible for offline assessment of image quality to ensure compliance with the radiometric and geometric requirements of the spacecraft and the ETM+ sensor throughout the Landsat mission. One of the most important roles of the IAS is generation of the Calibration Parameter File (CPF) that contains all of the necessary parameters for generating a Level-1 product. The IAS also became responsible for the routine radiometric and geometric calibration of the L5 TM following its transition to bumper mode operations in early 2002.

2. REVISED L5 TM RADIOMETRIC CALIBRATION PROCEDURE

Over the lifetime of L5, there have been three U.S. data product generation systems. The initial processing system for L5 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 it 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 it has always processed TM data with the National Landsat Archive Production System (NLAPS).

Historically, the L5 TM calibration procedure in NLAPS (adopted 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 EROS[4]. 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).

3. CALIBRATION BASED ON IMAGE STATISTICS

Data continuity within the Landsat Program requires consistency in interpretation of image data acquired by different imaging instruments. This section provides the comparisons of the reflectance measurements obtained from the L5 TM and L7 ETM+ scenes acquired eight days apart. The goal of this analysis is to show the improvement in consistency of the L5 with L7 data achieved by implementation of the LUT approach in the L5 data product generation system.

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 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[5].

The test site used for the current work is Railroad Valley Playa in Nevada (RVPN). The RVPN is a very homogeneous, dry lakebed with a predominantly clay composition, making it a relatively smooth, bright surface compared to most land covers. It is a desert site with no vegetation, and aerosol loading is typically low. The test site is located between the cities of Ely and Tonopah, Nevada, at latitude-longitude (lat-long) coordinates 38.5° N and 115.7° W, at an elevation of 1.3 km above sea level. It is referenced in the Worldwide Reference System 2 (WRS-2) with path 40 and row 33[6].

3.2 Landsat orbit and image pairs

L5 and L7 satellites operate in a sun-synchronous orbit with a repeat cycle of 16 days, completing 233 orbits/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 (ascending passes are at night) 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. L7 orbits eight days behind L5 or vice-versa. Therefore, a given area on the ground is imaged by L5 or L7 every eight days.

To perform cross-calibration between these two sensors, cloud-free scenes were selected over the RVPN test site. Thirteen image-pairs acquired (eight days apart) from 1999 to 2002 were used in this analysis. Table 2 lists all of the L5 TM and the L7 ETM+ scenes that were selected for the cross-calibration study. Along with the scene ID number, it also lists the date of acquisition, Day-Of-Year (DOY), and the sun elevation angle for the scenes. Table 3 summarizes the 13 image pairs that were used. There are three image pairs from 1999, six from 2001, and four from 2002.

3.3 Geometric matching

The L7 and L5 sensors differ slightly in their along-track and across-track pixel sampling. Due to wearing of the bumpers used by the L5 TM scanning mirror, along-track gaps between scans are longer for L5 TM than they are for L7 ETM+. For the same reason, and because the ETM+ scan time is slightly longer than the specification, there are also across-track differences in the ground coverage[5].

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 ETM+ and 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, in approximate size of 5 to 50 km^2, were defined. Both bright and dark regions were selected to obtain maximum coverage over each sensor's dynamic range. To avoid registration problems, ETM+ and TM image pairs can be geometrically co-registered, but that involves resampling. For this particular study, any kind of resampling was avoided to obtain the highest radiometric accuracy without corrupting the pixel values due to resampling. Radiometric effects due to residual image misregistration were avoided by using the large areas common to both the ETM+ and TM image pairs.

3.4 Data processing system

Level 1R (L1R) scenes from the ETM+ and TM sensors were used for this particular 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 L5 TM data were processed at the National Center for EROS, using two different calibration procedures through the NLAPS. The first calibration procedure used the IC calibration (based on linear regression through the detector responses to all lamp states collected during a scene acquisition time), and the second approach used the revised (LUT gain model) calibration procedure. The L7 ETM+ scenes were processed through the IAS using the most currently available CPF.

3.5 Regions of interest

Regions of Interest (ROI) were selected within each respective ETM+ and 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. 2 shows the selected regions that were common to the ETM+ and the respective 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.

For relatively "clear" Landsat scenes, a reduction in between 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. IMPROVEMENT IN ABSOLUTE CALIBRATION ACCURACY OF L5 WITH L7

Results of reflectance comparison for spectral bands 1-7 are presented in Fig. 3. The plots on the left side in each of these figures relate reflectances extracted from L5 TM L1R data to corresponding reflectances obtained from L7 ETM+ 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 points out the idealized perfect agreement between the reflectances obtained from both sensors for a particular band. The plots on the right side represent percentage differences in observation using the IC and LUT approaches in L5 processing relative to L7 data.

