REMOVAL OF THEMATIC MAPPER STREAKING AND STRIPING ARTIFACTS

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ABSTRACT

Some images produced by the Thematic Mappers on Landsats 4 and 5 have displayed a variety of imaging artifacts, including streaking and striping. Various techniques have been employed to remove these artifacts, but many of these have limitations and will occasionally induce artifacts of their own. As part of the planned radiometric calibration and correction process being designed for Landsat 7, a diffuse reflective surface which will obscure the entire aperture will be used as a uniform calibration target to equalize the output of all of the detectors in each of the reflective spectral bands. Analyses of this procedure with Landsat 5 Thematic Mapper imagery have provided results indicating not only that the potential exists for eliminating virtually all visible streaking and striping in Landsat 7, but that correction factors can be generated which may eliminate much of the streaking in Landsat 4 and 5 as well. Additionally, virtually all striping can be eliminated through the proper selection and application of dark shutter information. This paper provides a description of the assumptions made and analyses performed in evaluating the proposed equalization and destriping algorithms for Landsat 7, the results of the study, and the correction factors derived for the Landsat 5 Thematic Mapper.

1. INTRODUCTION

The deployment of Landsats 4 and 5 and their associated Thematic Mappers in the early 1980s provided the remote sensing community with an excellent source of multispectral imagery. However, like many imaging sensors, occasional artifacts appeared in the imagery which are characteristic of whisk broom systems. Two of the more prominent of these artifacts were streaking, a systematic darkening or lightening of the output samples from a single detector relative to its neighbors, and striping (sometimes called banding), a systematic darkening or lightening of the output samples from all of the detectors during a scan relative to the adjacent scans. The latter is generally the more prevalent.

Thematic Mapper (TM) striping has been associated with a variety of characteristics and names, most often Scan Correlated Shift, in which the phenomenon is linked to a response difference between the forward and reverse scans. On an absolute scale, the intensity of striping is small, generally less than 2 digital numbers (counts) out of a maximum possible range of 256. Yet the human eye is remarkably sensitive to such low intensity patterns. Additionally, the visual effect is amplified when narrow dynamic range images (water, plains, deserts, etc.) are contrast-stretched to bring out low level details.

Different techniques have been developed in an attempt to remove such artifacts (Fischel, 1984). One of the more common of these is a form of histogram adjustment. Generally, this involves a shifting of the average calibrated output value from a single scan to match the average calibrated output value of the entire image, and then scaling the standard deviation of each scan to match that of the entire image. Very often this does improve the visual appearance of the image. However, the techniques rely upon certain assumptions about the scene content which are not always true, such as similar statistics at all scan locations, wide standard deviations, and unimodal distributions. Violation of any of these assumptions may cause the technique to lose its efficacy, or even to induce its own artifacts.

The Landsat 7 Enhanced Thematic Mapper Plus (ETM+), currently being designed, will have a device which, it is expected, among other benefits, will provide the means for eliminating much of the potential streaking. The ETM+ will have a calibration paddle which, when commanded once every few weeks, will swing into a position in front of the aperture, completely blocking the field of view. On the surface of the paddle facing the aperture will be a highly diffuse, reflective, uniform panel which will reflect sunlight into the aperture, providing a known (through modeling) radiance with which the reflective bands of the sensor can be radiometrically calibrated on an absolute basis. Part of the calibration plan calls for equalizing the detector calibration curves (i.e. ensuring that, given the same input, the calibrated output of each detector is equal) utilizing the extreme uniformity of the panel. It is expected that once the detector calibration curves have been equalized, the discrepancies in estimating the calibration curves which can cause streaking, will be eliminated.

As an adjunct to this equalization process, new processing techniques involving the use of dark shutter information were investigated for their potential to minimize remaining image artifacts. One technique based upon characteristics of the DC restore function and short term time variations in detector response was proposed as the most effective candidate.

