Revised Landsat-5 TM Radiometric Calibration Procedures and Postcalibration Dynamic Ranges

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***Abstract*—Effective May 5, 2003, Landsat-5 (L5) Thematic Mapper (TM) data processed and distributed by the U.S. Geological Survey (USGS) Earth Resources Observation System (EROS) Data Center (EDC) will be radiometrically calibrated using a new procedure and revised calibration parameters. This change will improve absolute calibration accuracy, consistency over time, and consistency with Landsat-7 (L7) Enhanced Thematic Mapper Plus (ETM+) data. Users will need to use new parameters to convert the calibrated data products to radiance. The new procedure for the reflective bands (1–5,7) is based on a lifetime radiometric calibration curve for the instrument derived from the instrument's internal calibrator, cross-calibration with the ETM+, and vicarious measurements. The thermal band will continue to be calibrated using the internal calibrator. Further updates to improve the relative detector-to-detector calibration and thermal band calibration are being investigated, as is the calibration of the Landsat-4 (L4) TM.**

***Index Terms*—Bias, gain, irradiance, Landsat, Lmax, Lmin, lookup table (LUT), National Landsat Archive Production System (NLAPS), radiance, radiometric calibration, reflectance, temperature, Thematic Mapper (TM).**

I. Introduction

THE ABILITY to detect and quantify changes in the earth's environment and its global energy balance depends on satellite sensors that can provide calibrated, consistent measurements of the earth's surface features. Two such satellites in near-polar orbit, Landsat-4 and Landsat-5 (L4 and L5), carry the Thematic Mapper (TM). When launched, these satellites marked a significant advance in remote sensing through the addition of a more sophisticated sensor system, an increased data acquisition and transmission capability, and more rapid data processing at highly automated data-processing facilities.

L5 (Fig. 1) was developed by the National Aeronautics and Space Administration (NASA) and launched in March 1984. After on-orbit checkout, it was initially operated by the National Oceanic and Atmospheric Administration (NOAA). In September 1985, operation of L5 was turned over to a private company, Earth Observation Satellite Company (EOSAT), now known as Space Imaging. In July 2001, the still-operational L5 and its entire image archives were turned back over to the U.S. Government to be operated by the U.S. Geological Survey (USGS).

Fig. 1. Landsat-5 satellite.

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 NOAA, and later EOSAT adopted it when they assumed operational control of the Landsat Program. EOSAT updated their 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).

After more than 19 years of service, the L5 TM continues to operate well. Nevertheless, the instrument has aged, and its characteristics have changed since launch. Research has shown that the method of radiometric calibration used to date by NLAPS (and TIPS) systems has been degraded by changes over time in the instrument's internal calibrator. This document presents the development of an improved calibration procedure.

This document also provides Landsat data users with methods and parameters for converting the digital numbers (DNs) from the image data to useful quantities such as spectral radiance (L_λ), and top-of-atmosphere (TOA) reflectance (ρ_P), or temperature (T) estimates. These conversions will provide a better basis for the comparison of data between images taken from different acquisition dates and/or by different sensors.

Historically, L5 TM calibration information has been presented in spectral radiance units of milliwatts per square centimeter per steradian per micrometer [mW/(cm^2 $\cdot$ sr $\cdot$ μm)]. To maintain consistency with L7 ETM+, this discussion uses spectral radiance units of watts per square meter per steradian per micrometer [W/(m^2 $\cdot$ sr $\cdot$ μm)]. Please note that the conversion factor is 1 : 10 when going from mW/(cm^2 $\cdot$ sr $\cdot$ μm) units to W/(m^2 $\cdot$ sr $\cdot$ μm).

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II. L5 TM Radiometric Calibration Modification

The L5 TM calibration procedure in NLAPS (previously used in TIPS) prior to May 5, 2003 used the instrument's response to the internal calibrator (IC) on a scene-by-scene basis to determine the gain and offset to be applied. The IC consists of three silicon-detector-stabilized tungsten miniature lamps, a blackbody, and a shutter. Each lamp has a different attenuating filter and, thus, has a different brightness level. A total of eight brightness levels can be produced with the three-lamp combination. The shutter includes optics that pipe the light from the lamps to the active shutter surface and reflect light from the blackbody. The lamps are sequenced through the eight possible lamp states during the 26-s interval that constitutes a TM scene. At the end of each 72-ms active scan, the shutter passes in front of the focal plane preventing the detection of the earth's surface radiance. During this period, the detectors see the dark shutter followed by (or preceded by, depending on the scan direction) a pulse of light from the internal lamps or blackbody source.