The plots clearly indicate a significant improvement toward consistency of L5 data with L7 data achieved using the LUT approach as opposed to the historical IC calibration procedure. The average percent differences in reflectances obtained from the L5 TM (using IC and LUT) relative to the L7 ETM+ are summarized in Table 4. In band 1, the average percentage difference reduces from about 15.67% (L7 ETM+ and L5 IC) to 2.53% (L7 ETM+ and L5 LUT); in band 2, from 15.75% to 2.03%; in band 3, from 14.96% to 2.57%; in band 4, from 11.96% to 3.67%; in band 5, from 11.22% to 4.38%; and in band 7, from 8.68% to

5.02%. Similarly, the Root Mean Square (RMS) values are summarized in Table 5. The RMS values give another statistical measure of the magnitude of the variation between the measurements.

The intent of the IC lamp system was to provide known radiance levels for absolute radiometric calibration. The IC reflective band procedure for in-flight calibration regresses the current detector responses from the lamps against the pre launch lamp radiances to get the gains and biases. These gains and biases are applied to the raw imagery during radiometric calibration to create Level-1 products. The detector response to the lamp data from 2002 and later suggest that the output is tending to decrease, after reaching a maximum in early 2002[8]. There is a sudden drop out in the detector responses to the lamp in the 2002 datasets. Therefore, the gains derived for the 2002 dataset are significantly different from the gains derived for the 1999 and 2001 datasets. Accordingly, it can be observed from the plots in Fig. 3 that the L5 TM reflectances obtained using IC calibrations have significant variations. The data points are not clustered together and lie on both sides of the one-to-one line.

It is very apparent from the table and the plots that there is a significant improvement in the consistency obtained between the sensors when L5 TM data are processed using the revised LUT calibration approach as opposed to the historical IC method. 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 L7 ETM+ and corresponding L5 TM spectral bands[7]. The consistency between results from the image pairs is within four percent in the Visible and Near Infrared (VNIR) bands and within six percent in the Short Wave Infrared (SWIR) bands, which is well beyond the specified ±six percent overall uncertainty for the targets with unknown spectral signatures[5].

5. SUMMARY

Data continuity within the Landsat Program requires consistency in interpretation of image data acquired by different 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 Landsat-5 (L5) Thematic Mapper's (TM) capabilities in this role, image pairs from the L5 TM and Landsat-7 (L7) Enhanced Thematic Mapper Plus (ETM+) 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 analyses show improvement in consistency of the L5 with L7 imagery achieved through implementation of the LUT approach in L5 data product generation. The reflectance estimates obtained from the L5 TM agree with those from the L7 ETM+ in the Visible and Near Infrared (VNIR) bands to within four percent and in the Short Wave Infrared (SWIR) bands to within six percent.

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Table 1. L5 TM and L7 ETM+ spectral coverage and ground sample distance[2, 3]

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

Band	Type	L7 ETM+ Spectral Range (um)		Detectors	GSD (m)
1	Si Photodiode	Blue-Green	0.450 - 0.515	16	30
2	Si Photodiode	Green	0.525 - 0.605	16	30
3	Si Photodiode	Red	0.630 - 0.690	16	30
4	Si Photodiode	Near-IR	0.775 - 0.900	16	30
5	InSb	Mid-IR1	1.550 - 1.750	16	30
6	HgCdTe	Thermal-IR	10.40 - 12.50	8	60
7	InSb	Mid-IR2	2.090 - 2.350	16	30
8	Si Photodiode	Pan	0.520 - 0.900	32	15

Table 2. L7 ETM+ and L5 TM data over RVPN from 1999 to 2002

Railroad Valley Playa in Nevada (Path 40, Row 33)			
Scene ID	Date (YYYY-MM-DD)	DOY (Day Of Year)	Solar zenith angle in degrees
L5 TM Scenes			
LT5040033199926410	1999-09-21	264	44.11
LT5040033199928010	1999-10-07	280	49.17
LT5040033000123710	2001-08-25	237	36.36
LT5040033000125310	2001-09-10	253	40.63
LT5040033000126910	2001-09-26	269	45.47
LT5040033000128510	2001-10-12	285	50.62
LT5040033000220810	2002-07-27	208	31.27
LT5040033000222410	2002-08-12	224	34.22
LT5040033000224010	2002-08-28	240	37.88
L7 ETM+ Scenes			
LE7040033009927250	1999-09-29	272	45.14
LE7040033009928850	1999-10-15	288	50.49
LE7040033000124550	2001-09-02	245	37.48
LE7040033000126150	2001-09-18	261	42.23
LE7040033000127750	2001-10-04	277	47.42
LE7040033000221650	2002-08-04	216	30.68
LE7040033000223250	2002-08-20	232	34.14

