Revised Landsat-5 Thematic Mapper Radiometric Calibration

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***Abstract*—Effective April 2, 2007, the radiometric calibration of Landsat-5 (L5) Thematic Mapper (TM) data that are processed and distributed by the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) will be updated. The lifetime gain model that was implemented on May 5, 2003, for the reflective bands (1–5, 7) will be replaced by a new lifetime radiometric-calibration curve that is derived from the instrument's response to pseudoinvariant desert sites and from cross calibration with the Landsat-7 (L7) Enhanced TM Plus (ETM+). Although this calibration update applies to all archived and future L5 TM data, the principal improvements in the calibration are for the data acquired during the first eight years of the mission (1984–1991), where the changes in the instrument-gain values are as much as 15%. The radiometric scaling coefficients for bands 1 and 2 for approximately the first eight years of the mission have also been changed. Users will need to apply these new coefficients to convert the calibrated data product digital numbers to radiance. The scaling coefficients for the other bands have not changed.**

***Index Terms*—Bias, calibration, characterization, gain, Landsat-5 (L5), Libya, lookup table (LUT), National Land Archive Production System (NLAPS), offset, radiance, reflectance, relative spectral response (RSR), spectral bands, Thematic Mapper (TM).**

I. Introduction

LANDSAT-5 (L5) was launched on March 1, 1984, with the Thematic Mapper (TM) Earth-imaging sensor onboard. The satellite and sensor continue to operate today, after more than 23 years of service. The TM has seven spectral bands: six 30-m reflective bands and one 120-m thermal band. TM bands have center wavelengths of approximately 0.49, 0.56, 0.66, 0.83, 1.67, 11.5, and 2.24 μm, respectively. The raw and calibrated data products are quantized to eight bits.

The TM incorporates an internal calibrator (IC) with lamps for the reflective bands, a blackbody source for the thermal band, and a temperature-monitored shutter for all the bands. The IC is located behind the primary instrument telescope. The calibrator is synchronized with the scan mirror such that the detectors view the calibration sources during each scan mirror turnaround (when no scene data are being taken).

The operations of the satellite and its ground processing system have evolved over the years [1]. The U.S. Geological Survey (USGS) has operated L5 since 2001 and currently processes TM data through the National Land Archive Production System (NLAPS). Most users order the fully processed (Level 1G) data products, to which both radiometric and geometric corrections have been applied. An exponential-decay model was implemented in 2003 [2] to represent the radiometric response or gain of each reflective band as a function of time since launch. The exponential model and coefficients are used to generate a day-specific band-average lookup table (LUT) [3] of detector gains for use in processing. After the application of the LUT gains, the data are rescaled to a fixed radiance range (referred to as the postcalibration dynamic range) represented by LMIN (radiance corresponding to "zero" DN) and LMAX (radiance corresponding to "255" DN). The thermal-band gain is calculated based on the responses to the IC shutter and blackbody, and image data are similarly rescaled to a fixed radiance range. Note that the Landsat-7 (L7) Enhanced TM Plus (ETM+) products are scaled to an LMIN value of "one" DN, and the "zero" DN is reserved for the fill data.

II. Radiometric Calibration Procedure

Data continuity requires consistency in the interpretation of image data acquired by different sensors. Calculation of radiance is the fundamental step in putting data from multiple sensors and platforms onto a common radiometric scale. The following is a partial list of variables used for radiometric calibration.

Q	Raw quantized voltage or response [DN].
G	Detector gain or reponsivity [DN/(W/(m^2 · sr · μm)].
B	Detector bias or background response [DN].
L_λ	Spectral radiance at the sensor's aperture [W/(m^2 · sr · μm)].
Q_{cal}	Quantized calibrated pixel value [DN].
$Q_{\mathrm{cal\,min}}$	Minimum quantized calibrated pixel value ($\mathrm{DN} = 0$) corresponding to LMIN$_\lambda$.
$Q_{\mathrm{cal\,max}}$	Maximum quantized calibrated pixel value ($\mathrm{DN} = 255$) corresponding to LMAX$_\lambda$.
LMIN$_\lambda$	Spectral radiance that is scaled to $Q_{\mathrm{cal\,min}}$ [W/(m^2 · sr · μm)].
LMAX$_\lambda$	Spectral radiance that is scaled to $Q_{\mathrm{cal\,max}}$[W/(m^2 · sr · μm)].

