Department of the Interior
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LANDSAT 4/5 THEMATIC MAPPER (TM) IMAGE ASSESSMENT SYSTEM (IAS) RADIOMETRIC ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD)

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USGS
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Executive Summary

This Algorithm Theoretical Basis Document (ATBD) defines the algorithms the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center uses for the radiometric processing of Landsat Thematic Mapper (TM) imagery. The Image Assessment System (IAS) uses the radiometric processing algorithms described in this document to generate Landsat 5 (L5) TM Level 1 Radiometrically Corrected (L1R) data products.

This document is consistent with all other relevant requirements and interface documents connected with these systems.

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Section 1 Introduction

1.1 Purpose

This document describes the radiometric processing algorithms and data flows used in the Landsat Thematic Mapper (TM) Image Assessment System (IAS). These algorithms are implemented as part of the IAS Level 1 processing, radiometric characterization, and radiometric calibration software components. These algorithms create accurate Landsat 1 (L1) output products, characterize the TM radiometric performance (noise, dynamic range, anomalies, etc.), and derive improved estimates of absolute and relative radiometric calibration parameters. These algorithms produce outputs that are stored in the IAS database and are routinely trended as part of the radiometric performance monitoring. This document also presents background material describing the TM sensor and its radiometric calibration devices.

Section 2 Overview and Background

The Landsat 5 (L5) TM instrument is the Landsat Project's workhorse, operating over 25 years after launching on March 1, 1984. L5 provides sixteen-day repeating coverage with an orbit offset of eight days relative to the Landsat 7 (L7) Enhanced Thematic Mapper Plus (ETM+). The L5 TM is the same type of sensor as the TM previously flown onboard Landsat 4 (L4), and has six spectral bands that cover the visible to the infrared wavelengths, along with a thermal band.

The L7 IAS has been modified to accommodate a multi-mission architecture and can now process and trend L4/L5 TM data sets. The IAS system was extended to handle Multispectral Scanner (MSS) data sets.

2.1 Mission Objective

The objective of the L5 TM mission is to provide global, seasonally refreshed, high-resolution (30-meter multispectral, 120-meter thermal) imagery of the Earth's land areas from a near-polar, sun-synchronous orbit. These data perform the following:

- Enable 16-day coverage for locations around the world where L5 TM data can be directly downlinked
- Cross-calibrate to other Landsat imagers for a consistent scientific utility

The Calibration Analysts use the IAS radiometric algorithms described in this document to ensure that the radiometric behavior of the TM is sufficiently characterized to meet the mission objectives.

2.2 TM Historical Perspective

The L4 system was an experimental Earth resources monitoring system with the new powerful remote-sensing capabilities of the TM. It provided a transition for both foreign and domestic users from the MSS data to the higher resolution and data rate of the TM. It had a complete end-to-end highly automated data system, designed to be a new generation system, and was a major step forward in global remote-sensing applications. The L4 mission, launched in 1982 and operated until 1993, consisted of an orbiting satellite (flight segment) with the necessary wideband data links, support systems, and a ground segment. The L4 flight segment consisted of two major systems:

- The instrument module, which contained the instruments with the mission-unique subsystems, such as the solar array and drive, the Tracking and Data Relay Satellite System (TDRSS) antenna, the Wide-Band Module (WBM), and the global positioning system.
- The Multimission Modular Spacecraft (MMS), which contained the modularized and standardized power, propulsion, attitude control, and communications and data handling subsystems.

The flight segment was designed with three years nominal lifetime in orbit, with the option to extend through an in-orbit replacement capability when the Space Shuttle became operational. The spacecraft was placed into an orbit having a descending node equatorial crossing between 9:30 a.m. and 10:00 a.m. local time. The spacecraft and attendant sensors were operated through the Ground Spaceflight Tracking and Data Network (GSTDN) stations before the TDRSS was available.

An identical back-up spacecraft, Landsat-D Prime (National Space Science Data Center (NSSDC) ID Landsat-E) was placed in storage and launched on March 1, 1984, as L5.

Section 3 Instrument Description

The Landsat TM is a whiskbroom electro-mechanical-optical sensor. It has seven spectral bands ranging from the visible through the thermal wavelengths. Bands 1-3 cover the visible portion of the spectrum, Band 4 covers the near infrared portion, Bands 5 and 7 cover the shortwave infrared portion, and Band 6 covers the thermal portion.

Each of the reflective bands (Bands 1-5 and Band 7) consists of 16 photodiode detectors. Bands 1-4 are silicon-based detectors, and Bands 5 and 7 are Indium Antimonide (InSb) detectors. Band 6 consists of an array of four Mercury Cadmium Telluride (HgCdTe) detectors. The spatial resolution of the reflective bands is nominally 30 meters, while the thermal band is 120 meters. In the IAS environment, detectors are numbered in reverse sequence (i.e., the first row in each scan of reflective bands corresponds to a response of Detector 16, the second row to Detector 15, and so forth to Detector 1; the thermal band detectors are numbered from 4 to 1) when moving north-to-south within a scene. The database, Calibration Parameter File (CPF), and all correction algorithms utilize the same notational system without exception.

As a whiskbroom scanner, the TM scan mirror sweeps the detectors across the Earth's surface in an east-to-west direction, while orbital motion provides the north-to-south dimension. A device known as the Scan Line Corrector (SLC) corrects the scans for orbital motion effects making the scans essentially parallel with each other. Figure 3-1 shows the optical layout of the sensor.

A typical Landsat TM scene consists of 384 scans and is acquired in approximately 24 seconds.

