Landsat-5 Thematic Mapper Thermal Band Calibration Update

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***Abstract*—The Landsat-5 Thematic Mapper (TM) has been operational since 1984. For much of its life, the calibration of TM has been neglected, but recent efforts are attempting to monitor stability and absolute calibration. This letter focuses on the calibration of the TM thermal band from 1999 to the present. Initial studies in the first two years of the TM mission showed that the thermal band was calibrated within the error in the calibration process (±0.9 K at 300 K). The calibration was not rigorously monitored again until 1999. While the internal calibrator has behaved as expected, recent vicarious calibration results show a significant offset error of 0.092 W/m^2 · sr · μm or about 0.68 K at 300 K. This offset error was corrected on April 2, 2007 within the U.S. processing system through the modification of a calibration coefficient for all data acquired on or after April 1, 1999. Users can correct their own Level-1 data processed prior to April 2, 2007, by adding 0.092 W/m^2 · sr · μm to their radiance level products. The state of the calibration between 1985 and 1999 is unknown; no changes for data acquired in those years are being recommended here.**

***Index Terms*—Band 6, calibration, Landsat, Thematic Mapper (TM), thermal, validation.**

I. Introduction

THE LANDSAT-5 Thematic Mapper (TM) has been monitoring the globe since it was launched in March 1984. Landsat-5 orbits at 705 km and has a repeat cycle of 16 days. The multispectral TM includes bands in the visible, near-infrared, and short-wave infrared, as well as a single thermal band. The calibration of the thermal band will be the focus of this letter.

For its first 18 months, Landsat-5 was operated by the U.S. Government. In late 1985, the satellite was turned over to a private company in a commercialization effort. In July 2001, the still-functional satellite was returned to government control, and the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) took the lead in operating it as well as archiving and processing all of the TM data. Since then, a strong effort by the USGS and the National Aeronautics and Space Administration (NASA) has been placed on calibration and validation of the 22+ years of archive of TM data.

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TABLE I
PRELAUNCH-DETERMINED COEFFICIENTS FOR THE THERMAL CALIBRATION MODEL THAT WERE STILL IN USE IN THE PROCESSING SYSTEM AT EROS UNTIL APRIL 2, 2007 [4]

detector	a [unitless]	b [unitless]	c [W/m^2 sr µm]
1	0.69	0.841	1.702
2	0.65	0.841	2.050
3	0.69	0.831	1.646
4	0.64	0.829	2.030

The thermal band, i.e., Band 6, was reported to be calibrated to within the error of the calibration process (± 0.9 K) in 1984 and 1985 [1]. Between 1986 and 1999, little effort was made to monitor the calibration of the Landsat-5 TM thermal band. At least one study suggested that the calibration of the thermal band was off by many degrees [2], but this is now believed to be the result of the processing system not having applied any calibration, rather than an actual change in the instrument calibration. The Landsat-7 Science Team included two independent teams from the Rochester Institute of Technology (RIT) and NASA Jet Propulsion Laboratory (JPL), who were tasked to validate the calibration of the Enhanced Thematic Mapper Plus (ETM+) thermal band. In 2001, they began to monitor the TM thermal band calibration as well.

II. Internal Calibration

The TM onboard thermal calibration system consists of a single onboard cavity blackbody and a black highly emissive shutter [3]. The blackbody sits off the optical axis at a controlled temperature. The shutter, which also carries the visible calibration lamps across the optical axis, has on it a toroidal mirror, which reflects radiation from the blackbody onto the optics and through to the cooled focal plane. The nonmirror part of the shutter is coated with a high-emissivity paint and sits at the instrument ambient temperature. Outputs from thermistors monitoring the temperatures of some components within TM are included in the downlinked data.