Table 3. L7 ETM+ and L5 TM image pairs

Image Pairs		
	L7 ETM+	**L5 TM**
Year	**DOY**	
1999	288	280
1999	272	280
1999	272	264
2001	277	285
2001	277	269
2001	261	269
2001	261	253
2001	245	253
2001	245	237
2002	232	240
2002	232	224
2002	216	224
2002	216	208

Table 4. Average percent difference with respect to L7 ETM+

Average percent difference		
Band	**L5 IC**	**L5 LUT**
1	15.67	2.53
2	15.75	2.03
3	14.96	2.57
4	11.96	3.67
5	11.22	4.38
7	8.68	5.02

Table 5. Root Mean Square (RMS)

Root Mean Square (RMS)		
Band	**L5 IC**	**L5 LUT**
1	17.01	3.22
2	16.67	3.06
3	15.95	3.78
4	14.08	4.73
5	13.76	5.69
7	11.93	6.30

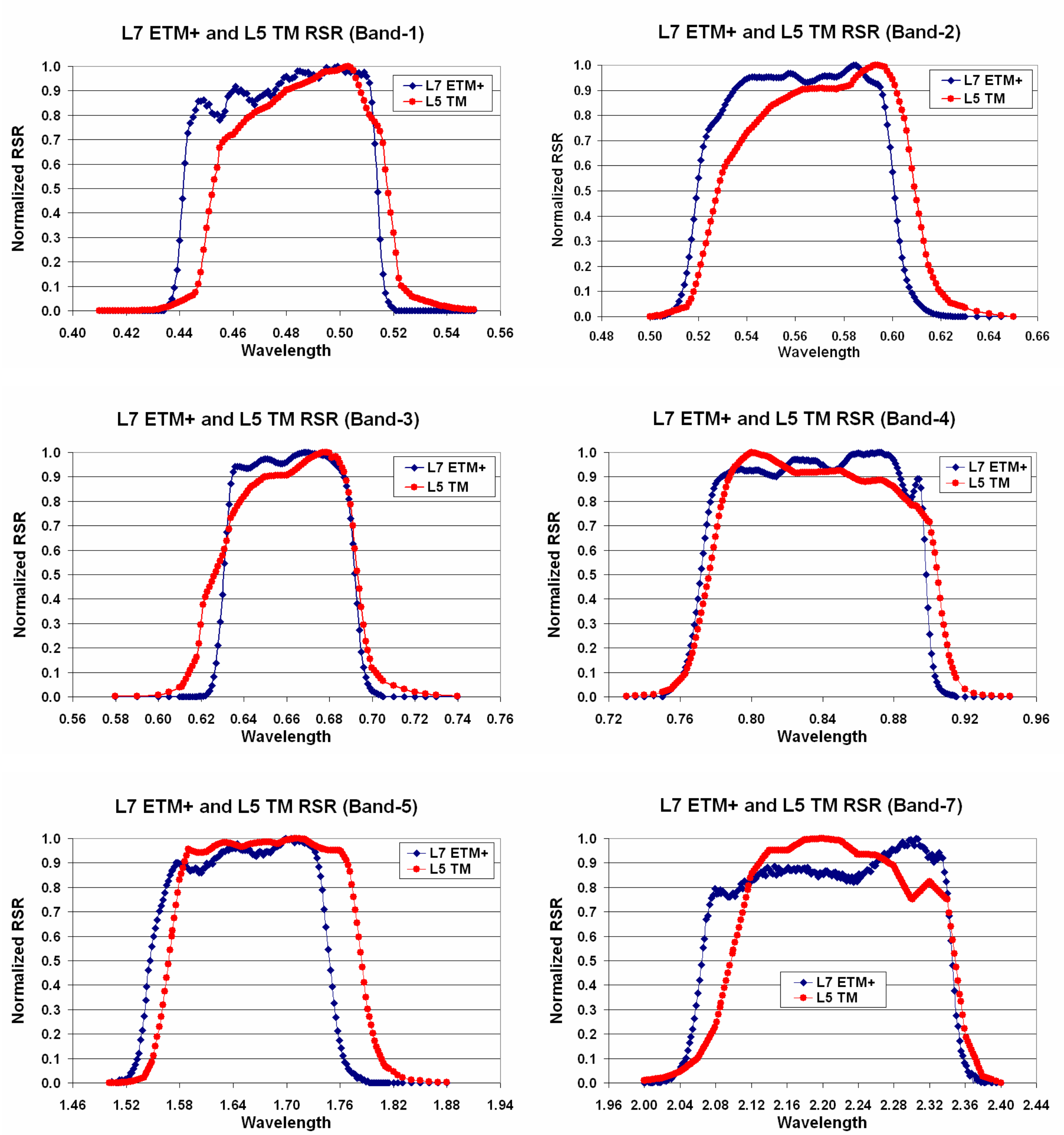


Figure 1. Relative Spectral Response (RSR) profiles of L7 ETM+ and L5 TM

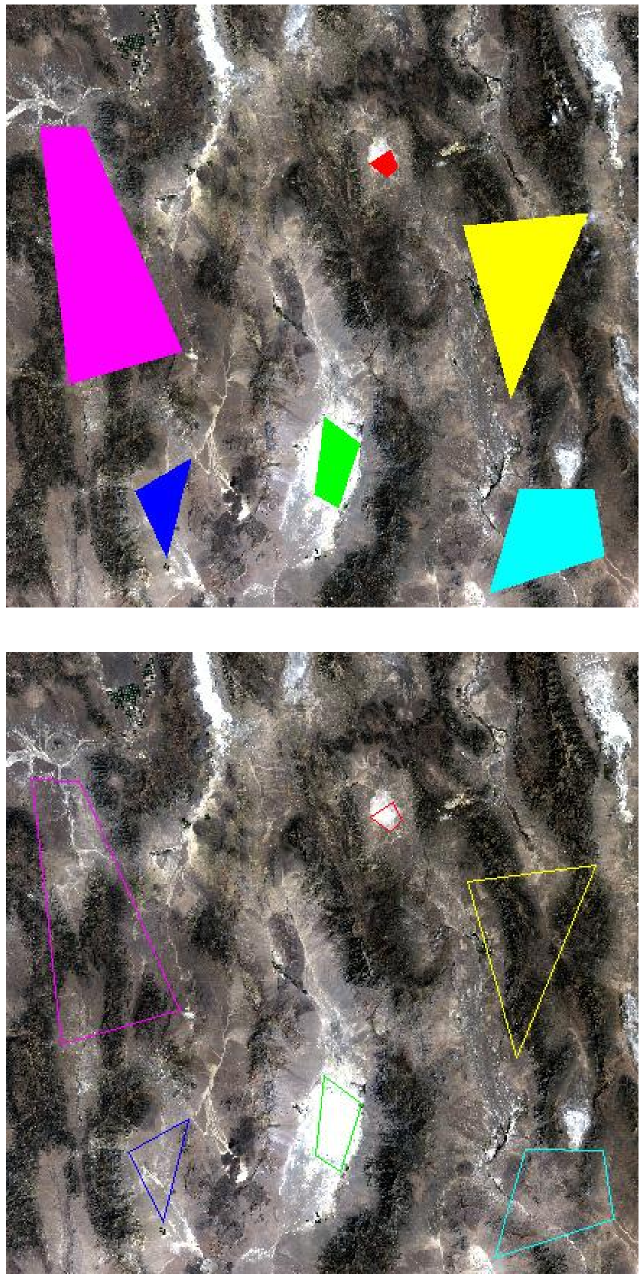
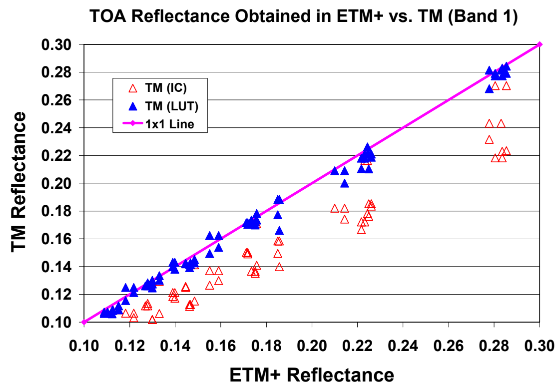
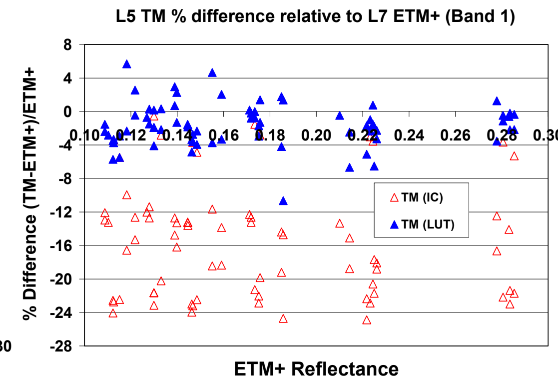
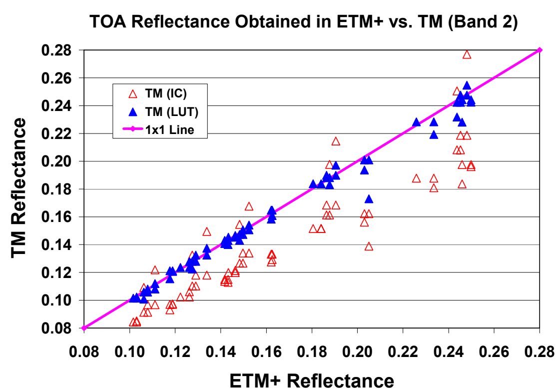
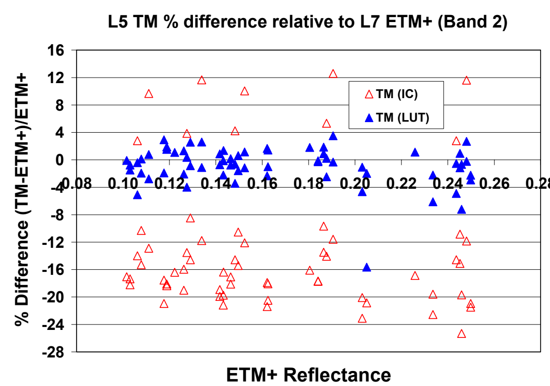


