A Lifetime Radiometric Calibration Record for the Landsat Thematic Mapper

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Abstract

A coordinated effort on the part of several agencies has led to the specification of a definitive radiometric calibration record for the Landsat-5 Thematic Mapper (TM) for its 17-year lifetime since launch in 1984. Analogous work for the Landsat-4 TM, launched in 1982, is in progress. The time-dependent calibration record for Landsat-5 TM has been placed on the same radiometric scale as the Landsat-7 Enhanced Thematic Mapper Plus (ETM+). Once implemented operationally, the lifetime radiometric calibration record for Landsat will facilitate the examination of a continuous, near-global data set at 30-m scale that spans almost two decades.

Introduction

A primary goal of the Landsat program is to provide a means to place the current Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and the Landsat-4/5 Thematic Mapper (TM) sensors on a comparable radiometric scale. This will allow the possibility of examining a continuous, near-global data set reaching back to 1982 with a view to monitoring global and regional land dynamics at a 30-m scale where both natural and anthropogenic disturbances can be assessed. The challenges include characterisation of the radiometric behaviour of the Landsat-5 TM over its 17-year lifetime since 1984 and cross-calibration of the TM and ETM+ sensors. Analogous trend characterisation work for the Landsat-4 TM, launched in 1982, is in progress.

The present paper reports on a collaborative effort between several agencies towards the aforementioned characterisation of the lifetime Landsat-5 TM radiometric calibration record and specifications for the related calibration algorithms. The specifications include (1) anchoring of the Landsat-5 TM calibration record to the Landsat-7 ETM+ absolute radiometric calibration, (2) new time-dependent calibration processing equations and procedures applicable to raw Landsat-5 TM data and (3) equations for recalibration processing of some of the existing processed data sets in the North American context.

Radiometric Cross-Calibration Between Sensors

Early in its mission, the Landsat-7 spacecraft was temporarily placed in a "tandem" orbit very close to that of the Landsat-5 spacecraft in order to facilitate the establishment of sensor calibration continuity between the Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and Landsat-5 Thematic Mapper (TM) sensors. The key period for the tandem configuration was June 1-4, 1999, during which hundreds of nearly-coincident matching scenes were recorded by both the Landsat-7 ETM+ and, in cooperation with Space Imaging / EOSAT and international ground stations, the Landsat-5 TM as well. A cross-calibration methodology, described elsewhere (Teillet et al., 2001), has been formulated and implemented to use image pairs from the tandem configuration period to radiometrically calibrate the solar reflective spectral bands of Landsat-5 TM with respect to the excellent radiometric performance of Landsat-7 ETM+. The radiometric calibration uncertainty for the ETM+ is considered to be ± 3 % (one sigma) (Barker et al., 2000).

Only two of the matching scenes are known to have coincident ground measurements associated with them. One in particular is the Railroad Valley Playa in Nevada (RVPN), which is used on a regular basis for sensor radiometric calibration based on surface measurements and which has a relatively stable and uniform surface compared to the majority of terrestrial surface types. Therefore, the RVPN results from the tandem-based cross-calibration analysis are considered to be the definitive set of Landsat-5 TM gain coefficients for June 1999 (Table 1). Tandem-based cross-calibration results from other image pairs (not shown) indicate a repeatability of the approach on the order of ± 2 %. For spectral bands 1-4, the estimated uncertainty of this top-of-atmosphere radiance calibration is ± 3.6 % (one sigma), based on the root-sum-square of ± 3 % for ETM+ calibration and ± 2 % for the tandem-based cross-calibration. Uncertainty estimates have yet to be determined for spectral bands 5 and 7, but experience suggests that they will be approximately 50 % greater than the uncertainties in the first four spectral bands. Comparisons with results from independent methods used by the University of Arizona (Table 1) indicate that the tandem-based cross-calibration is in reasonable agreement with the independent results (within 2.5 % on average and no worse than 5.1 %). A comparison between the 1999 and prelaunch TM gain coefficients is also included in Table 1. The large changes in gain in spectral bands 1-3 underscore the importance of post-launch calibration updates during the lifetime of the mission.

Table 1. Comparison of tandem-based (RVPN Xcal) and vicarious (RVPN UAZ) calibration results for Landsat-5 TM gain coefficients for the RVPN test site in June 1999. A comparison between RVPN Xcal and prelaunch gain coefficients is also included. Gains are in units of counts/(W/(m2 sr µm)).