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G_{rescale} Band-specific rescaling gain factor $[(\text{W}/(\text{m}^2 \cdot \text{sr} \cdot \mu\text{m}))/\text{DN}]$.
B_{rescale} Band-specific rescaling bias factor $[\text{W}/(\text{m}^2 \cdot \text{sr} \cdot \mu\text{m})]$.

A. Conversion to Radiance for L0Rp Products (Q-to- L_λ)

The pixel values in the raw data products (L0Rp) are represented as Q. The detectors exhibit linear response to the Earth's surface radiance. The response is quantized into 8-bit numbers that represent brightness values between 0 and 255 in the L0Rp. Instrument gains (G) and biases (B) are used to convert the raw data (Q) to at-sensor spectral radiance (L_λ). This process is given by the relationships

$$Q = G \times L_\lambda + B$$
$$L_\lambda = \frac{(Q - B)}{G}.$$

The G's are the band-average time-dependent gain coefficients generated from the lifetime gain models and stored in the LUT. The B's are the line-by-line biases that are based on the dark shutter responses acquired from each scan line. During processing, the band-average LUT gains are combined with the detector relative gains and the band rescaling gains to obtain a detector specific processing gain. Note that the G and B are only to be used on the L0Rp.

B. Conversion to Radiance for L1 Products (Q_{cal}-to- L_λ)

The pixel values in the Level 1 (L1) data are represented as Q_{cal}. During the radiometric calibration, pixel values (Q) from L0Rp image data are converted to units of absolute radiance using 32-bit floating-point calculations. The absolute-radiance values are then scaled to 8-bit values representing the calibrated digital numbers (Q_{cal}) before output to the distribution media. Conversion from Q_{cal} in L1 products back to L_λ requires knowledge of the original rescaling factors. This process is given by the following relationship:

$$L_\lambda = \left(\frac{\text{LMAX}_\lambda - \text{LMIN}_\lambda}{Q_{\text{cal max}} - Q_{\text{cal min}}}\right)(Q_{\text{cal}} - Q_{\text{cal min}}) + \text{LMIN}_\lambda$$

or

$$L_\lambda = \left(\frac{\text{LMAX}_\lambda - \text{LMIN}_\lambda}{255}\right) Q_{\text{cal}} + \text{LMIN}_\lambda$$

where

$$Q_{\text{cal max}} = 255$$
$$Q_{\text{cal min}} = 0$$

or

$$L_\lambda = G_{\text{rescale}} \times Q_{\text{cal}} + B_{\text{rescale}}$$

TABLE I
THIS MODEL IS USED IN LUT FORM (LUT07) TO REPRESENT THE BAND-AVERAGE GAIN OF THE TM BANDS. COEFFICIENTS a_0 AND a_2 ARE IN UNITS OF $\text{DN}/(\text{W}/\text{m}^2 \cdot \text{sr} \cdot \mu\text{m})$ AND THE a_1 COEFFICIENTS ARE 1/YEAR

L5 TM gain model fitting coefficients (LUT07)			
Band	**a_0**	**a_1**	**a_2**
1	0.2901	0.1399	1.209
2	0.1246	0.1045	0.6305
3	0.0839	0.2386	0.9028
4	0	0	1.082
5	0	0	8.209
7	0	0	14.695

where

$$G_{\text{rescale}} = \frac{\text{LMAX}_\lambda - \text{LMIN}_\lambda}{255}$$
$$B_{\text{rescale}} = \text{LMIN}_\lambda.$$

The LUT gains are used for converting the Q in the L0Rp to spectral radiance, while the rescaling gains (G_{rescale}) are used to convert the Q_{cal} in the L1 data to spectral radiance. The conversion from Q to Q_{cal} is performed during the L1-product generation; accordingly, users with L1 data do not apply the LUT gains for conversion to radiance.