The L4/L5 satellites were placed in a sun-synchronous orbit with an orbital inclination of approximately 98 degrees, to allow repeat coverage of the Earth every 16 days.

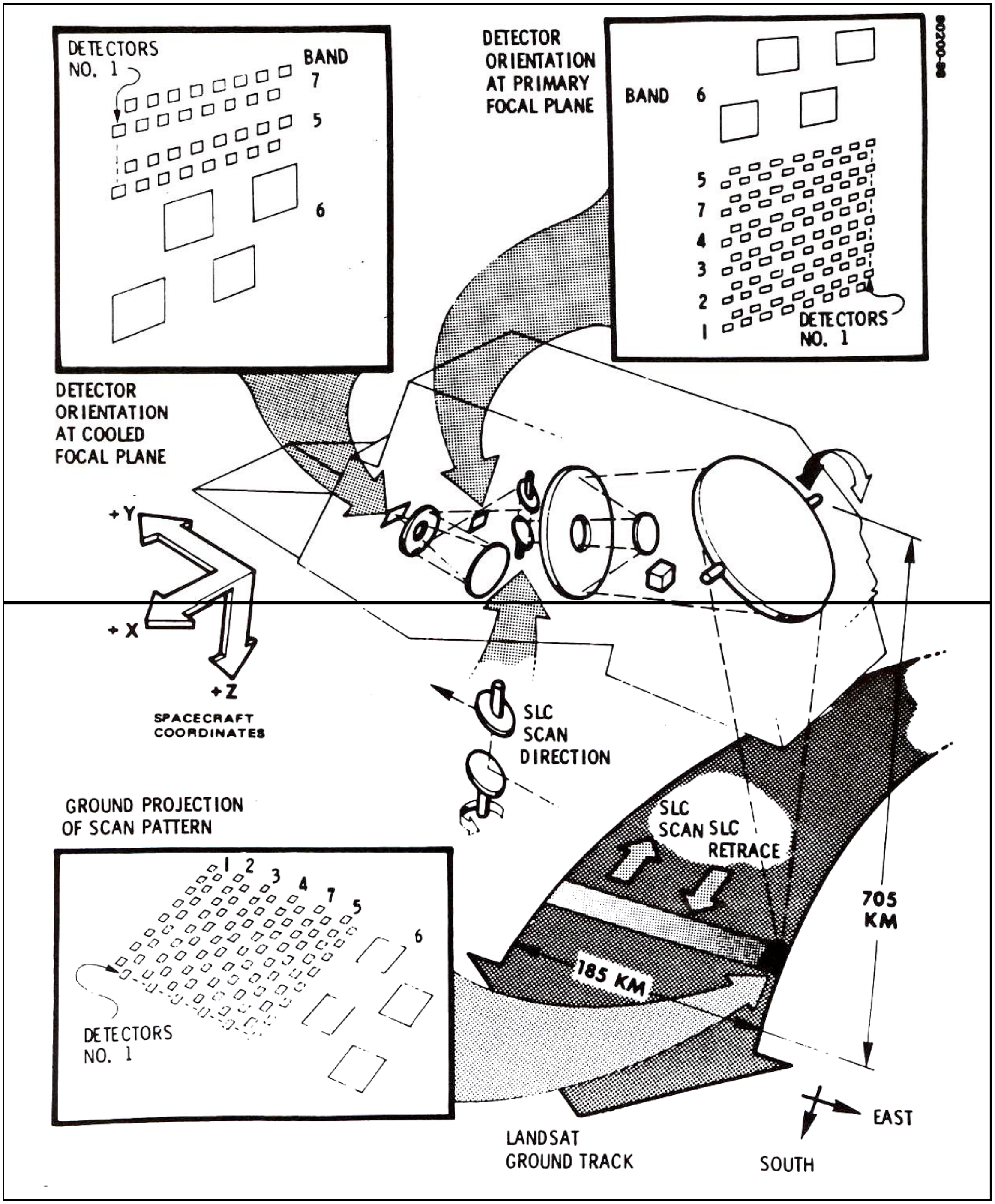

Figure 3-1. Landsat TM Detector Orientation to Ground Track

3.1 Relative Spectral Responses

The TM instruments incorporate seven spectral bands. Bands 1-4 are located on the primary focal plane and cover the visible and near infrared region. The cold focal plane houses Band 6, which is used for thermal measurements, and Bands 5 and 7, which provide a Short Wavelength Infrared (SWIR) response. Figure 3-2 displays the L5 TM relative spectral responses. The L4 TM has a similar, but slightly different, relative spectral response.