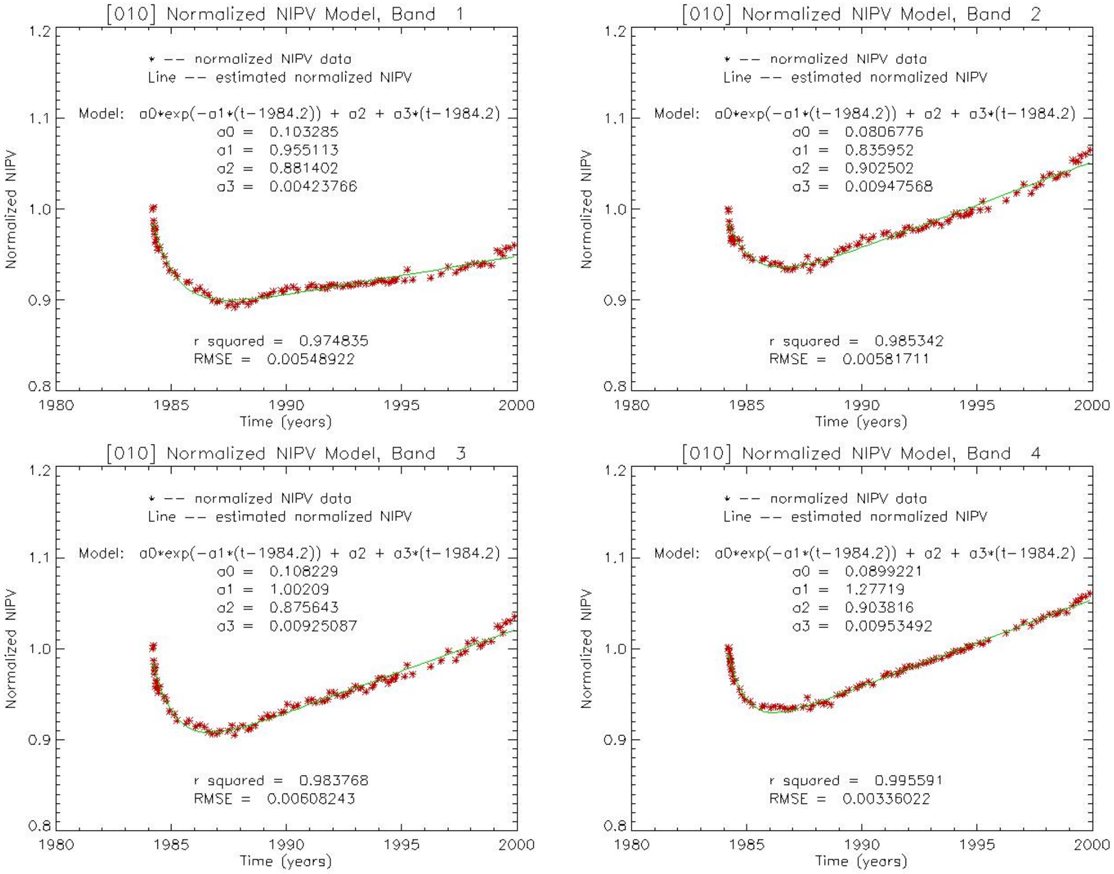
Spectral Band	**RVPN Xcal**	**RVPN UAZ**	**% Diff re Xcal**		**RVPN Xcal**	**Prelaunch Calibration**	**% Diff re Prelaunch**
1	1.243	1.211	-2.6 %		1.243	1.555	-20 %
2	0.6561	0.6270	-4.4 %		0.6561	0.786	-17 %

3	0.9050	0.8953	-1.1 %		0.9050	1.020	-11 %
4	1.082	1.111	+2.7 %		1.082	1.082	0 %
5	7.944	8.097	+1.9 %		7.944	7.875	+0.88 %
7	14.52	15.26	+5.1 %		14.52	14.77	-1.7 %

TM Internal Calibrator Trend Analysis

The TM sensors on both Landsat-4 and Landsat-5 included an onboard calibration system called the Internal Calibrator (IC) (Mika, 1997). Techniques have been developed to analyse data from the IC for the lifetime of the Landsat-5 TM (Helder, 1996; Helder et al. 1996; Markham et al., 1998; Helder et al., 1998a,b). The analysis indicates that only the IC pulses from reverse scans and lamp state #2 (010) should be used for characterising the trend and for radiometric processing during TM product generation.