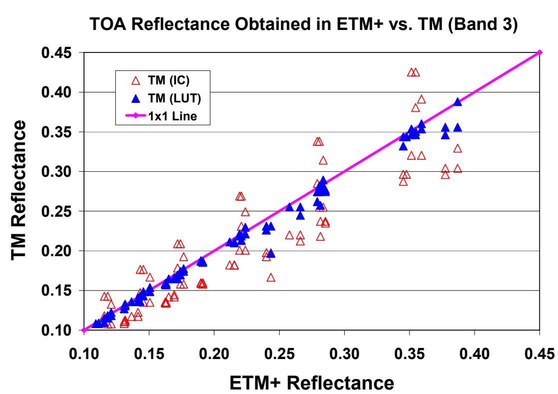
Figure 2. Areas in common between the L7 ETM+ (2001 DOY 245) and the L5 TM (2001 DOY 253) image pairs

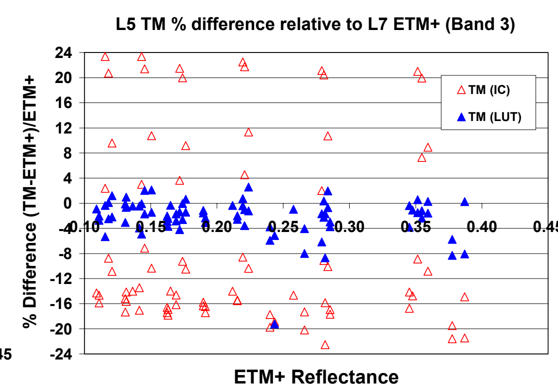

TOA Reflectance Obtained in ETM+ vs. TM (Band 1)
TM Reflectance
ETM+ Reflectance
TM (IC)
TM (LUT)
1x1 Line
0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30


L5 TM % difference relative to L7 ETM+ (Band 1)
% Difference (TM-ETM+)/ETM+
ETM+ Reflectance
TM (IC)
TM (LUT)
8 4 0 -4 -8 -12 -16 -20 -24 -28
0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30


TOA Reflectance Obtained in ETM+ vs. TM (Band 2)
TM Reflectance
ETM+ Reflectance
TM (IC)
TM (LUT)
1x1 Line
0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28


L5 TM % difference relative to L7 ETM+ (Band 2)
% Difference (TM-ETM+)/ETM+
ETM+ Reflectance
TM (IC)
TM (LUT)
16 12 8 4 0 -4 -8 -12 -16 -20 -24 -28
0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28


