Thematic Mapper Radiometric Correction Research and Development Results and Performance

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ABSTRACT: This paper describes the purpose of the TIPS R&D effort at NASA and discusses three tasks undertaken during that period to enhance the TM radiometric correction algorithms. These include changes made to resolve problems of TM-5 light leak, saturated calibration pulse states and the scene content correction failure on certain types of data.

The paper also documents the radiometric correction performance for the two TM instruments and describes the requirements for relative radiometric correction levied on the ground correction system and the algorithm used to measure performance.

INTRODUCTION

THIS PAPER DISCUSSES THREE MODIFICATIONS made to the Thematic Mapper Image Processing System (TIPS) radiometric correction process during the R&D period, before turnover of the Landsat Ground Segment to the National Oceanic and Atmospheric Administration. The purpose of the R&D period was to enhance the correction performance of the ground processing of Thematic Mapper (TM) data, and correct for any sensor anomalies that were possible. Because this period lasted only a few months, problems that required substantial software or hardware modifications (scan level corrections, forward–reverse differences, etc.) were not considered. Emphasis was placed on enhancing the algorithms, within the constraints of the existing hardware and software.

The paper begins with a brief review of the major steps in TM radiometric correction, and in that context describes how the effects of the Landsat-5 light leak and the saturated calibration lamp states were overcome. It also discusses limitations applied to the scene content correction (histogram equalization) process, to control it from diverging on certain types of data.

The last part of this paper documents the radiometric correction performance for the two TM instruments. It describes the requirements for relative radiometric correction levied on the ground correction system and the algorithm used to measure performance.

TM RADIOMETRIC CORRECTION

TM radiometric correction takes place as part of the TM Archive Generation (TAG) software package. The TAG process accepts a high density tape (R-tape) containing raw data and creates another high density tape called an A-tape. This is an archival product containing data which has been only radiometrically corrected, but has all the geometric correction parameters appended. The actual geometric correction takes place in a subsequent process.

The TAG process consists of three phases. The first phase screens the R-tape and extracts calibration, shutter and subsampled histogram data, for each channel, from each scan. The data are accumulated and saved for the next part, called the Calculation Phase. During this phase the Radiometric Correction Data Generation (RCDG) software module is initiated, which computes the radiometric correction gains and biases for all channels. The gains and biases are used to generate Look Up Tables which are applied to raw data during the third phase of TAG. The lookup tables are applied on the fly, to correct the data as they are read in from the R-tape and written onto the A-tape. A detailed description of the TM radiometric correction process can be found in Singh (1983).

The aim of radiometric correction is to convert quantized detector voltage samples (raw DNs) into sample values representing input radiance. The RCDG package does this by using the calibration values for different lamp states, to compute the gain and bias. This defines the linear transfer curve for each channel.

$$Lr = Ga * L + Ba \qquad (1)$$

L is the input radiance and Lr is the raw pixel value in DNs. The actual gain (Ga) and bias (Ba) are estimated by performing a linear regression between

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the calibration lamp state radiances (determined prior to launch of the satellite) and the corresponding calibration counts.

The estimated input radiance range is normalized to a quantized radiance scale (0–255).

$$Lq = L * Gd + Bd \tag{2}$$

Lq represents the quantized input radiance. The normalization is such that $Lq = 0$, corresponds to the minimum radiance (R_{min}) to which the sensor band is being calibrated. Similarly, $Lq = 255$ corresponds to the maximum calibration radiance (R_{max}). These fix the values of Gd and Bd:

$$Gd = 255/(R_{max} - R_{min}) \text{ and}$$

$$Bd = -Gd * R_{min}$$

From (1),

$$L = (Lr - Ba)/Ga$$

Substituting in (2) we have,

$$Lq = Lr * Gj + Bj \tag{3}$$

where $Gj = Gd/Ga$ and

$$Bj = Bd - (Gd/Ga) * Ba$$

Gj and Bj are known as the normalized gain and bias for the channel. Expression (3) relates the raw DNs to quantized input radiance, also referred to as corrected DNs. The R_{min} and R_{max} values for each band are documented in Barker (1985, Appendix 9.1).

The normalized gains and biases can be used to generate the LUTs, or they can be modified by the (optional) scene content correction step. The latter adjusts each channel gain and bias based on the individual channel and the band average histograms.