The instrument gain is calculated from the blackbody and the shutter, i.e.,

$$G_{\mathrm{in}} = \frac{Q_{\mathrm{bb}} - Q_{\mathrm{sh}}}{L_{\mathrm{bb}} - L_{\mathrm{sh}}} \tag{1}$$

and

$$G_{\mathrm{ext}} = aG_{\mathrm{in}} \tag{2}$$

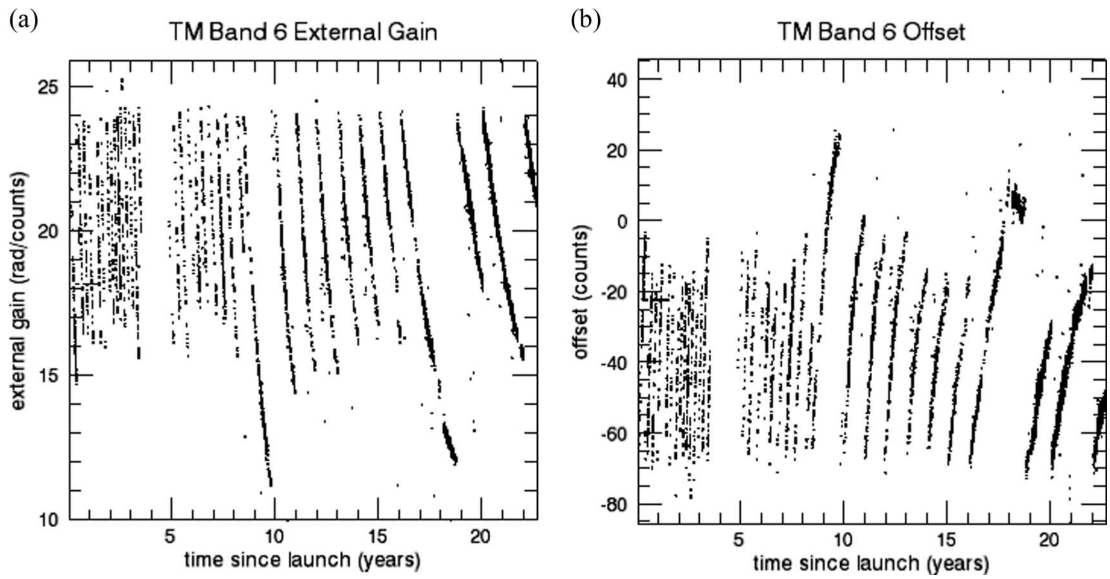

Fig. 1. Internal calibrator data of TM Band 6 as trended by the NLAPS processing system. The band is affected by the buildup of ice on the Dewar window, which changes the amount of energy reaching the detectors. When the ice is melted off, the detectors return to full responsivity. These gains and offsets are used in the processing system; thus, the variation is fully accounted for.

where Q_{bb} is the average digital number of the internal blackbody (calibration pulse), Q_{sh} is the average digital number of the shutter, L_{bb} is the spectral radiance of the blackbody as calculated from the blackbody temperature, L_{sh} is the spectral radiance of the shutter as calculated from the shutter temperature, and a is the per-detector prelaunch-determined gain ratio between the gain determined by the calibration system, G_{in}, and the gain of the full system, G_{ext} (Table I).

The offset Q_0, or the response of the system to zero radiance, was modeled during prelaunch testing. The final model relied on constant coefficients rather than including any dependence on instrument temperatures, unlike the Landsat-7 ETM+ thermal model. These prelaunch-determined coefficients had not changed since launch. The offset is calculated from these coefficients, the shutter, and the internal gain, i.e.,

$$Q_0 = Q_{\mathrm{sh}} - G_{\mathrm{in}}(bL_{\mathrm{sh}} - c) \tag{3}$$

where b and c are per-detector prelaunch-determined constants (Table I). The processing system at EROS, the National Landsat Archive Production System (NLAPS), calculates the gain and offset on a per-scene basis and records these to a database. Radiance images are generated using the per-scene gains and offsets. Thus

$$L_\lambda = (Q - Q_0)/G_{\mathrm{ext}} \tag{4}$$

where L_λ is the spectral scene radiance, and Q is the raw digital count from the scene.