III. REVISED RADIOMETRIC CALIBRATION

Since the implementation of the current LUT procedure in the NLAPS systems on May 2003 [1], [2], studies have continued in order to validate and refine the lifetime gain model. These validation studies have relied primarily on the data acquired over pseudoinvariant desert sites but have been hindered by the limited amount of data available over any one site for the 23-year life of the mission. Recently, the European Space Agency (ESA) provided a significant number of scenes over a North African desert site in Libya (path 181 row 40) that are acquired during most of the L5 mission. These data indicate an exponential decay of about 19%, 16%, and 8%, respectively, for TM bands 1, 2, and 3. This degradation is similar in magnitude to the current model but has a longer time constant. Bands 4, 5, and 7 did not show any clear trends over the full mission using the Libya site or the other sites. Preliminary analyses that resulted in this calibration change can be found in [4] and [5]; a more thorough treatment of the analyses leading to the change is planned for a forthcoming journal article. The time-dependent equations for L5 TM gain $G_{\text{new}}(t)$, which are applicable to the raw data, take the form

$$G_{\text{new}}(t) = a_0^x \exp\left(-a_1^x(t - 1984.2082)\right) + a_2$$

where the time t is in decimal years, a_0 is a scaling factor for the exponential decrease, a_1 is a time constant of the exponential decrease, a_2 is a required offset, and 1984.2082 refers to "time zero," which is the acquisition date of the first on-orbit L5 TM data available in the U.S. archive (March 16, 1984). The coefficients a_0, a_1, and a_2 are summarized in Table I.

In response to the aforementioned results, a revised lifetime gain model was implemented in NLAPS. This model is based on the pseudoinvariant desert-site data and the cross calibration