Before launch, the effective radiance of each lamp state for each reflective band detector was determined by comparing the detector's response to the internal lamp to its response to an external calibrated source. For the thermal band, calibration parameters were calculated that relate the gain and bias calculated with the IC to the true external gain and offset. The reflective calibration band algorithm for in-flight data regresses the current detector responses against the prelaunch radiances of the lamp states: the slope of the regression represents the gain and the intercept represents the bias. For the thermal band, the IC-determined gains and biases are adjusted using the prelaunch calibration parameters. Constant values of gain and bias are used for each detector for a scene.

Recently published studies have shown that the assumption of the constancy of the radiance of the internal lamps with time is not valid [1], [2]. At least two of the three lamps show discontinuities in their outputs over time, and a number of the TMs bands show increases in response with time to the internal lamps, a trend not evident in the vicarious calibration results [3]. The gains and biases calculated using the existing procedure have become less reliable with time. Earlier studies [4] have also shown that the constancy of the biases within a TM scene is a poor assumption for bands 1–4.

Based on these analyses, a new formulation for the instrument gain was developed [5].[1] This formulation models the gain of each band as a time-dependent equation. The model initially consisted of the sum of two terms representing an initial exponential decrease in response (believed to be due to outgassing from the spectral filters), and a linear increase in response (attributed to behavior within the lamp system), and were based on a normalized instrument response to the one calibration lamp [010] with a continuous output. The linearly increasing component was not included in the final model, as it is believed to be a lamp artifact, and is not apparent in the vicarious calibration measurements. The final model curve was then scaled to the cross-calibration gain estimates for the L7 ETM+ obtained in June 1999 [6]. For bands 5 and 7, before generating the model equations, detector responses were corrected for variation due to the buildup of an ice film on the cold focal plane window (see http://iplab2out.sdstate.edu). Thus, time-dependent calibration lookup tables (LUTs) were generated from the lifetime gain model equations for all bands.

[1]See also Image Processing Lab, South Dakota State University (http://iplab2out.sdstate.edu).

To reiterate, **the modified approach will no longer use the IC gain on a scene-by-scene basis for calibration of the reflective bands. Calibration of reflective band image data will be implemented through a time-dependent calibration LUT generated from the lifetime gain equations.** Simultaneous with this change, the biases are now applied line-by-line based on the dark shutter responses acquired from each scan line, and the regression based offset will be discarded. This approach will be similar to the current calibration method of the L7 ETM+. The implementation of the line-by-line bias subtraction will correct for the scan-correlated shift (SCS) radiometric artifact that is caused due to the change in the bias of the detectors between scans. The direct measurement of dark response of the instrument is also a better bias estimate than that produced by regression of the instrument responses to the eight lamp states using no longer reliable prelaunch lamp state radiances.

Calibration of the thermal band image data will continue with the current IC-based approach. As with the reflective bands 5 and 7, the thermal band gain is affected by the ice buildup on the cold focal plane window. However, analyses of the blackbody source and the absolute calibration of TM thermal data suggest that it is behaving as expected; based on these analyses, the decision was made to continue using the IC to calibrate the thermal band. Ongoing analysis has indicated that the calibration of this band is accurate to within 1 °C.

At this time, no modifications will be 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 produced.

III. Conversion to Radiance for Level 1 Products

Calculation of radiance is the fundamental step in putting image data from multiple sensors and platforms into a common radiometric scale. During Leve1 1 (L1) product generation, pixel values (Q) from Level 0 (L0) (raw) unprocessed image data are converted to units of absolute radiance using 32-bit floating-point calculations. The absolute radiance values are then scaled to eight-bit values representing calibrated digital numbers (Q_{cal}) before output to the distribution media.