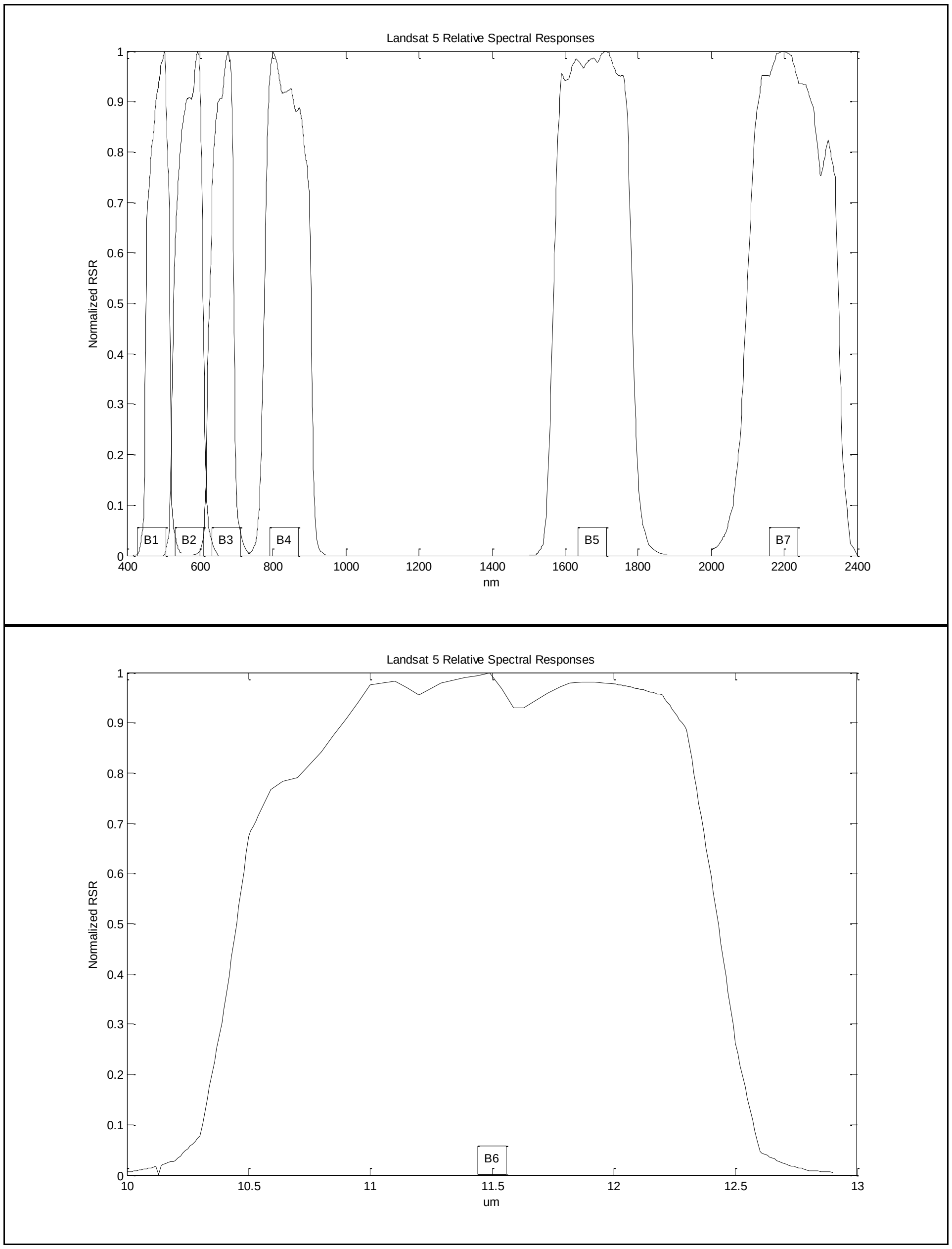

Figure 3-2. Landsat 5 TM Relative Spectral Responses

Section 4 Radiometric Processing Algorithm Flows

Figure 4-1 provides the nominal TM processing flow for radiometric correction of a Level 1 Radiometrically Corrected (L1R) daytime scene. Figure 4-2 provides the nominal TM processing flow for radiometric correction of an L1R night scene. Figure 4-3 provides the algorithm predecessor requirements for both L1R day and L1R night correction.