IC analysis results for the solar-reflective bands also indicate that the Landsat-5 TM lifetime radiometric trend takes a combined exponential plus linear form (shown for spectral bands 1-4 in Figure 1). The exponential part is deemed to be a



true change in the TM (likely due to outgassing from the spectral filters during the first few years after launch) and the subsequent linear increase is considered to be a change in the IC system (likely due to changes in the lamp characteristics) rather than a true TM change. Thus, in formulating the final temporal characterisation (described in the next section), the linear trend is removed from the entire lifetime IC record based on the post-1988 fit. Preliminary analysis of the IC data for the thermal band (band 6) indicates that the calibration parameters provided with each calibrated product can be used to convert to radiance throughout the TM mission lifetime for products generated using the IC data (which tracked temperature fluctuations in the system). A similar analysis is in progress to characterise the Landsat-4 TM IC data.

Figure 1: Lifetime plots of normalised net IC pulse values (NIPV) for lamp state [010] as a function of time since launch for Landsat-5 TM spectral bands 1-4.

Improved Radiometric Calibration for Raw Solar-Reflective TM Data

The lifetime IC trend model for the Landsat-5 TM has been scaled to match the Landsat-7 ETM+ gain coefficient in each spectral band for June 1, 1999, as determined by the tandem-based cross-calibration for the RVPN test site. The resulting curves (Figures 2-7) are generally consistent with independent vicarious calibration results obtained by the University of Arizona over the years (Thome et al., 1997) and by South Dakota State University in 1999 (Black et al., 2001). The time-dependent equations for Landsat-5 TM gain, $G_{new}(t)$, applicable to raw data, thus take the form

$$G_{new}(t) = a0*\exp(-a1*(t - 1984.2)) + a2 \quad , \quad (1)$$

where the time t is in years, the coefficients a0, a1, and a2 are given in Table 2, and 1984.2 refers to the launch date of Landsat-5. Note that the TM gain coefficients in the solar reflective bands have been constant to within the accuracy of the calibration methodology since approximately 1987.

Table 2. Coefficients for time-dependent characterisation of Landsat-5 TM lifetime gain based on IC trend analysis, anchored to Landsat-7 ETM+ via cross-calibration using the tandem image pair for RVPN in 1999. Coefficients a0 and a2 are in units of counts/(W/(m2 sr µm)) and the a1 coefficients are dimensionless.

Spectral Band	a0	a1	a2
1	0.1457	0.9551	1.243
2	0.05865	0.8360	0.6561
3	0.1119	1.002	0.9050
4	0.1077	1.277	1.082
5	0.2434	1.207	7.944
7	0.4036	0.9991	14.52

Recommendations for Radiometric Calibration Processing of Raw Data for the Solar-Reflective Bands

The operational radiometric processing of raw TM data involves many steps. While it is beyond the scope of this paper to describe the details, the following sequence of steps outlines how the new lifetime gain equation should fit into the radiometric calibration processing of raw archival data for the solar-reflective bands. Computationally, some of the steps will be wrapped up together.

- Correction for the memory effect.
- Correction for scan-correlated shifts via bias subtraction on a scan-specific basis.

- No correction for the coherent noise effect (typically on the order of 0.15 DN or less).
- Correction for cold focal plane filming due to outgassing.
- Correction for relative detector gain differences using lifetime scene statistics and normalisation to band average.
- Absolute radiometric calibration using the new gain equation based on the IC trend fit tied to Landsat-7 ETM+ (equation 1).
- Bias processing unchanged (stability has been good). Some oscillations due to temperature are captured in the processing.
- Output scaling to allow use of time-invariant calibration coefficients by users.