In order to test the hypotheses of whether such equalization techniques would prove effective in removing streaking and striping, it was decided that, since no data is yet available from the ETM+, some simulated version of the calibrator panel equalization would be used to calculate correction coefficients which could be applied to real TM reflective band imagery. This simulation was created by locating an extremely uniform region within a Landsat 5 TM image, assuming that it was perfectly uniform, calculating the correction coefficients, applying them to the entire image from which the extraction was made, and to other images, both of the same scene as well as others collected at different times, and evaluating the results both quantitatively and qualitatively. A similar procedure was investigated as an alternative to using pre-launch measured detector gains for Landsat 4 (Fischel, 1984). The details of the process follow.

2. CHARACTERIZATION OF THEMATIC MAPPER RESPONSE

At the end of every scan of the TM, a shutter passes in front of the focal plane. The shutter provides both a dark source (blocking light from the aperture) and a light source for reflective band calibration. The light intensity is varied by turning on and off, in different combinations, three different calibration lamps providing seven different light levels. Each level is maintained for approximately 40 scans. Therefore, when provided radiance estimates for the light levels, eight different calibration points are available for establishing an estimate of each detector's response curve. Since the detectors are assumed to be linear, a linear least squares curve fit is calculated for all of the points providing a gain and bias value for each detector.

In the ETM+ the configuration is very similar, except that only one lamp will be used, thus providing a single light intensity level instead of seven non-zero levels.

3. ESTABLISHMENT OF A UNIFORM EQUALIZATION TARGET

Creation of an equalization target required two steps. First, a Level 0 (raw, uncalibrated detector outputs) image of a known relatively uniform scene was selected. In this case it was fortunate that Santa Barbara Research Center, the developer of the TM, was kind enough to lend us images of the Libyan desert collected by Landsat 5 from 1984 to 1991, which they had used for detector response drift studies in recent years. The August 27, 1991 image was selected as the source for equalization.

Second, an automated search of the image from spectral band 1 was conducted to find the most uniform area within the scene. A sliding window, 512 by 512 pixels in size, was placed over the image, beginning in the upper left hand corner. The standard deviation of the pixels within the window was calculated and stored with the window location. The window was then repeatedly shifted maintaining a 64 pixel overlap with the previous window, and the accompanying standard deviation calculated for each area until the entire image had been covered. That window of pixels with the smallest standard deviation was assumed to be the most uniform area within the scene. In the case of this image, this was in the location starting at sample 449 and line 2049 (lines are designated as running in the cross track direction). Statistics for this region were:

μ=115.1 DN
σ=2.51 DN
Min=104 DN
Max=149 DN

The standard deviation was actually small enough to be comparable to the estimated system noise level.

4. EXTERNAL EQUALIZATION PROCESSING

The average Entrance Aperture Radiance (EAR) values were calculated from the uniform source image as follows:

For each reflective band, m, and each detector, k:

$$r_{k,m} = \frac{\left[\sum_{i=1}^{nscan} \sum_{j=1}^{nsamp} \frac{(eq\_source_{i,j} - bias_{i,j})}{G_{k,m}} \right]}{(nscan)(nsamp)} \qquad (1)$$

$$\text{r\_avg}_m = \frac{\sum_{k=1}^{\text{ndet}} r_{k,m}}{\text{ndet}} \tag{2}$$

Where:

i = scan index
j = sample index
ndet = no. of detectors per focal plane (default = 16)
nscan = no. of scans (default = 32)
nsamp = no. of samples (default = 512)
eq_source = raw uniform image from detector k, band m (DN)
bias = average response value to shutter for sample j, from scan i, detector k, band m (DN)
G = gain for detector k, band m (DN/radiance) **
r = average EAR for detector k, band m (radiance)
r_avg = average EAR across all detectors in a band m (radiance)
** Each detector gain is currently implemented as a nominal constant value across all scans.

Shutter data collected at the same time as the equalization source image was extracted from the calibration data and averaged to provide estimates of the offset bias for each pixel on each individual scan. The best results (i.e. minimized streaking and striping) were achieved when using the extraction technique described below.