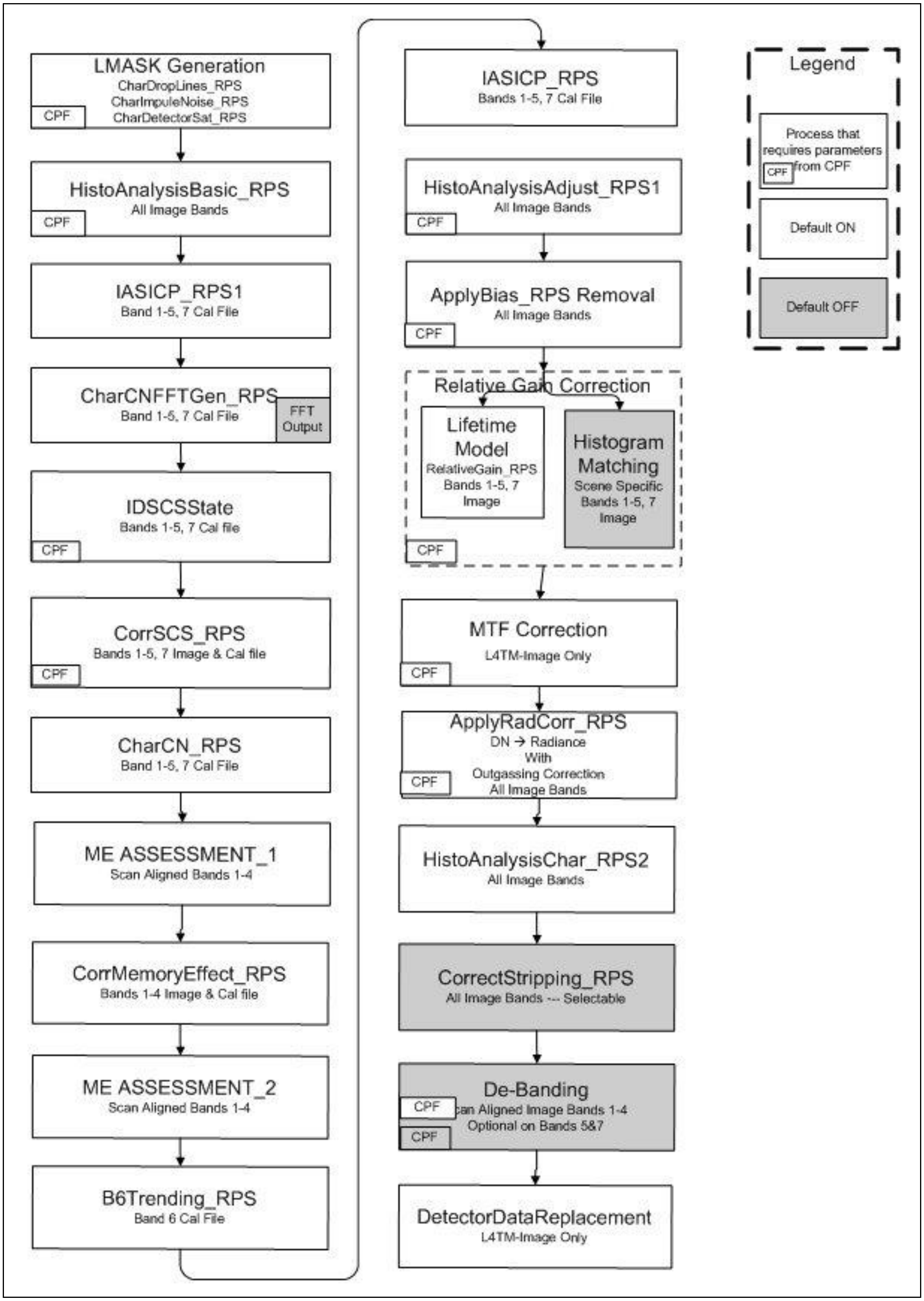

Figure 4-1. Nominal TM L1R Day Process Flow

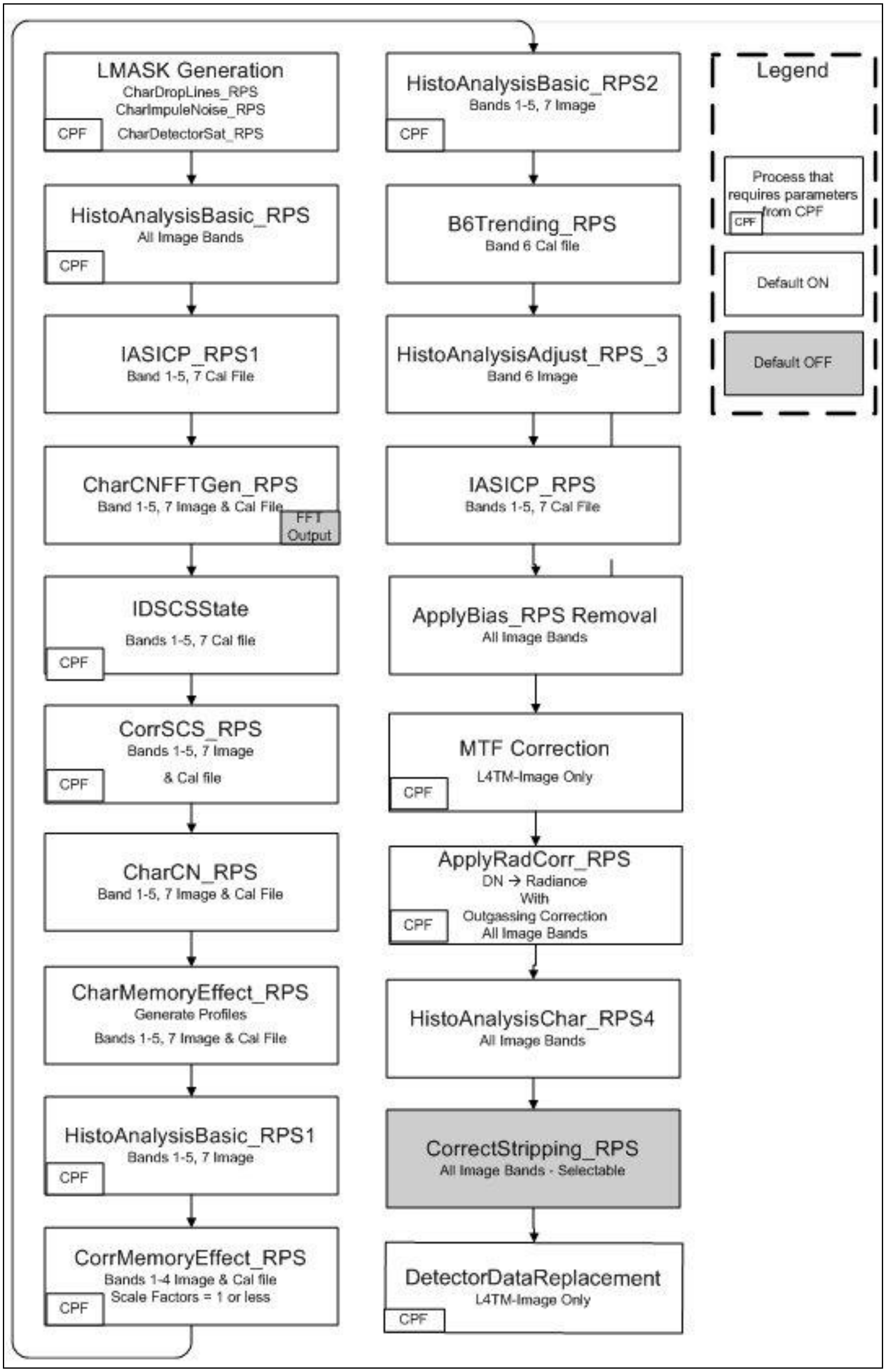

Figure 4-2. Nominal TM L1R Night Process Flow

NOMINAL DAY FLOW R9.0																			
Need:	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16] [17]		[19]	
To Run:																			
[1] CharDropLines																			
[2] CharImpulseNoise_RPS	M																		
[3] CharDetectorSat_RPS	M	M																	
[4] HistoAnalysisBasic_RPS	M	M	M																
[5] IASICP_RPS1	M	M	M																
[6] CharCNFFTGen_RPS	M																		
[7] IDSCSState-CorrSCS_RPS	M	M	M																
[8] CharCN_RPS	M					M													
[9] ME_Assessment_1	M	M	M																
[10] CorrMemoryEffect_RPS	M	M	M				R												
[11] ME_Assessment_2	M	M	M				R		M	M									
[12] B6Trending_RPS	M	M	M																
[13] IASICP_RPS	M	M	M		R		R			R									
[14] HistoAnalysisAdjust_RPS1	M	M	M				R			R									
[15] ApplyBiasRemoval_RPS	M	M	M				R			R		M	M						
[16] RelativeGain_RPS (lifetime)	M	M	M				R			R		M	M						
[14] Relative Gain (histogram)	M	M	M				R			R		M	M	M					
[15] ApplyRadCorr_RPS	M	M	M				R			R		M	M		M				
[16] HistoAnalysisChar_RPS2	M	M	M				R			R		M	M		M				
[17] CorrectStriping_RPS (histogram)	M	M	M				R			R		M	M		M	M			
[18] Debanding	M	M	M				R			R		M	M		M				
NOMINAL NIGHT FLOW R9.0																			
Need:	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16] [17] [18]			[16]
To Run:																			
[1] CharDropLines																			
[2] CharImpulseNoise_RPS	M																		
[3] CharDetectorSat_RPS	M	M																	
[4] HistoAnalysisBasic_RPS	M	M	M																

[5] IASICP_RPS1	M	M	M																
[6] CharCNFFTGen_RPS	M																		
[7] IDSCSState-CorrSCS_RPS	M	M	M																
[8] CharCN_RPS	M					M													
[9] CharMemoryEffect_RPS	M	M	M				M												
[10] HistoAnalysisBasic_RPS1	M	M	M	R			R												
[11] CorrMemoryEffect_RPS	M	M	M				R												
[12] HistoAnalysisBasic_RPS2	M	M	M	R			R			R	R								
[13] B6Trending_RPS	M	M	M																
[14] HistoAnalysisAdjust_RPS3	M	M	M	R			R			R	R	R	M						
[15] IASICP_RPS	M	M	M		R		R				R								
[16] ApplyBiasRemoval_RPS	M	M	M		R		R				R				M				
[17] ApplyRadCorr_RPS	M	M	M				R				R				M	M			
[18] HistoAnalysisChar_RPS4	M	M	M				R				R				M	M M			
[19] CorrectStripping_RPS	M	M	M				R				R				M	M M M			M

Figure 4-3. Algorithm Predecessor Requirements (L1R Day and L1R Night)

Section 5 Payload Correction Data (PCD) Temperature Extraction