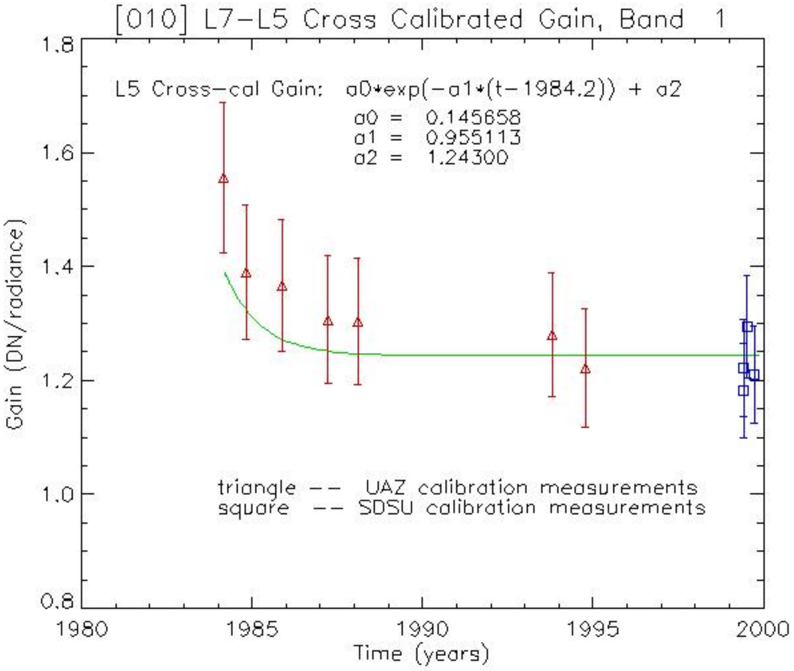


Figure 2: Lifetime gain plot for Landsat-5 TM spectral band 1, tied to Landsat-7 cross-calibration measurements. DN = digital counts, radiance is in counts/(W/(m2 sr μm)), UAZ = University of Arizona and SDSU = South Dakota State University.

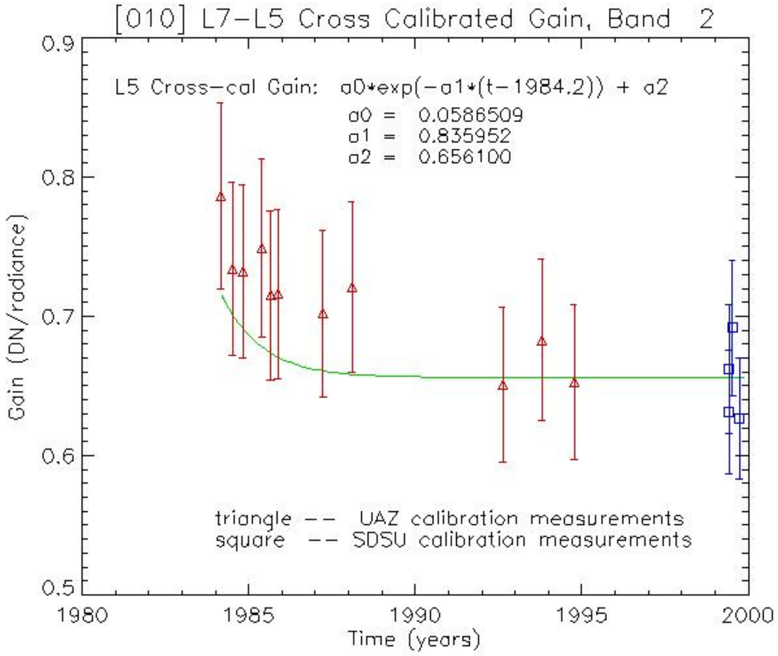


Figure 3: Lifetime gain plot for Landsat-5 TM spectral band 2, tied to Landsat-7 cross-calibration measurements. DN = digital counts, radiance is in counts/(W/(m2 sr μm)), UAZ = University of Arizona and SDSU = South Dakota State University.