Subtracting the appropriate bias allowed for computation of the signal counts, which when divided by the detector gain, yielded radiance. The radiance values were averaged over samples and scans to produce an average EAR for a detector. After all detectors in a band had been processed, the average EAR across the band was also calculated. The ratio of these average radiance values, r_avg and r, became equalization coefficients which were used to equalize imagery.

Once the coefficients had been calculated, they were applied both to the remainder of the image from which they were derived and to other images produced by the same sensor using the following processing steps:

For each reflective band, m, and each detector, k :

$$\text{output}_{i,j} = \left[\frac{(\text{input}_{i,j} - \text{bias}_{i,j})}{G_{k,m}} \right] \left[\frac{\text{r\_avg}_m}{r_{k,m}} \right] \tag{3}$$

$$\text{output\_byte}_{i,j} = \text{INT} \left[(\text{output}_{i,j}) \frac{255.}{R_{max}} + 0.5 \right] \tag{4}$$

Limit output_byte between 0 and 255

Where:

input = raw input image from detector k, band m (DN)
output = corrected radiance image from detector k, band m (floating point radiance)
output_byte = byte scaled output radiance image from detector k, band m
R_{max} = maximum radiance for band m (radiance)

The average bias was again computed on an individual scan basis and removed.

5. BIAS REMOVAL

Enough emphasis cannot be placed on the proper calculation and removal of scan dependent bias levels. Most of the visible residual striping in TM imagery was found to be due to the incomplete compensation of the individual bias associated with each scan. Early in the study it was assumed that subtracting the proper average dark shutter value from the image pixel values in the same scan would eliminate scan to scan bias variations causing striping. However, use of the averaging window specified in the Long Term Parameter File (see window w2 in Figure 1) provided with the images for determining average dark responses actually induced striping. A variety of averaging windows was tried before the final windows, w6 and w7, were selected for their minimization of striping. The key ingredient in selecting the proper window was to avoid readings obtained during DC restore. DC restore is a process in which the output is set equal to a non-zero constant number of DN (in this case, two). This very process invalidates any data taken during that time which is meant to characterize the detector response. The data from window w2 in forward scans was positioned in the DC restore region. It therefore failed to correct for all of the scan to scan variations. A comparison of dark shutter responses from Landsat 5, using both the window in the Long Term Parameter File and the new window w6 used in this study, can be found in Figure 2.

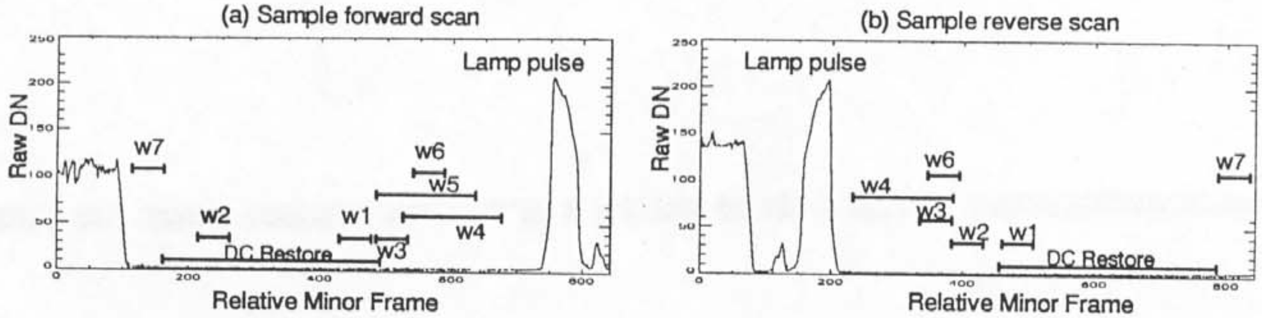
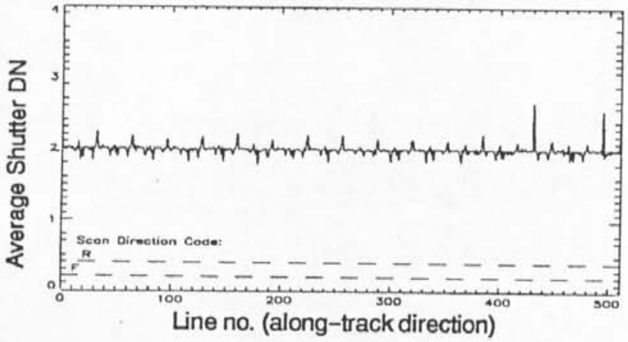


Figure 1. Various window positions during dark shutter collection attempted during this study.