Conversion from calibrated digital numbers (Q_{cal}) in L1 products back to at-sensor spectral radiance (L_λ) requires knowledge of the original rescaling factors. The following equation is used to perform a Q_{cal}-to-radiance conversion for a L1 product:

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

where

L_λ spectral radiance at the sensor's aperture in W/($\mathrm{m}^2 \cdot \mathrm{sr} \cdot \mu\mathrm{m}$);

Q_{cal} quantized calibrated pixel value in DNs;

TABLE I
L-5 TM POSTCALIBRATION DYNAMIC RANGES FOR U.S. PROCESSED NLAPS DATA

Spectral Radiances, $LMIN_\lambda$ and $LMAX_\lambda$ in W/(m^2.sr. µm)								
Processing Date	From March 1, 1984 To May 4, 2003				After May 5, 2003			
Band	$LMIN_\lambda$	$LMAX_\lambda$	$G_{rescale}$	$B_{rescale}$	$LMIN_\lambda$	$LMAX_\lambda$	$G_{rescale}$	$B_{rescale}$
1	-1.52	152.10	0.602431	-1.52	-1.52	193.0	0.762824	-1.52
2	-2.84	296.81	1.175100	-2.84	-2.84	365.0	1.442510	-2.84
3	-1.17	204.30	0.805765	-1.17	-1.17	264.0	1.039880	-1.17
4	-1.51	206.20	0.814549	-1.51	-1.51	221.0	0.872588	-1.51
5	-0.37	27.19	0.108078	-0.37	-0.37	30.2	0.119882	-0.37
6	1.2378	15.303	0.055158	1.2378	1.2378	15.303	0.055158	1.2378
7	-0.15	14.38	0.056980	-0.15	-0.15	16.5	0.065294	-0.15

$Q_{\rm calmin}$ minimum quantized calibrated pixel value (DN $=$ 0) corresponding to $\rm LMIN_\lambda$;
$Q_{\rm calmax}$ maximum quantized calibrated pixel value (DN $=$ 255) corresponding to $\rm LMAX_\lambda$;
$\rm LMIN_\lambda$ spectral radiance that is scaled to $Q_{\rm calmin}$ in W/(m$^2\cdot$ sr $\cdot$ μm);
$\rm LMAX_\lambda$ spectral radiance that is scaled to $Q_{\rm calmax}$ in W/(m^2 $\cdot$ sr $\cdot$ μm).

The above equation can also be defined as

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

where

$$G_{\rm rescale} = \left(\frac{\rm LMAX_\lambda - LMIN_\lambda}{Q_{\rm cal\,max}}\right)$$
$$B_{\rm rescale} = {\rm LMIN}_\lambda.$$

$G_{\rm rescale}$ [units of W/(m$^2\cdot$sr$\cdot\mu$m)/DN] and $B_{\rm rescale}$ [units of W/(m^2 $\cdot$ sr $\cdot$ μm)] are band-specific rescaling factors typically given in the NLAPS product header file (.h1) and the product generation work order report (.wo).

Table I provides band-specific $\rm LMAX_\lambda$ and $\rm LMIN_\lambda$ parameters and the corresponding $\rm G_{rescale}$ and $B_{\rm rescale}$ values used at different times for the NLAPS processing system. The units of spectral radiance are W/(m^2 $\cdot$ sr $\cdot$ μm).

Users should note that products generated before May 5, 2003 and converted to radiance using older LMINs and LMAXs will not provide the same radiances as those processed since May 5, 2003 and converted to radiance with the new LMINs and LMAXs. A recalibration procedure is under development to give users the ability to recalibrate their existing L1 L5 TM data products to a greater accuracy without having to reprocess the L0 (raw) image data. Additional details describing the recalibration methodology and steps will be published and made available on the web in the near future.

For "early mission" L5 TM data (acquired after launch in 1984 through mid-1985), the change in postcalibration dynamic ranges will introduce high-radiance striping and saturation of $Q_{\rm cal}$ values below 255. This striping results from each detector saturating at a different DN in the calibrated data products. Users should consider all the detectors saturated in areas where they observe this high radiance striping.

Historically, an identical postcalibration dynamic range has been defined for both the L4 and L5 TM sensors, even though the relative spectral response functions are not identical in the two sensors. Beginning May 5, 2003, the new postcalibration dynamic ranges are considered to be valid only for the L5 TM calibrated products. As mentioned earlier, L4 TM sensor calibration will continue using the postcalibration dynamic ranges as previously defined.