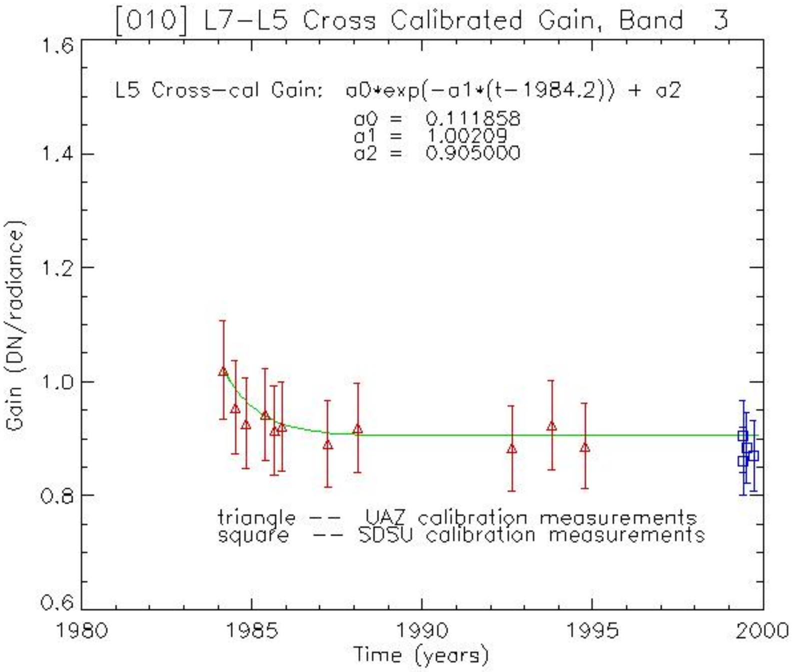


Figure 4: Lifetime gain plot for Landsat-5 TM spectral band 3, tied to Landsat-7 cross-calibration measurements. DN = digital counts, radiance is in counts/(W/(m2 sr μm)), UAZ = University of Arizona and SDSU = South Dakota State University.

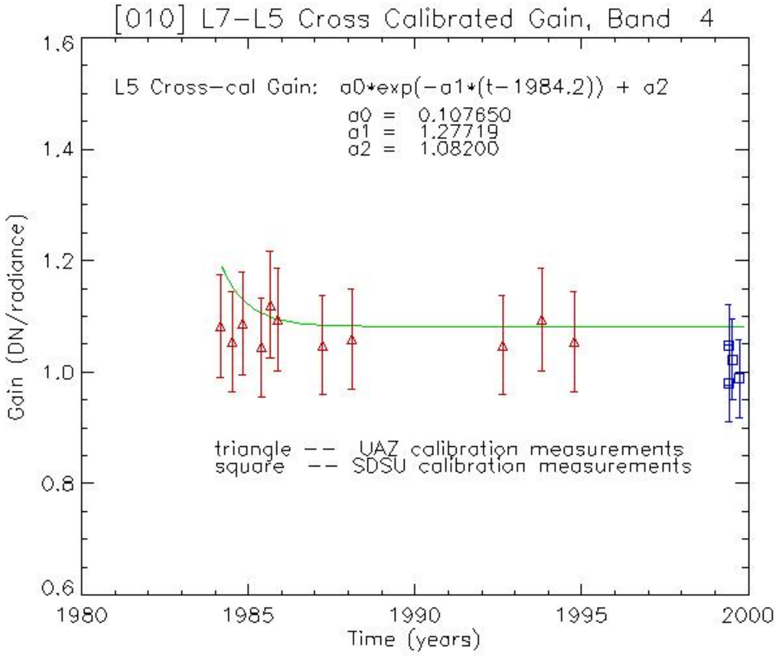


Figure 5: Lifetime gain plot for Landsat-5 TM spectral band 4, tied to Landsat-7 cross-calibration measurements. DN = digital counts, radiance is in counts/(W/(m2 sr μm)), UAZ = University of Arizona and SDSU = South Dakota State University.