The cold focal plane of Landsat-5 is affected by the buildup of a contaminant, presumably ice, on the Dewar window. This slow buildup of ice affects the transmission of the window, decreasing the amount of energy reaching the Band 6 detectors as the layer gets thicker (Bands 5 and 7 are affected differently than the thermal band). Fig. 1 is a plot of the onboard calibrator gain G_{ext} and offset Q_0. The thermal band gain has traditionally been used as the bellwether for when to perform the operation to melt off the ice (known as outgassing). The occurrence of this procedure can be clearly seen in Fig. 1(a); the responsivity drops slowly while the ice layer is building, then jumps when the layer of ice is suddenly removed. The calibration gain and offset of TM Band 6 have never been stable as a result of the ice buildup, but these internal calibrator gains and offsets are used in the calibration of the data; thus, the variation in responsivity is fully accounted for by the calibration process.

III. Vicarious Calibration

Investigators from JPL and RIT were part of the Landsat-7 Science Team. Their monitoring of the Landsat-7 thermal band detected an offset error in its calibration soon after launch [5]. Since 2001, when Landsat-5 was turned back over to USGS, these teams have also been monitoring the absolute calibration of the TM Band 6. Working primarily with water targets (Lakes Tahoe, Erie, and Ontario), the groups predict the satellite-reaching radiance based on their ground measurements [6], [7]. JPL was able to extend the vicarious calibration record back to 1999 using the archive of Lake Tahoe buoy data. The potential exists to extend this effort further back in time using data from the National Data Buoy Center and other water bodies. However, this letter only considers data in the ETM+ era (beginning April 1999).

Since 1999, the vicarious calibration data are showing a statistically significant bias (Fig. 2), with TM predicting slightly less than 1 K too low. The bias error is not dependent on target radiance. As shown in (3), internal instrument temperatures

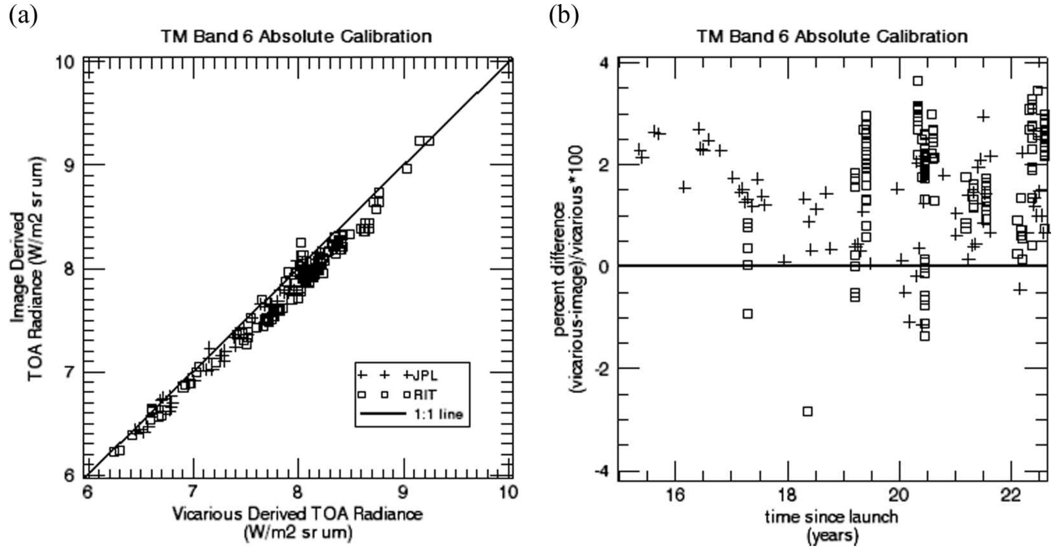

Fig. 2. TM Band 6 vicarious calibration data for both JPL and RIT collections. In a perfectly calibrated system, the data will fall on the 1 : 1 line in (a). TM has a statistically significantly offset error, with most of the data lower than the 1 : 1 line. This results in a positive percent difference, as shown in (b), where the offset error is clear over time.