TABLE II
TM SOLAR EXOATMOSPHERIC SPECTRAL IRRADIANCES

Units: ESUN = W/(m^2. µm)		
Model:	Chance Spectrum CHKUR	
Band	Landsat 4	Landsat 5
1	1957	1957
2	1825	1826
3	1557	1554
4	1033	1036
5	214.9	215.0
7	80.72	80.67

IV. RADIANCE TO TOA REFLECTANCE

For relatively "clear" Landsat scenes, a reduction in between-scene variability can be achieved through a normalization for solar irradiance by converting the spectral radiance, as calculated above, to a planetary or exoatmospheric reflectance. When comparing images from different sensors, there are two advantages to using reflectance instead of radiances. 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. The combined surface and atmospheric reflectance of the earth is computed according to

$$\rho_P = \frac{\Pi \cdot L_\lambda \cdot d^2}{{\rm ESUN}_\lambda \cdot \cos\theta_s}$$

where
ρ_P unitless planetary reflectance;
L_λ spectral radiance at the sensor's aperture;
d earth–sun distance in astronomical units;
$\rm ESUN_\lambda$ mean solar exoatmospheric irradiances;
θ_s solar zenith angle in degrees.

Table II gives solar exoatmospheric spectral irradiances ($\rm ESUN_\lambda$) for the L4/L5 TM using the CHKUR solar spectrum in MODTRAN 4.0 [7]. This spectrum is being used for Landsat-7 ETM+ [8] and is believed to be an improvement over the spectra used for previously presented L4/L5 TM solar

TABLE III
EARTH–SUN DISTANCE IN ASTRONOMICAL UNITS

DOY	Distance	DOY	Distance	DOY	Distance
1	0.9832	121	1.0076	242	1.0092
15	0.9836	135	1.0109	258	1.0057
32	0.9853	152	1.014	274	1.0011
46	0.9878	166	1.0158	288	0.9972
60	0.9909	182	1.0167	305	0.9925
74	0.9945	196	1.0165	319	0.9892
91	0.9993	213	1.0149	335	0.986
106	1.0033	227	1.0128	349	0.9843
DOY- Day of Year (Julian Day)				365	0.9833

TABLE IV
TM THERMAL BAND CALIBRATION CONSTANTS

Units	$W/(m^2.sr.\mu m)$	Kelvin
Constant	K1	K2
Landsat 4	671.62	1284.30
Landsat 5	607.76	1260.56

irradiance values [9]. The primary differences are in bands 5 and 7. For comparisons to other sensors, users need to verify that the same solar spectra are used for all sensors.

The reflectance calculation depends on the earth–sun distance. Table III presents earth–sun distance in astronomical units for various days throughout a year.

V. TM BAND 6 AT-SATELLITE TEMPERATURES

Thermal band data (band 6) from L 4/5 TM can also be converted from spectral radiance (as described above) to effective at-satellite temperature. The effective at-satellite temperature of the imaged earth surface assumes unity emissivity. A conversion formula is

$$T = \frac{\mathrm{K2}}{\ln\left(\frac{\mathrm{K1}}{L_\lambda} + 1\right)}$$

where

T effective at-satellite temperature in kelvin;
K2 calibration constant 2 in kelvin;
K1 calibration constant 1 in $\mathrm{W/(m^2 \cdot sr \cdot \mu m)}$;
L_λ spectral radiance at the sensor's aperture.

Table IV gives values of calibration constants K1 and K2 defined for the L4/5 TM sensors.

VI. CONCLUSION

An improved LUT-based absolute radiometric calibration for the solar reflective bands has been presented that covers the lifetime of the L5 TM. The modification in calibration procedure has been implemented in the NLAPS for all of the L5 TM products processed after May 5, 2003. It is expected that radiometric accuracy of $\pm 5\%$ could be obtained by reprocessing raw archival data with these lifetime calibration updates. It is expected that a similar analysis can be completed for the L4 TM, which will extend the radiometric accuracy of the 30-m Landsat coverage back to 1982.

It is remarkable that the L5 TM has continued to perform so well for a time period far exceeding its original design life. It is believed that full implementation of these processing changes will lead to a superior L5 TM data product that will be comparable to L7 ETM+ radiometery, and will provide the basis for continued long-term studies of the earth's land surfaces.

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