(a) Using window from Landsat 5 Long Term Parameter File



(b) Using window w6

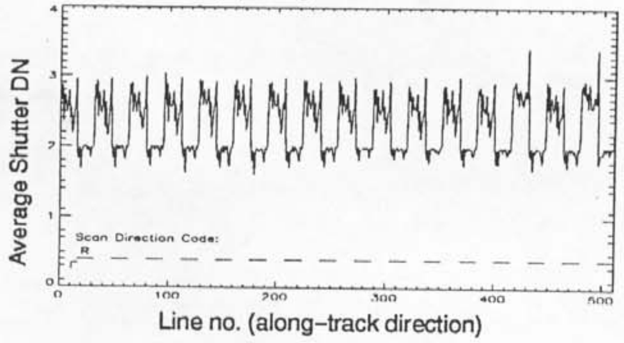


Figure 2. Average Dark Shutter Response for Each Line Using Different Shutter Extraction Windows Sample Data Taken from Libyan Desert 1991 Scene Band 4 (Note: Lower valued areas in Figure (b) are reverse scan)

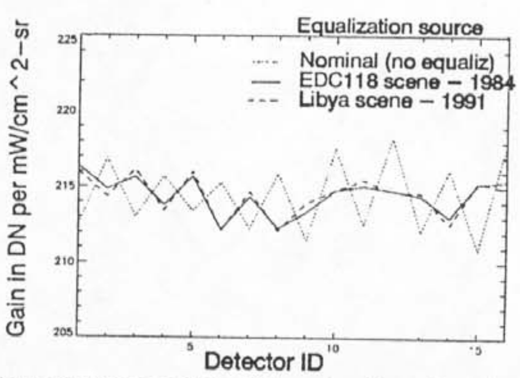


Figure 3. Detector Gains Determined from Equalization of 1984 and 1991 Scenes vs. Nominal Gains from Long Term Parameter File (Band 1)

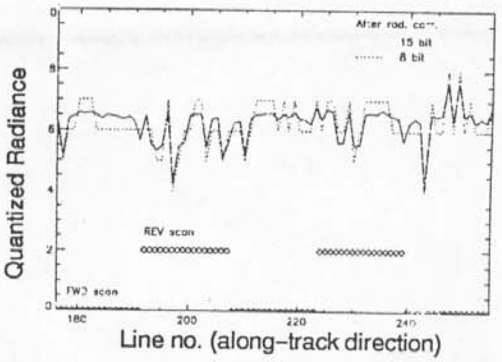


Figure 4. Along Track Profiles Through Uniform Lake Quantized to 8 and 15 Bit Precision Levels

Later in the study, some imagery processed with this technique began to show residual striping that varied in intensity with scan position, in this case peaking at the right side of the image. This is a phenomenon sometimes called scan droop. A comparison of average shutter values before and after DC restore indicated that the detector response apparently gets "pumped up" after DC restore and slowly drops a fraction of a DN during the scan. A new technique was developed based upon the assumption that the DC restore in each scan was reinitializing the detector response to its higher value. Two average samples were collected during each dark shutter using windows w6 and w7. Then, using the average calculated after

DC restore (ADC) from the previous scan, and the average calculated before DC restore (BDC) from the current scan, a linear interpolation was performed to determine and remove the bias at each pixel location on the current scan. The first scan of an image was processed with the original technique and window w6 since no previous scan data was available.