5.1 Introduction

This routine extracts all information related to on-sensor temperature measurements acquired during a Landsat TM data collect and stored in the Payload Correction Data (PCD) file associated with a Level 0 Reformatted (L0R) scene. As a part of the scene ingest process, this information is converted to temperature estimates intended for use in temperature sensitivity analyses and/or correction of TM radiometric data.

5.2 Background

The Landsat TM contains sensors that generate a set of 'housekeeping' data that monitor the instrument operating status and health. Some of these sensors output a set of raw 'count' values representing the temperature at / near various components within the instrument collected at approximately 16-second intervals; as a result, an individual scene may contain one or more unique sets of temperature measurements. All sampled housekeeping data (including the temperature-related data) are tagged with acquisition times and written to a PCD file that is part of the auxiliary data associated with a given L0R data product.

5.3 Inputs

- L0R PCD file
- Temperature conversion coefficients

5.4 Outputs

- Blackbody temperature (floating point)
- Silicon focal plane assembly temperature (floating point)
- Calibration shutter flag temperature (floating point)
- Baffle temperature (floating point)
- Cold focal plane monitor temperature (floating point)
- SLC temperature (floating point)
- Calibration shutter hub temperature (floating point)
- Relay optics temperature (floating point)
- Primary mirror temperature (floating point)
- Secondary mirror temperature (floating point)
- Attitude displacement sensor assembly temperature (up to four measurements) (floating point)

5.5 Algorithm Description

Prior to transmission to the receiving ground station, the sampled temperature sensor outputs (in digital counts) are written to word 72 (as defined in [1]) within specific minor frames of PCD data, starting at minor frame number 16. During scene ingest, the count values are extracted and converted to temperature estimates (in units of ºC) using a polynomial function of the form:

$$T = A_0 + A_1C + A_2C^2 + A_3C^3 + A_4C^4 + A_5C^5 \qquad (1)$$

where C is the sampled count value from the temperature sensor of interest, and A_i is the conversion coefficients for the desired temperature.

Table 5-1 provides the conversion coefficients for each temperature measured in the TM (see 5.6).