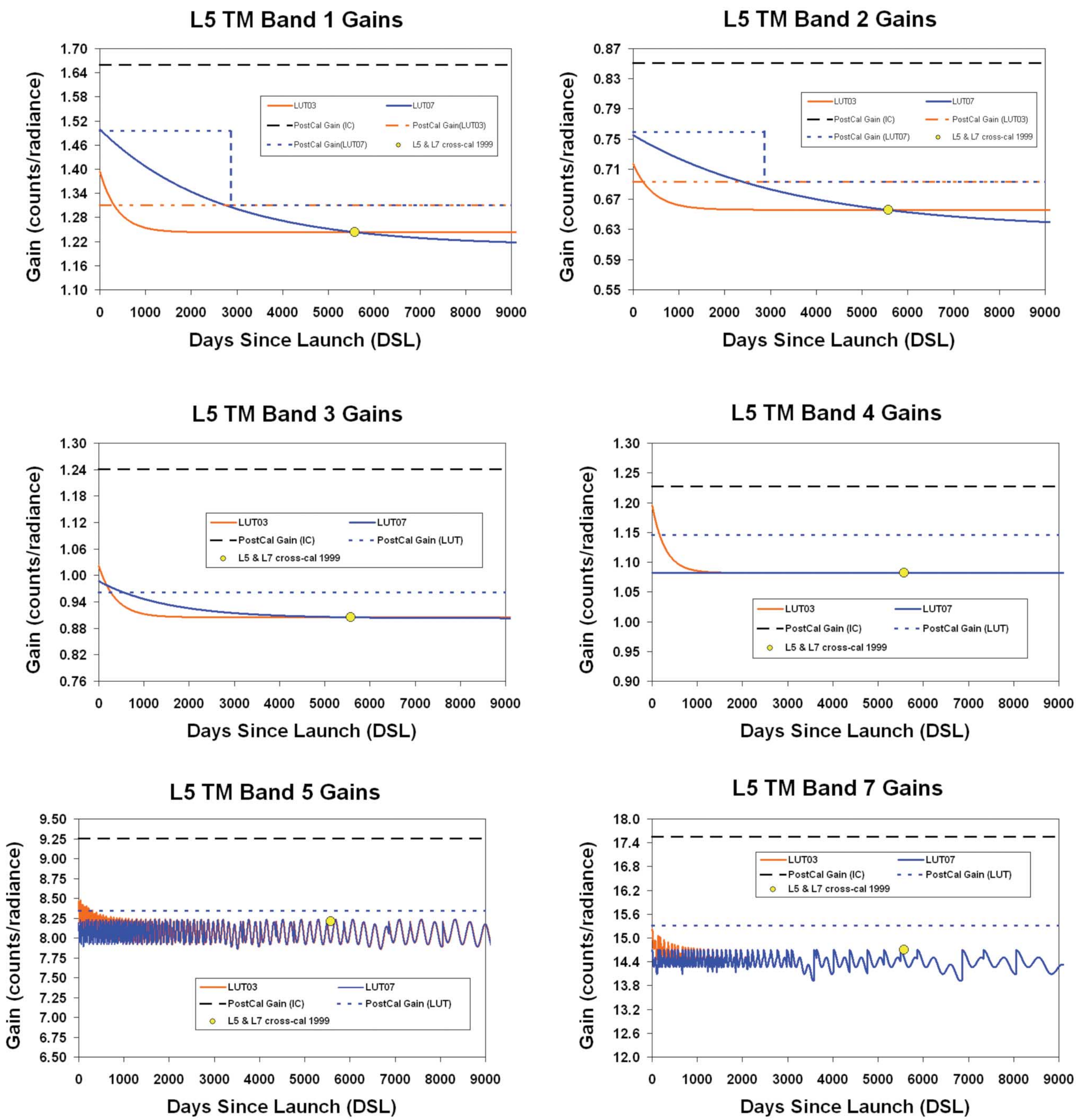

Fig. 1. Lifetime band-average gains implemented in 2003 (LUT03) and 2007 (LUT07) for the L5 TM reflective bands, including postcalibration gains.

of L5 TM with the L7 ETM+ from June 1999 [6]. Effective April 2, 2007, the revised LUT calibration model will be used for all of the L5 data that are processed and distributed by the USGS Earth Resources Observation and Science (EROS). The LUT model implemented in 2003 (LUT03) will be replaced by a new lifetime radiometric-calibration LUT model (LUT07). Although this calibration update applies to all reflective bands and all archived and future L5 TM data, the principal improvements in the calibration are for the data acquired during the first eight years of the mission, where the change in the instrument-gain values is as much as 15%. Fig. 1 shows the comparison of the LUT07 versus the LUT03.

IV. Revised L5 TM $LMAX_\lambda$ for Bands 1 and 2

The radiometric scaling coefficients for bands 1 and 2 for approximately the first eight years (1984–1991) of the mission have also been changed to optimize the dynamic range and better preserve the sensitivity of the early mission data. Tables II and III list band-specific $LMAX_\lambda$ and $LMIN_\lambda$ parameters used by the L5 TM processing system for the data processed from different time periods. The numbers highlighted in gray are the revised $(LMAX_\lambda = 169.0, 333.0)$ postcalibration dynamic ranges for the data acquired between March 1, 1984, and December 31, 1991, and processed using

TABLE II
POSTCALIBRATION DYNAMIC RANGES FOR THE L5 TM DATA PROCESSED TO L1 BEFORE APRIL 2, 2007

Spectral Radiances, LMIN and LMAX in W/(m^2.sr.µm)						
Processing Date	From March 1, 1984 To May 4, 2003			From May 5, 2003 To April 1, 2007		
Band	LMIN	LMAX$_{(IC)}$	1/G$_{rescale(IC)}$	LMIN	LMAX$_{(LUT03)}$	1/G$_{rescale(LUT03)}$
1	-1.52	152.10	1.66	-1.52	193.0	1.31
2	-2.84	296.81	0.85	-2.84	365.0	0.69
3	-1.17	204.30	1.24	-1.17	264.0	0.96
4	-1.51	206.20	1.23	-1.51	221.0	1.15
5	-0.37	27.19	9.25	-0.37	30.2	8.34
6	1.2378	15.303	18.13	1.2378	15.303	18.13
7	-0.15	14.38	17.55	-0.15	16.5	15.32

TABLE III
POSTCALIBRATION DYNAMIC RANGES FOR THE L5 TM DATA PROCESSED TO L1 AFTER APRIL 2, 2007

Spectral Radiances, LMIN and LMAX in W/(m^2.sr.µm)				
Processing Date : From April 2, 2007				
Band	Acquisition Date	LMIN	LMAX$_{(LUT07)}$	1/G$_{rescale(LUT07)}$
1	**Mar 1, 1984 - Dec 31, 1991**	**-1.52**	**169.0**	**1.50**
	Jan 1, 1992 - Present	-1.52	193.0	1.31
2	**Mar 1, 1984 - Dec 31, 1991**	**-2.84**	**333.0**	**0.76**
	Jan 1, 1992 - Present	-2.84	365.0	0.69
3	Mar 1, 1984 - Present	-1.17	264.0	0.96
4	Mar 1, 1984 - Present	-1.51	221.0	1.15
5	Mar 1, 1984 - Present	-0.37	30.2	8.34
6	Mar 1, 1984 - Present	1.2378	15.303	18.13
7	Mar 1, 1984 - Present	-0.15	16.5	15.32