Note that the beginning of each dark shutter window does not occur simultaneously for every detector. Because of the shutter mechanism's configuration, detector one "sees" the dark shutter before detector sixteen in reverse scans. In that case window placement must be shifted slightly in time for each detector to obtain the proper, corresponding shutter values. Table 1 presents the locations of the final extraction windows chosen for Landsat 5.

SCAN DIRECTION	SHUTTER EXTRACTION WINDOWS		
	BEFORE DC RESTORE START MINOR FRAME	AFTER DC RESTORE START MINOR FRAME	NO. OF MINOR FRAMES
Forward	109	538	52
Reverse	342	728 (Det. 1) – 781 (Det. 16)	52

Table 1. Final Landsat 5 TM shutter extraction parameters

6. RESULTS

The previous processing scheme was tested on the following Landsat 5 images.
WRS Path=188 Row=041 Libyan Desert collections:
8 September, 1984
29 August, 1986
1 September, 1987
9 September, 1990
27 August, 1991

WRS Path = 033 Row = 033 Colorado Springs: 27 July, 1985
WRS Path = 172 Row = 066 Zambia: 20 June, 1984
WRS Path = 172 Row = 071 Zambia: 20 June, 1984
WRS Path = 172 Row = 072 Zambia/Zimbabwe: 20 June, 1984
WRS Path = 172 Row = 076 Botswana: 20 June, 1984

Unfortunately, the pre-1991 Libyan Desert images provided shutter data that was pre-averaged over the window designated in the Landsat 5 Long Term Parameter File, thus making a analysis of those images with the new window impossible. However, it was still possible to evaluate the impact of the newly calculated gain coefficients on levels of streaking in all of the images. The new detector gain coefficients calculated from the earlier1984 Zambian image can be found in Table 2. Figure 3 provides a sample comparison of the relative detector gains provided in the Long Term Parameter file with the image, to the detector gains determined from the equalization procedure with the 1991 Libyan desert scene and the 1984 scene of Zambia. The 1984 and 1991 equalization values are virtually identical while the Long Term Parameter values are clearly different graphically indicating the reason for the streaking in images produced with the Long Term Parameter gains and that the relative gains of the detectors have been extremely stable over many years.

Streaking performance was consistently good across all years and for all of the reflective bands except band 5, not because of an inherent deficiency in the process, but because data were unavailable for determining new coefficients for band 5 since it saturated in the 1991 image. A quantitative determination of streaking (here defined as the difference between the average value of one line from one detector and the average value from the two surrounding lines from two adjacent detectors) was sometimes difficult to establish because of scene content. However, residual streaking values varied from a high of less than 0.5 DN to a low of 0.015 DN. Band 2 consistently provided the highest amount of residual streaking. More variation of residual streaking was seen from band to band than from image to image.
It was also discovered during the study that residual streaking levels were so small that the quantization of the final pixel values to 8 bits (256 gray levels) from the calculated real numbers was actually serving to increase visible streaking. An along track profile through a lake in the Colorado Springs image is presented in Figure 4 quantized to 8 bits and 15 bits. The additional, stairstep variations displayed in the 8 bit quantized profile clearly serve to exacerbate small differences and cause streaking and striping.

Since striping compensation was calculated on a scan by scan basis using only dark shutter data, its magnitude is virtually independent of the equalization process. With very little uniform image data accompanied by raw shutter data, residual striping has also been very difficult to quantify. Using 15 bit quantization, the only way to effectively judge the degree of residual striping is by visual softcopy inspection and a contrast stretch of from 20 to 80 times (i.e. mapping 8 DN into 256 gray levels). The best estimates of performance with these procedures placed striping (which was defined simply as the average difference between two adjacent scans) at an average of approximately 0.15 DN, with a maximum of about 0.5 DN. Striping levels after processing are so small that they are comparable to an along track interference pattern which, it is thought, is caused by interference from the payload control data (PCD) sampling (≈ 32 khz). This interference pattern is usually so small that it can only be detected through the use of Fast Fourier Transforms or autocorrelation functions.