TABLE II
AVERAGE CALIBRATION ERROR FROM 1999 TO THE PRESENT. TEAM AVERAGES WERE WEIGHTED BY THE NUMBER OF COLLECTS TO CALCULATE THE FINAL CORRECTION AMOUNT

	Number of collects	Average Calibration Error (± 1σ) (W/m^2 sr μm)	Standard Error of the Mean	Equivalent Blackbody Temperature of calibration error (K at 300K)
JPL (day collects only)	56	0.082 ± 0.070	0.009	0.60
RIT	22	0.136 ± 0.092	0.020	1.00
weighted average		0.092	0.009	0.68

TABLE III
NEW c COEFFICIENTS, WHICH WERE MODIFIED TO CORRECT FOR THE 0.092 W/m^2 · sr · μm OFFSET ERROR

detector	c_{new} [W/m^2 sr μm]
1	1.639
2	1.990
3	1.583
4	1.971

are not included in the calibration model. Although this is a likely source of the calibration error, a correlation between the calibration error and component temperatures could not be proven. As a result, it was decided to apply a constant offset correction for all data since April 1999 based on the JPL and RIT vicarious data. The gain calculation will remain unchanged.

The average error predicted from July 1999 to October 2006 by JPL is 0.082 W/m^2 · sr · μm; by RIT, it is 0.136 W/m^2 · sr · μm (Table II). The two teams have different collection techniques and have a different range of temperatures on any single collection. To combine the results, a weighted average was taken, weighting the data by the number of dates on which collections were made. This results in an offset error of 0.092 ± 0.009 (standard error of the mean) W/m^2 · sr · μm or 0.68 K at 300 K.[1]

[1]This is different than the results that were previously published in [8], due to an additional six months of vicarious calibration data being included in the averages.

IV. UPDATE AND VALIDATION

To correct for the offset error in the processing system, the scene radiance from (4) needed to increase by 0.092 W/m^2 · sr · μm, i.e.,

$$L_{\lambda,\mathrm{new}} = \frac{(Q - Q_0)}{G_{\mathrm{ext}}} + 0.092. \tag{5}$$

The corrected offset is then

$$Q_{0,\mathrm{new}} = Q_{\mathrm{sh}} - G_{\mathrm{in}}(bL_{\mathrm{sh}} - c) - 0.092G_{\mathrm{ext}}. \tag{6}$$

To simplify the change to the processing system, a single coefficient c was changed to incorporate this correction. Thus

$$c_{\mathrm{new}} = c_{\mathrm{original}} - (0.092 \cdot a). \tag{7}$$

The new c coefficients are listed in Table III. These values were tested on seven Lake Tahoe scenes in NLAPS and an independent external processing system. The seven scenes were processed with the current c coefficients and the updated

c coefficients. The per-detector scene averages and the per-detector lake averages were compared. The full-scene average radiance for the seven scenes changed by 0.092 $W/m^2 \cdot sr \cdot \mu m$. The average radiance for the areas around the Lake Tahoe buoys changed by 0.088 $W/m^2 \cdot sr \cdot \mu m$.

Products processed at EROS on or after April 2, 2007, include this 0.092 $W/m^2 \cdot sr \cdot \mu m$ correction in the Level-1 data acquired on or after April 1, 1999. For users already owning processed data acquired since April 1999, adding 0.092 $W/m^2 \cdot sr \cdot \mu m$ to a radiance level product is equivalent to getting the data reprocessed by EROS.

It is not clear if the offset changed during the lifetime of the mission or if this calibration error has been in the system since launch. There is hope that archived data from buoys on the Great Lakes from the National Data Buoy Center can be used to track the calibration further back in time, but this has not yet been attempted.

V. Conclusion

Although initially shown to be calibrated in 1984 and 1985, the calibration of the Landsat-5 TM thermal band was not monitored again until 1999. Between 1999 and 2006, vicarious calibration efforts revealed an offset error of 0.092 $W/m^2 \cdot sr \cdot \mu m$ in the thermal band. This error was corrected by modifying a calibration coefficient in the processing system beginning April 2, 2007. Only data acquired on or after April 1, 1999, and processed by EROS are affected by this update. No change has been made to data acquired before April 1, 1999. Users with Level-1 data can add 0.092 $W/m^2 \cdot sr \cdot \mu m$ to their radiance products to manually correct for the offset error. Further updates to improve the thermal band calibration over the lifetime of Landsat-5 are being investigated.

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