TABLE IV
RESCALING GAINS AND BIASES USED FOR THE CONVERSION OF L1 CALIBRATED DATA PRODUCT DIGITAL NUMBERS (Q_{cal}) TO SPECTRAL RADIANCE (L_λ)

Rescaling Gain (G$_{rescale}$) and Bias (B$_{rescale}$)								
Processing Date	Mar 1, 1984 - May 4, 2003		May 5, 2003 - Apr 1, 2007		Apr 2, 2007 - Present			
Acquisition Date	Mar 1, 1984 - May 4, 2003		Mar 1, 1984 - Apr 1, 2007		Mar 1, 1984 - Dec 31, 1991		Jan 1, 1992 - Present	
Band	G$_{rescale(IC)}$	B$_{rescale}$	G$_{rescale(LUT03)}$	B$_{rescale}$	G$_{rescale(LUT07)}$	B$_{rescale}$	G$_{rescale(LUT07)}$	B$_{rescale}$
1	0.602431	-1.52	0.762824	-1.52	0.668706	-1.52	0.762824	-1.52
2	1.175100	-2.84	1.442510	-2.84	1.317020	-2.84	1.442510	-2.84
3	0.805765	-1.17	1.039880	-1.17	1.039880	-1.17	1.039880	-1.17
4	0.814549	-1.51	0.872588	-1.51	0.872588	-1.51	0.872588	-1.51
5	0.108078	-0.37	0.119882	-0.37	0.119882	-0.37	0.119882	-0.37
6	0.055158	1.2378	0.055158	1.2378	0.055158	1.2378	0.055158	1.2378
7	0.056980	-0.15	0.065294	-0.15	0.065294	-0.15	0.065294	-0.15

the updated desert-site lifetime model. All data for the other bands and data for bands 1 and 2 from January 1, 1992, onward will continue to be scaled to the same LMINs and LMAXs. Table IV summarizes the band-specific rescaling gains and biases (G_{rescale}) and B_{rescale}) that the users will need to convert the Q_{cal} in L1 products to L_λ.

Fig. 1 shows the comparison of the two L5 TM radiometric-calibration LUT-gain models. It also compares the postcalibration gains (where the postcal gain $= 1/G_{\mathrm{rescale}}$), in relation to the instrument band-average gains, that were generated by the LUT processing for all of the bands. In particular, for bands 1 and 2, it can be seen that the revised LUT gains are significantly different from the previous lifetime model, particularly in the early part of the mission. The revised postcalibration dynamic ranges are only applicable to the data processed after April 2, 2007, using the updated lifetime gain model (LUT07). The new LMAXs should not be applied to the data processed using the IC gains. L5 TM data products (particularly, the early mission bands 1 and 2) that were generated before April 2, 2007, will not provide the same radiances as those processed since April 2, 2007. Landsat-4 (L4) TM sensor calibration will continue to use the postcalibration dynamic ranges previously defined.

V. CONCLUSION

An improved lifetime gain model, based on the instrument's detector response to pseudoinvariant desert-site data and cross calibration with the L7 ETM+, has been implemented for the absolute radiometric calibration of the L5 TM solar reflective bands. The modification in the calibration procedure has been implemented in NLAPS for all of the L5 TM products processed at the USGS EROS after April 2, 2007. This change will improve absolute calibration accuracy of data acquired during the early mission of the L5 TM sensor. The new lifetime gain model for the reflective bands (1–5, 7) is based on a lifetime radiometric-calibration curve that is derived from the instrument's response to desert sites and cross calibration with the ETM+. In this calibration update, only the LMAXs and the corresponding G_{rescale} values for bands 1 and 2 for approximately the first eight years of the mission have been changed. Users will need to apply new postcalibration dynamic ranges (G_{rescale} and B_{rescale}) to convert the newly processed calibrated data products to radiance. All data for the other bands and data for bands 1 and 2 from January 1, 1992, onward will continue to be scaled to the same LMINs and LMAXs as before. The revised postcalibration dynamic ranges are only applicable to the data processed after April 2, 2007, with the updated lifetime gain model (LUT07). The new LMAXs should not be applied to the data processed using IC gains. L4 TM sensor calibration will continue to use the postcalibration dynamic ranges as previously defined.

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