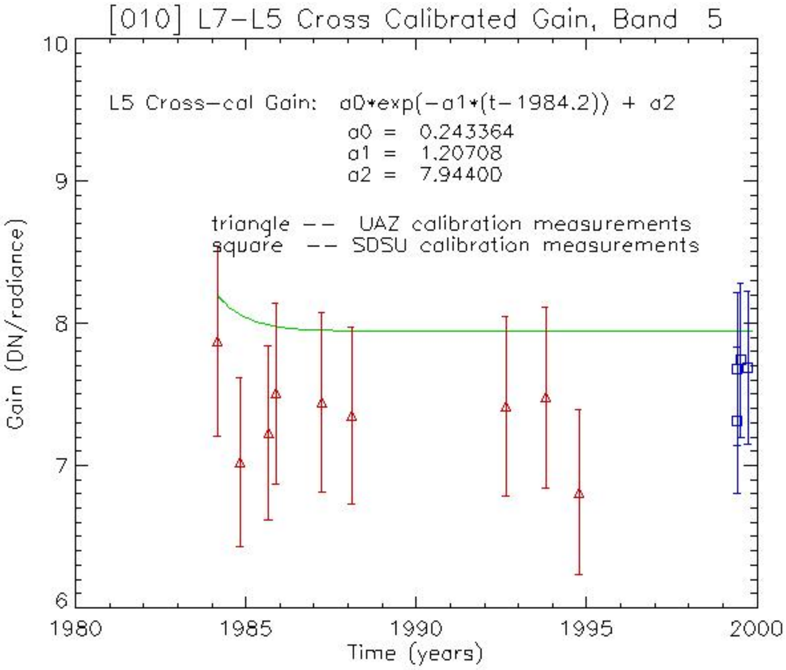


Figure 6: Lifetime gain plot for Landsat-5 TM spectral band 5, tied to Landsat-7 cross-calibration measurements. DN = digital counts, radiance is in counts/(W/(m2 sr μm)), UAZ = University of Arizona and SDSU = South Dakota State University.

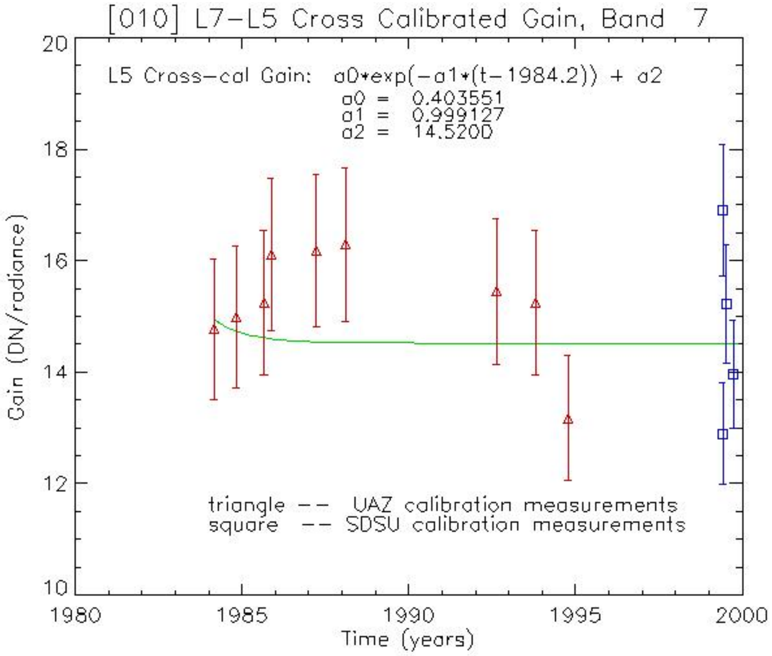


Figure 7: Lifetime gain plot for Landsat-5 TM spectral band 7, tied to Landsat-7 cross-calibration measurements. DN = digital counts, radiance is in counts/(W/(m2 sr μm)), UAZ = University of Arizona and SDSU = South Dakota State University.

Radiometric Recalibration Algorithm for Existing Data Products

Over the lifetime of the Landsat-5 TM, significant investments have been made to collect radiometrically calibrated TM data over large geographic areas of interest in a variety of application contexts. The question arises as to whether an algorithm can be defined to recalibrate these Level-1 image data while taking advantage of the new definitive TM calibration record but without having to reprocess raw (Level-0) data. In North America, the vast majority of calibrated Landsat-5 TM images have been processed on either National Land Archive Processing Systems (NLAPS) built by MacDonald Dettwiler and Associates (MDA) or TM Image Processing System (TIPS) Level-1P (cubic convolution resampling) at Space Imaging EOSAT. The TM image products generated by all these systems have been or could have been bias corrected, de-striped based on scene statistics, and calibrated using the onboard IC system.