Given this brief description of the TM radiometric correction process, the next three sections discuss problems that emerged during the evaluation of TM-4 and TM-5 data. They will be described in context of the above discussion along with the solutions implemented to resolve them.

TM-5 LIGHT LEAK

Owing to a gap between the lenses and the shutter flag frame on Landsat-5, some scene data leaks through and shows up as a secondary pulse in the calibration region. The effect is stable (i.e., the gap and the secondary pulse size is not affected by time) (Barker, 1985, pages III-80, 123). The actual size of this pulse is a function of the light leaking through and is largest for band 5. It was noticed just after launch, though some evidence exists that it was present in prelaunch testing as well.

The calibration pulse extraction algorithm searches for the pulse in a 148 pixel window for each line (a line is the set of pixel values in a scan for a channel). The process consists of searching for the pulse from both ends of the window. A pulse edge is detected if 20 adjacent pixels containing values greater than 19 counts are found. Once the left and right edges are detected, the pulse center is determined as the average of the left and right edge positions. The pulse value is then defined by summing 65 pixel values centered around the pulse center. In case the left or right edges are not found (as for the 000 lamp state when all the lamps are off), the algorithm sums 65 pixel values starting from the left edge of the 148 pixel window.

There were two concerns regarding the light leak. The first concern was whether the secondary pulse would ever be large enough to trigger a false pulse edge. By examining several cloud covered scenes (which would cause the largest secondary pulse) it was determined that, with one exception, the secondary pulse shape always fell below the pulse edge detection thresholds, and would not affect the pulse extraction. The exception was some channels for band 5 for which the gap seems to be the largest. Occasionally, a false edge would be triggered resulting in an invalid calibration value. To resolve this, the pulse extraction thresholds were changed for band 5 channels. For these channels, pulse edges are now detected if 28 adjacent pixels with counts greater than 16 are found. This change in the threshold parameters ensured that the secondary pulse would not cause false edge detection and still allowed the regular calibration pulses to be extracted.

The second concern was lamp state 000 when all calibration lamps are off. Here, the calibration pulse is absent, and a sum over a specified region of the calibration extraction window is taken. For the reverse scans this meant including the secondary pulse, as it lies in the beginning 65 pixels of the window. There was no way to overcome this problem without substantial change to the extraction software. It was therefore decided to collect faulty lamp state 000 data, but exclude it from the computation of the gains and biases, for all reflective band channels, as is described later.

A condition similar to the lamp state 000 effect also occurs, again for band 5 channels, for lamp state 001. The pulses from lamp state 001 for band 5 were so poor that at times no calibration pulse was being detected. The calibration pulse occasionally fell below the extraction thresholds. When this happened, the calibration region was treated as for state 000 above, and a similar problem with the secondary pulse resulted. The new thresholds described above were also designed to maximize the extraction of this type of pulse. Currently, it is being extracted properly. However, in time the channel gains may decay. This would again cause the pulse to fall below the extraction thresholds. It was therefore decided to remove this state from the computation of the gains and biases, for band 5 only.

The gains and biases of Equation (1) are computed by performing a regression between the eight calibration lamp radiances and the pulse values. The software was modified to allow for the elimination of regression points via parameterized weights. Thus, weights for lamp state 000 for all reflective bands and state 001 for band 5 were set to zero, eliminating them from the computation of the gains and biases.

SATURATED CALIBRATION STATES

Out of the eight calibration lamp states it was noticed that for the brightest lamp state (state 111, when all 3 lamps are on), calibration values for some bands will saturate (Barker, 1985, page III-86). This is true for both Landsat-4 and Landsat-5. The saturation effect would cause an undesirable effect during the regression. Similar reasoning holds for state 000 where the saturation can take place on the low end of the scale. A set of experiments was performed to determine the effect of this phenomenon. Based on those results, it was decided to eliminate states 111 from the regression for both instruments. All eight points are not really needed to determine the gains and biases. Thus six out of eight states are now being used to compute the gains and biases, except for band 5 of TM-5, where state 001 has also been excluded. Also, due to the same low end saturation problem, the shutter data are not considered in the regression step.

SCENE CONTENT CORRECTION (SCC) LIMITATIONS

The scene content correction step takes place after the computations of the gains and biases shown in (1), and their subsequent normalization (3). It is an optional step but one that is always followed in practice. Its purpose is to minimize or eliminate sensor striping (Barker, 1985, page III-89).