TEMP	A_0	A_1	A_2	A_3	A_4	A_5
Blackbody	17.073	0.10263	2.2576×10^{-4}	0.0	0.0	0.0
Silicon FPA	10.049	0.83456×10^{-1}	0.14176×10^{-3}	0.0	0.0	0.0
Cal Shutter Flag	36.898	-0.1598	1.957×10^{-6}	0.0	0.0	0.0
Baffle	-2.9072	0.089583	2.7115×10^{-4}	0.0	0.0	0.0
Cold FPA	-162.94	-0.1000	0.0	0.0	0.0	0.0
Scan-Line Corrector	147.84	-1.8384	0.016092	-9.2715×10^{-5}	2.839×10^{-7}	-3.683×10^{-10}
Cal Shutter Hub	121.23	-1.9147	0.019275	-0.11865×10^{-3}	0.37343×10^{-6}	-0.47899×10^{-9}
Relay Optics	121.23	-1.9147	0.019275	-0.11865×10^{-3}	0.37343×10^{-6}	-0.47899×10^{-9}
Primary Mirror	121.23	-1.9147	0.019275	-0.11865×10^{-3}	0.37343×10^{-6}	-0.47899×10^{-9}
Secondary Mirror	121.23	-1.9147	0.019275	-0.11865×10^{-3}	0.37343×10^{-6}	-0.47899×10^{-9}

Table 5-1. L4 / L5 TM Temperature Conversion Coefficients (ºC)

As mentioned previously, a PCD file from an ingested L0R scene can contain multiple sets of temperature measurements. Consequently, all unique sets of temperature measurements must be extracted and stored in the IAS database (PCD_Major_Frames table).

5.6 References

GSFC. 435-D-400. Landsat to Ground Station Interface Description. Revision 9. January 1986. pp. 36-57.

Section 6 Floating Point Processing Methodology

6.1 Introduction

Processing all TM image and calibration file data use floating-point number representations. The conversion from L0R 8-bit unsigned integers to float data occurs at the beginning of the process stream, and ultimately results in radiometrically corrected image data as the output of the radiometric processing system. The numerical values of these output data are in floating point format and represent physical units of radiance, W / (m^2 * sr * μm). Intermediate product dumps may be enabled during work order generation and are provided in a floating point format. During processing via the Geometric Processing System (GPS), the application of radiance limits (i.e., Lmin and Lmax) and rescaling to the final historical 8-bit integer Landsat TM product occurs.

6.2 Inputs

- L0R image data (all bands) (byte)
- L0R calibration data (all bands) (byte)

6.3 Outputs

- L0R image data (all bands) (floating point)
- L0R calibration data (all bands) (floating point)

6.4 Algorithm

For each band of image and calibration data, perform the following steps:

1. Allocate buffers to hold the byte input data and the floating point output data products
2. Read in each line of byte input data
3. Convert the lines of input data to their equivalent floating point representation
4. Copy the lines of floating point data to their proper location in the buffer representing the output data product

6.5 Issues

None

6.6 References

None

Section 7 LMASK — Dropped Line Detection

7.1 Introduction

This algorithm detects full dropped lines in L0R image and calibration file data. Pixels flagged as dropped are recorded in the LMASK routine with a value of “1,” and are subsequently ignored during numerical calculations within the IAS. This algorithm parallels the implemented L7 IAS, and is executed first in the LMASK population sequence.

The U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) preprocessing systems providing the IAS with Landsat Archive Conversion System (LACS) L0R data replace corrupt minor frames in both scene and calibration (cal) file data with a fixed byte pattern of 0s for odd detectors and 255s for even detectors. This dropped data replacement, while filtered from calibration calculations, flows through most IAS radiometric algorithms as though it were valid data, and can be expected to appear in the final output product unless a data replacement routine is implemented.

Note 5/2/2007: TM LACS data do not contain the 0-255 Digital Number (DN) fill pattern discussed in this Algorithm Theoretical Basis Document (ATBD), nor are there current plans to implement a fill pattern. The IAS Drop Line detection is currently implemented based on analysis of the Mirror Scan Correction Data (MSCD) flags as discussed herein.

7.2 Inputs

- MSCD filled_scan flag data
- MSCD scan_sync flag data
- MSCD minor frame fill count for scans
- Scan Line Offset (SLO) scan offsets
- L0R image data (floating point)
- L0R calibration data (floating point)

7.3 Outputs

Locations of full dropped lines for the scene and Internal Calibrator (IC) files are under consideration by line, starting minor frame, and length.

This information is stored in the LMASK. Summary dropped line counts report to the process report file for both the image and calibration file.

7.4 Algorithm

MSCD for "filled_scan_flag" determine whether a scan has any fill data on a scan-by-scan basis. For those scans with fill data, test minor frames for the 0, 255 fill pattern. Verify the minf_filled count in the MSCD.

The MSCD FilledScanFlag contents are encoded as follows:

0: no fill data used in the current scan
1: entirely filled scan
2: bad time code

The MSCD ScanSyncFlag contents are encoded as follows:

0: no fill data used in this scan
1: major frame lock loss

If a major frame lock loss is detected and/or a full dropped scan is detected, then increment counts for dropped image and cal file scans occur. Report the counts in the DropLine report file and record the locations in the LMASK. No further significant dropped line / data detection methodology is implemented within this algorithm that actively searches for corrupted information. Reliance is placed on accurate detection and labeling in the preprocessing data systems.

7.5 Issues

Note 5/19/2008: TM LACS data does not contain the 0-255 DN fill pattern discussed in this ATBD, nor are there current plans to implement a fill pattern. The IAS DropLine detection is currently implemented based on analysis of the MSCD flags as previously discussed.

Note 5/16/2008: Partial dropped lines are not flagged in LACS's L0R data and IAS does not handle the dropped line algorithm.