The sensor radiometric calibration at the time the original Level-1 product was generated can be written in any given solar-reflective spectral band as

$$Q = G_{old}(t)\ L^* + B_{old}(t)\ , \qquad (2)$$

where Q is image quantised level (in counts), L* is top-of-atmosphere (TOA) radiance (in Watts/(m^2 sr µm)), $G_{old}(t)$ is sensor gain (in counts per unit radiance) at time t, and $B_{old}(t)$ is the zero-radiance bias (in counts) at time t. In North American processing systems and likely others elsewhere, the image quantised levels are further scaled in any given solar-reflective spectral band such that the user equation to obtain radiance from the original product is

$$L^* = (Q_{cal,old} - B)\ /\ G\ , \qquad (3)$$

where $Q_{cal,old}$ is the quantised level (in counts) in the original image product, G is time-independent sensor gain (in counts per unit radiance), and B is the time-independent zero-radiance bias (in counts). The time-independent calibration coefficients have usually been supplied with the image product and have been made widely available to the user community.

The new sensor radiometric calibration equation can be written in any given solar-reflective spectral band as

$$Q = G_{new}(t)\ L^*_{new} + B_{old}(t)\ , \qquad (4)$$

where $G_{new}(t)$ is the updated sensor gain (in counts per unit radiance) applicable at time t. It is assumed that there is no need to update the zero-radiance bias $B_{old}(t)$, which is not considered to have changed significantly over time. Let the user equation to obtain radiance from the new, recalibrated image data be

$$L^*_{new} = (Q_{cal,new} - B)\ /\ G\ , \qquad (5)$$

where $Q_{cal,new}$ is the quantised level (in counts) in the recalibrated image data. The combination of equations (2)-(5) leads to the following transformation to obtain recalibrated image data from the original image product:

$$Q_{cal,new} = (Q_{cal,old} - B)\ (G_{old}(t))\ /\ (G_{new}(t)) + B\ . \qquad (6)$$

Thus, the key to recalibration is knowledge of the original gain $G_{old}(t)$ used to generate the product, which was presumably based on the IC pulse data in the original processing. Two cases are distinguished, based on whether $G_{old}(t)$ is known or not for a given calibrated product. In both cases, it is assumed that the equations for $G_{new}(t)$ are available, based on IC trend characterisation using reverse scans and lamp state #2 (010), and anchored to the Landsat-7 ETM + radiometric calibration (equation 1).

When $G_{old}(t)$ is known for a specific product, it becomes a simple task to remove the old gain (equation 6). A special case of this situation is when prelaunch coefficients are known to have been used instead of IC-based values.

In order to deal with cases when $G_{old}(t)$ is not available for specific products, a gain history needs to be developed based on IC trend characterisations. These trend fits will need to be tailored to the different historical periods of processor algorithms as a function of epoch, forward/reverse scans, lamp states, and reference detectors. Some of the IC trends will be noisier than others, but estimates of uncertainty due to the scatter can be generated in each case. Also, each trend set will have to be anchored to $G_{old}(t)$ space. The generation of these trend sets as a function of gain history is currently in progress.

In a small number of cases, users have collections of Level-0 TM data for which no radiometric processing was applied during product generation. Calibrated data can be obtained in the solar-reflective bands for these data by using equation (1) for the gain coefficients and the well-documented time-invariant bias coefficients. However, it should be noted that the resulting imagery will not be corrected for TM artefacts such as the memory effect and scan-correlated shifts, nor will they have been de-striped for relative detector gain differences.

Concluding Remarks

Absolute radiometric calibration equations have been specified for the lifetime of the Landsat-5 TM (solar reflective bands). Implementation considerations are currently being examined. Final analysis of IC trends for the thermal (band 6) is in progress. It is expected that a similar analysis can be completed for the Landsat-4 TM, thus extending the 30-m Landsat coverage back to 1982.

The merits and feasibility of placing Multispectral Scanners (MSS) data from the first five Landsat missions, extending back to 1972, on the same radiometric scale need to be assessed before undertaking any MSS recalibration effort. It is doubtful that the radiometric calibration accuracy of MSS data could be improved significantly.

Although accuracy assessments will be done in due course, it is anticipated that lifetime TM radiometric calibration can be established to approximately the following accuracies (with higher accuracies in bands 1-4 and greater uncertainties in bands 5 and 7):

- ±5%-15% (one sigma) with the current situation;
- ±5%-10% (one sigma) with recalibration equations for existing products in North America;
- ±3%-5% (one sigma) with new processing of raw archival data.

Acknowledgements

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