TOA Reflectance Obtained in ETM+ vs. TM (Band 3)
TM Reflectance
ETM+ Reflectance
TM (IC)
TM (LUT)
1x1 Line
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45


L5 TM % difference relative to L7 ETM+ (Band 3)
% Difference (TM-ETM+)/ETM+
ETM+ Reflectance
TM (IC)
TM (LUT)
24 20 16 12 8 4 0 -4 -8 -12 -16 -20 -24
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45

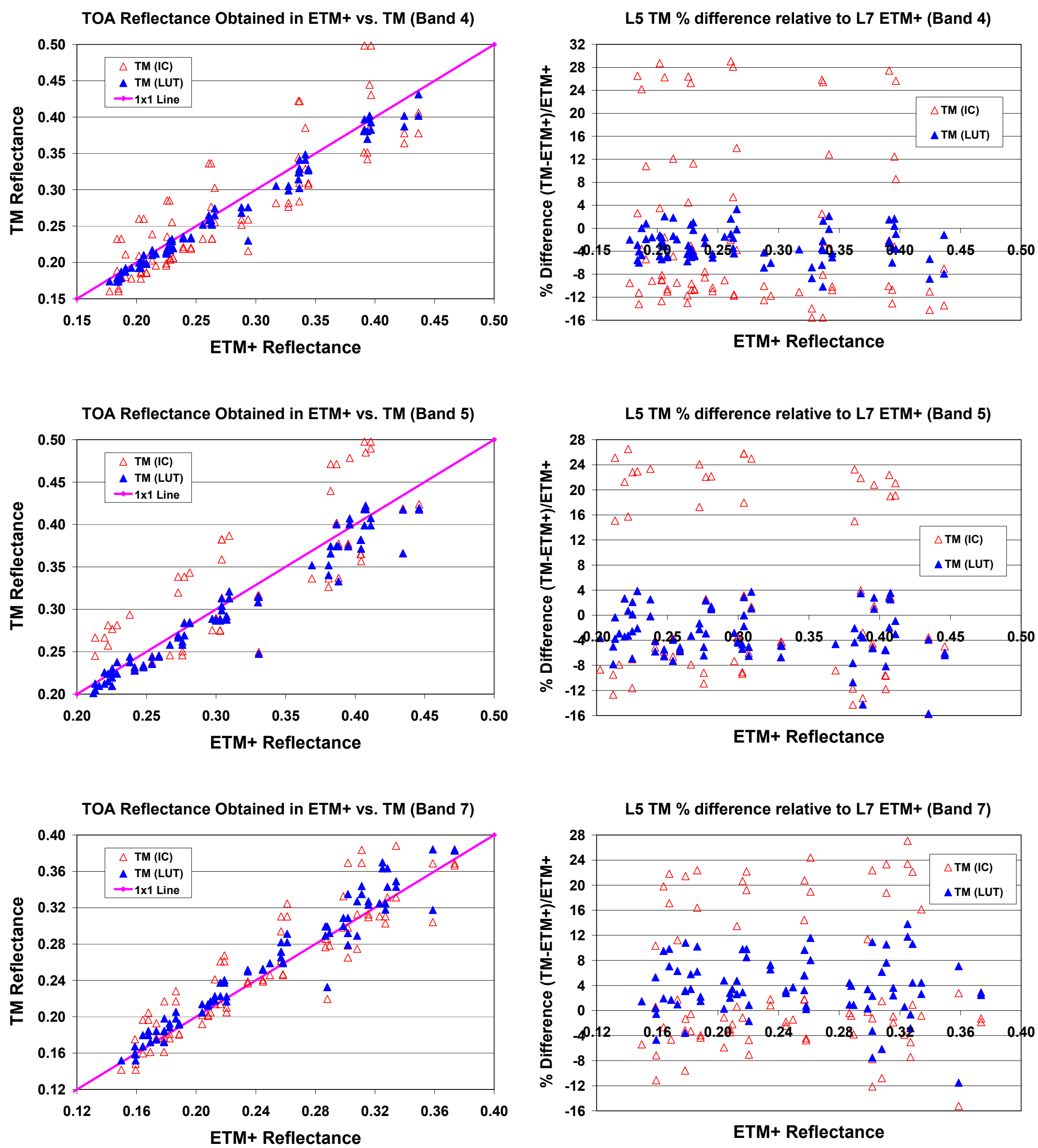


Figure 3. Comparison of reflectance measurements from large ground regions common to bands 1-7 of both L5 TM and L7 ETM+ instruments