7.6 References

USGS/EROS. LS-IAS-02. Landsat 7 (L7) Image Assessment System (IAS) Radiometric Algorithm Theoretical Basis Document (ATBD). Version 1.0. June 2003.

Section 8 LMASK — Impulse Noise Detection

8.1 Introduction

This algorithm detects solitary Impulse Noise (IN) artifacts in TM L0R image and calibration data using comparisons of absolute difference between a pixel and a median filter value obtained from that pixel's nearest neighbors. The affected pixel locations and their values (in DN) are recorded in the LMASK to allow exclusion from further radiometric characterization / processing. This algorithm runs only on data with essentially zero input radiance (i.e., reflective bands in night image data and shutter bias data from the calibration file).

8.2 Background

IN is a randomly occurring aperiodic noise source that appears as a sample value significantly different from an expected 'background' exhibited by its (typically along-scan) nearest neighbors. Sources of IN include the following:

- 'bit flips' (i.e., An 'on' bit recorded as 'off' or vice versa, due to transmission / recording errors affecting the data stream.)
- 'Single Event Upsets' (SEUs) (i.e., Significant increases in the analog output signal that the detector array produced due to the effects of charged particles striking the array. This effect appears as a saturated pixel with the value (2^N-1) DN (*N* being the radiometric resolution of the sensor data in bits), followed by a saturated pixel with the minimum possible DN value (0). Subsequent pixels manifest the 'expected' DN values.)

With L4/L5 TM data, bit flips resulting from transmission problems between the satellite and ground station or in cabling between processing systems on the ground typically cause IN.

8.3 Inputs

- L0R IC dark shutter region data (all reflective bands) (floating point)
- L0R night image data (all reflective bands) (floating point)
- LMASK

8.4 User-Selected Input Parameters

- Median filter width 'MFW.' The default value comes from the CPF and should be set to '3' (integer)

8.5 Input Parameters Obtained From the CPF

- Detector noise levels, *NL* (floating point)
- Detector-specific IN threshold values, *INThresh* (floating point)
- List of inoperable detectors

8.6 Outputs

- Updated LMASK with locations and values of IN-affected pixels
- Database-trended parameters:
    - Total number of IN-affected pixels (integer)
    - IN-affected pixel ‘coordinates’ (line / sample) (integer)
    - IN-affected pixel value (floating point)
    - Neighboring pixel values (floating point)

8.7 Algorithm Description

For each scan line of input image / calibration data not flagged in the LMASK as ‘dropped’ and representing an operable detector, perform the following steps:

1. Apply a 1D median filter of width *MFW* across the ‘valid’ data pixels to obtain median pixel values *MFV*. For image data, ‘valid’ pixels are those pixels within the bounds of the pixels containing image information; for calibration data, ‘valid’ pixels are those in the shutter region prior to the pulse for forward scans, and following the pulse for reverse scans. For the (*MFW*/2) pixels at the ‘edges’ of the data line where a median filter cannot be applied, maintain their current values.

2. For each ‘valid’ pixel between (*MFW*/2) and *n*-(*MFW/2*), calculate the ‘spike height’ *A*, which is the absolute value of the difference between the current pixel value, X_i, and the current median filter value *MFV* within the median filter window:

$$A_i = |X_i - MFV| \tag{1}$$

3. For each ‘valid’ pixel between (*MFW*/2) and *n*-(*MFW*/2), calculate the amount of variation, *B*, between the along-scan nearest neighbors of the current pixel, which is the absolute value of their difference:

$$B_i = |X_{i+1} - X_{i-1}| \tag{2}$$

4. Calculate a threshold value, *E*, as follows:

    a. If B_i is more than twice the detector noise level value, then

    $$E_i = \frac{INThresh * B_i}{2 * NL} \tag{3a}$$

    b. If B_i is less than or equal to twice the detector noise level value, then

    $$E_i = INThresh * NL \tag{3b}$$

5. If $A_i > E_i$, an IN pixel has been detected. Record the pixel coordinates and the IN pixel value in the LMASK. Record the pixel coordinates and values of all IN-affected pixels, the values of the nearest neighbor pixels, and the total count of all IN-affected pixels in the database. In the current implementation, pixels identified as IN are flagged with a “2” in the LMASK.

8.8 Issues

None

8.9 References

None

Section 9 LMASK-Saturated Data Detection

9.1 Introduction

This algorithm flags pixels in daytime L0R image data that have DN values previously determined as Analog / Digital (A/D) 'saturated.' The locations and DN values of these pixels should be recorded in the LMASK, allowing their exclusion from further radiometric processing / analysis, if desired.

9.2 Background

Three types of saturation artifacts may be observed in satellite imagery.

"A/D" Saturation. The analog input signal represents a radiance level outside the range that the detector's A/D converter(s) can properly process. The result is that the corresponding digital output is set to 0 DN at the lower end and (2^N-1) DN at the upper end, where N (= 8 for TM) is the signal quantization in bits. To avoid erroneous results in any radiometric analysis, these data values should be flagged for exclusion. For ETM+, A/D low- and high-saturated pixels have been historically flagged in the LMASK with values of "4" and "8," respectively. To maintain consistency, this convention is continued for TM.

"Analog" Saturation. The A/D converter saturates at a level below (2^N-1) DN at the upper-end and/or above 0 DN at the lower-end. This condition can be determined from histogram analysis. To avoid potentially erroneous results in radiometric analysis, these data values can be flagged for exclusion (in LMASK, "16" for low and "32" for high analog saturation).