DETECTOR	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5*	BAND 7
1	216.35583	91.01775	146.59180	85.23219	375.10727	587.15314
2	214.82460	90.95529	148.74100	84.86255	371.20142	579.55518
3	215.61977	90.03220	145.61705	84.80483	372.48212	585.76086
4	213.76900	91.11665	146.86333	83.56823	367.03473	585.35052
5	215.66486	90.19747	146.41582	84.66369	375.79434	590.46161
6	212.16615	91.46665	144.38597	84.89708	369.05185	572.74518
7	214.34270	89.85090	144.03462	85.61960	365.07385	580.03027
8	212.26170	91.63770	145.98790	85.10206	379.22787	574.37115
9	213.34251	89.52427	144.33228	83.57074	372.26974	582.75049
10	214.78102	90.43723	146.01863	85.16158	373.74826	573.30853
11	215.06982	90.68965	144.87016	84.80897	371.25192	587.31573
12	214.76381	90.89744	146.63857	84.36308	372.84979	577.11377
13	214.40010	90.07504	145.03952	84.31039	373.26019	578.58093
14	213.00774	89.80899	146.24689	85.02716	371.83533	574.29248
15	215.22348	90.61319	146.39751	84.62737	374.86841	581.24176
16	215.40404	89.33324	147.51375	84.78180	375.70493	581.90546

Table 2. Equalized detector gains $\left[\ G_{k,m}\right]\left[\frac{r_{k,m}}{r\_avg_m}\right]$ for Landsat 5 Thematic Mapper in units of DN per (mW/cm^2−sr).

One problem observed was the occasional appearance of a single scan droop stripe that would begin at one side of the image and fade away toward the other side. It was noted that, for those scans, the difference between the prior scan's average ADC and the current scan's BDC was biased by as much as 0.5 DN over the surrounding scan's values. A validity check was added to detect such occurrences and replace the non–representative value with the current scan's ADC value.. Because of the relative consistency of dark shutter values within an image, this procedure proved adequate for eliminating these stripes. No explanation has ever been postulated for the existence of these spurious values.

Some concern existed over the potential impact of another Landsat 5 TM artifact on this scan by scan compensation. Sometimes called memory effect or bright target recovery, it causes a detector to remain at full saturation output, sometimes for several hundred pixels, followed by occasional "ringing" after the detector has been saturated by a bright target (often clouds). If such a situation were to occur at the end of a scan, just before the dark shutter and lamp, it was thought that the effect might spill over to the shutter collection and interfere with the bias compensation. In fact, this memory effect did occur in the Colorado Springs image, in clouds, at one edge of the image. It produced some highly visible, long, but temporary streaks (each detector reacts differently). Yet it had no apparent impact on the quantitative window average or on the striping suppression.

7. CONCLUSIONS

Certain conclusions seem hard to ignore. First, the gains of individual detectors within a spectral band are extremely stable relative to one another. Any relative drift would have manifested itself as streaking after the correction was applied, since the same gain correction was used across all seven years of test data used and, at most, the apparent drift was limited to a fraction of a digital number. From this it can be concluded that the internal calibration lamps are not necessary for the removal of image artifacts (although they may be necessary for tracking overall array drift), and that the simple application of the constant gain coefficients in Table 2 can be used for improving all Landsat 5 TM imagery.

If, in the future, the detector gains do start to drift apart, the search procedure described earlier can be used to locate a new uniform area and to recalculate the gains.

Even more important is the proper selection and application of the window data within the dark shutter used for determining the average offsets for that scan, detector and sample. Most of the striping can be eliminated as long as both a window before and after (but not inside of) DC restore are selected, and a value interpolated from these selections is used to remove the bias at each image sample location.

Higher precision quantization provides a definite improvement in low level artifacting. Earlier investigations of higher precision radiometric storage were rejected because of its potential impact on the speed of later geometric processing stages. With advancements in computing power it is believed that this should no longer be a concern. However, if this is still a problem, it is suggested that the radiometrically corrected image still be stored with a higher precision, and that the dynamic range be cropped to a small range of interest prior to 8 bit quantization and submission to the geometric processing stage.

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