The need for Scene Content Correction (SCC) arises because of our inability to determine precisely the gains and biases using the Internal Calibrator (IC). The gains and biases calculated in (1) are estimates of the actual gains and biases that the channels were conforming to during flight. The lack of precise transfer curves results in residual striping in the corrected imagery.

The SCC is based on the assumption that over a period of time (several seconds), all 16 (4 thermal) channels in a band are exposed to the same input radiance distribution. This assumption can be utilized in fine-tuning the gains and biases shown in (3). Given a set of these initial values, the corresponding raw DN histograms and a reference radiance histogram, the question arises as to how the gains and biases can be adjusted to ensure that the individual raw DN histograms convert to the same reference radiance histogram. The expressions to achieve this are shown below.

$$Gj' = Gj \,/\, (\sigma/\sigma_j) \tag{4}$$

$$Bj' = Bj - Gj' * (\mu - (\sigma/\sigma_j) * \mu_j) \tag{5}$$

where

j is a particular channel in a band
Gj', Bj' are the new adjusted gain and bias
Gj, Bj are the old gain and bias
σ_j is the channel j histogram standard deviation
σ is the average band histogram standard deviation
μ_j is the channel j histogram mean
μ is the average band histogram mean

SCC can be applied in an iterative manner. The above expressions summarize one iteration or application of the process.

For the most part the process works very well and is able to eliminate striping from the imagery. However, two problem areas were determined. These actually were caused by situations when the implicit conditions for the SCC process were not being met. The first condition is that the process relies upon a "well-behaved" unimodal histogram for best performance. "Well-behaved" implies a reasonable variance, and a mean not close to the edge of the dynamic range. When this condition is not met, the process can diverge, as can be the case for flat scenes (e.g., scenes with lots of water). This can be understood upon examining (4). When the variances are small, the expression σ/σ_j tends toward the indeterminate form 0/0, resulting in an unreliable Gj', or divergence in the SCC process.

The second condition that SCC assumes is that the individual channel noise is very small and that all channels are equally noisy. This turned out to be false for band 7, channel 7, for TM-4. That channel is twice as noisy as the rest. In the process of computing the reference band histogram statistics, the ranges of the individual channel histograms are restricted to generate a common radiance region. This is to avoid using data when a channel has saturated. Normally, this is not a problem, but for band 7, channel 7 of TM-4, scenes containing water resulted in clipped histograms. The water data sit around 3 to 4 quantum level counts for band 7. For channel 7, because of the noise, it was spreading over into the 0 to 6 quantum level range. The low end corresponds to the DC restore bias and usually falls outside of the common radiance range. Thus a large part of the histogram for that channel was being excluded, resulting in a grossly different mean and standard deviation compared to the other channels. This manifested itself in diverging values for the gain and bias.

To correct for these problems, two limitations were imposed on the SCC algorithm. The first compared the new computed gain and bias with the old ones for each channel, and if it differed by more than a certain (parameterized) percent the new values were not selected (i.e., SCC was not applied for that channel). This was a simple but effective check based on the rationale that for flat scenes it is better to have some residual striping than to introduce gross artifacts in the data.

The second limitation was set up to restrain the common radiance range from becoming too small and thus clipping a lot of water data. This was implemented again as parameterized thresholds which were fine tuned empirically. They served to control the divergence mainly for Landsat-4 data.

PERFORMANCE BENCHMARK

The relative radiometric correction specification levied on the ground processing of TM data required the system to correct to within ±1 ql (quantum level) over the dynamic range of the sensor (NASA, 1980). This specification applies to the 16 channels (4 thermal) in a spectral band within a scan. This requirement means that if all the channels in a band are viewing the same radiance on the ground, the radiometric correction process should generate quantized radiance values which are within 2 ql of each other. This relative radiometric correction requirement is essentially to minimize or eliminate sensor striping.

To demonstrate that the ground system was meeting the performance requirements, an algorithm was designed to compute the "in-scan" variance, or a Radiometric Quality Indicator (*RQI*). The algorithm was designed as part of the TDQ (TM Data Quality) software package. This is an off-line (i.e., not part of regular production) process which ingests A-tape data for evaluation purposes. It measures the correction on a scan basis. These measurements can be aggregated over any contiguous set of scans in a scene.

The steps used in computing the *RQI* are given below:

(a) For each line calculate the line mean, x_i, *i*th line.

(b) Construct a low pass filter using the rule,

$$w_i = \tfrac{1}{6}\,[0.5 * x_{i-3} + x_{i-2} + x_{i-1} + x_i + x_{i+1} + x_{i+2} + 0.5 * x_{i+3}]$$

(c) Subtract filtered values w_i from line averages x_i,

$$y_i = x_i - w_i$$

(d) Define range of the 16 (4 thermal) channels for scan *j*,

$$r(j) = MAX[y(k)] - MIN[y(k)],$$
$$k = \text{line indices within scan } j.$$

(e) Calculate the off-line *RQI*,

$$RQI = \text{Average } r(j) \text{ over selected set of scans.}$$

TABLE 1. AVERAGE RQIs FOR LANDSAT-4 DATA. UNITS ARE QUANTUM LEVELS OR CORRECTED DNs

Area	No. of Scans	Bands 1	2	3	4	5	6	7
1	32	1.33	0.60	0.79	0.38	0.90	0.23	3.95 (7)
2	26	1.21	0.47	0.79	0.60	0.61	0.26	1.91 (6)
3	32	1.38	0.65	0.76	0.35	0.85	0.22	3.60 (32)
4	32	1.30	0.42	0.64	0.58	1.01	0.24	0.89
5	32	1.23	0.45	0.77	0.54	0.87	0.30	1.33 (10)
6	26	1.21	0.50	0.79	0.49	0.85	0.26	0.97
7	32	1.21	0.43	0.70	0.33	0.69	0.24	1.54 (2)
8	32	1.26	0.52	0.64	0.33	0.70	0.23	0.87
9	32	1.37	0.65	0.81	0.37	0.74	0.31	0.92

The indicator is based on the assumption that the scene content is a slowly varying function of the line averages. Thus by using a low pass filter, variations due to scene content can be subtracted out. Any remaining variation must be due to errors in the radiometric correction. Error measures (ranges) for a scan, $r(j)$, and the aggregation over a set of scans, *RQI*, can then be computed. The thresholds for meeting performance requirements are 2 ql for the range of an individual scan. For the average *RQI*, values less than 1.25 ql are normally indicative of within-specification correction. This value was determined empirically.

Tables 1 and 2 present *RQI* values for TM-4 and TM-5 data processing. The areas were selected from different scenes. Numbers in parentheses are the number of scans that exceeded the 2 ql limit. The TM-4 values were generated before the scene content correction limitations were implemented. Thus for TM-4 band 7, a lot of the scans exceeded the limit. For scenes that did not contain much water the correction was within specifications. Unfortunately, *RQI* data for TM-4 after the SCC limitations were implemented, was not available, as very few Landsat-4 scenes were being acquired and processed.

Table 2 shows that TM-5 data are being corrected well within requirements. These results reflect the performance of the radiometric correction after incorporating the postlaunch changes to the IC lamp radiances for band 3, discussed in Singh (1985) in this journal.

SUMMARY

The paper described three enhancements to the TIPS radiometric correction algorithms to resolve the problems discovered after launch of the instruments. The problems all dealt with relative radiometric correction, which is concerned with reducing the sensor striping in the imagery. Fine-tuning the pulse extraction algorithm and eliminating lamp states 111 and 000 (and 001 for band 5) from the regression step made the estimation of the gains and

TABLE 2. AVERAGE RQIs FOR LANDSAT-5 DATA. UNITS ARE QUANTUM LEVELS OR CORRECTED DNs

Area	No. of Scans	Bands 1	2	3	4	5	6	7
1	32	0.38	0.69	0.40	0.37	0.64	0.30	0.47
2	32	0.48	0.66	0.53	0.40	0.49	0.26	0.43
3	32	0.87	0.76	1.71	0.36	0.56	0.29	0.43
4	32	0.58	0.71	0.52	0.57	0.58	0.40	0.44
5	32	0.60	0.62	0.52	0.62	0.53	0.37	0.51
6	13	0.72	0.66	0.60	0.56	0.52	0.37	0.49

biases more reliable, as it minimized the effects of the saturated calibration values and the light leak.

The limitations imposed on the scene content correction were mainly for large flat scenes (water or clouds) and have little or no effect on typical scenes over land. They ensured that the process would generate a product which would be no worse than if SCC had not been applied. These facts were confirmed by monitoring the photo products being generated by the system and by computing the *RQI* numbers for TM-5 data.

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