Saturation artifacts produced when the analog electronic 'chain' (i.e., pre-amplifiers, amplifiers, and other analog elements) between the detector and the A/D converter as a whole saturate at a radiance level below (2^N-1) DN at the upper-end. This saturation artifact has not been observed in Landsat TM and ETM+ imagery.

Note: This algorithm flags pixels meeting a previously defined criterion (i.e., default values of 0 DN for lower-end A/D saturation and 255 DN for upper-end A/D saturation). 'Thresholds' for analog saturation are obtained either from prelaunch measurements or on-orbit characterization using histogram analysis or other techniques.

9.3 Inputs

- Non artifact-corrected L0R daytime image data (floating point)
- Non artifact-corrected L0R nighttime image data (floating point)
- Non artifact-corrected L0R IC data (floating point)
- LMASK (generated earlier in the process flow to record instances of dropped lines and impulse noise)

9.4 Outputs

- LMASK

    - Pixel locations of detected A/D saturation artifacts in image and IC data (integer)
    - Flag values representing lower-end / upper-end A/D saturation artifacts in image and IC data (integer)

- Output report for each band detailing total counts and relative percentages of A/D saturation artifacts in image data and IC data by detector

9.5 Algorithm

Ignoring pixels flagged in the LMASK as IN or dropped lines, perform the following steps on the input data:

1. Search the input data for low A/D saturation (i.e., 0 DN) and flag each detected pixel in the LMASK with a value of "4."
2. Search the input data for high A/D saturation (i.e., 255 DN) and flag each detected pixel in the LMASK with a value of "8."
3. Maintain a count of low- and high-saturated pixels for each detector.
4. Maintain a count of low- and high-saturated pixels per band.
5. Calculate the relative number of saturated pixels by detector (relative to the band average).

9.6 Issues

None

9.7 References

USGS/EROS. LS-IAS-02. Landsat 7 (L7) Image Assessment System (IAS) Radiometric Algorithm Theoretical Basis Document (ATBD). Version 1.0. June 2003.

Section 10 Scan-Correlated Shift Correction (L5-TM)

10.1 Introduction

This algorithm corrects the Scan-Correlated Shift (SCS) artifact observed in reflective band (i.e., Band 1-5 and Band 7) L5 TM image and calibration data; as currently implemented, the thermal information in Band 6 is neither characterized nor corrected. Extensive historical analysis of sequential night scene bias data resulted in a set of time-independent correction parameters designed to compensate for the two bias states observed in the L5 TM instrument. Development of a time-dependent parametric model is anticipated as data are processed through the IAS, and will be evolutionary in nature as additional SCS characterization analyses and modeling are performed.

10.2 Background

SCS is a sudden, random change in bias level that occurs, for all detectors, within a short time interval between active scans when no data are acquired. This action results in a ‘pseudo-constant’ bias level for each scan of image and calibration data. Historical investigation identified two bias states for the L5 TM, in contrast to four states identified for the L4 TM. Although all detectors change state at the same time in a ‘phase-locked’ manner, they do not necessarily begin in the same state, nor do they change to the same state. In other words, some detectors change from the ‘low’ state to the ‘high’ state, while other detectors change from the ‘high’ state to the ‘low’ state. If the operational bias state of one or more ‘reference’ detectors can be accurately determined, then the bias state of the remaining detectors can be inferred. When comparing a single detector to a reference, the terms ‘in-phase’ and ‘out-of-phase’ indicate the direction of correlated shift.

Helder, et. al estimated detector-specific SCS correction magnitudes for the L5 TM from an analysis of 27 consecutive night scenes acquired on October 21, 1985, based on a unique reference detector (Detector 1 of Band 2). Historical and recent investigations indicate that these magnitudes are stable over time, in that the difference in average DN values for each state does not appear to be time-dependent. Consequently, other detectors operating in-phase with Detector 1 of Band 2 (such as Detector 7 of Band 7) may be utilized as alternate or supplemental references to determine the operational bias state of the phase-locked system. If out-of-phase references are selected, the SCS magnitude corrections may be incorrectly applied, potentially accentuating the artifact. To support out-of-phase reference detector usage by a Calibration Analyst, the IAS user interface implementation should support a phase toggle selection. This toggle is nominally set to in-phase, with the run status saved to the database along with the reference detector utilized.

While confirming that the average state DN values for each state were constant over time, the recent analysis suggested that the absolute DN values for each state were increasing over time. The scan state implementation method implemented in IAS R8.0 accounts for this assumed linear change in absolute bias levels, upon which the dual bias states are superimposed. The CPF information triggers the phase toggle, and logically toggles the high-low states of the SCS state mask. Thus, an out-of-phase reference can emulate a mask normally produced by an in-phase reference detector.

10.3 Inputs

- Unprocessed reflective band image data (floating point)
- Unprocessed reflective band calibration data (floating point)
- LMASK

10.4 Parameters Obtained From the CPF

Application of the SCS correction algorithm to Scan Angle Monitor (SAM) and bumper mode data requires inputs read from the CPF for the following parameters:

- *bias_slope* (floating point) Slope of lifetime linear bias model.
- *bias_offset* (floating point) Offset of lifetime linear bias model at *testdata_DSL.*
- *testdata_DSL* (integer) Days since launch of the (1985, night-27) test data.
- *high_delta* (floating point) Upper control limit on average bias variation.
- *low_delta* (floating point) Lower control limit on average bias variation.
- reference band (integer)
- reference detector (integer)
- SCS amplitude (floating point)

The relevant parameters can be extracted from various CPF entries as defined in the following example for a Band 7 Detector 7 reference:

GROUP = SCAN_CORRELATED_SHIFT
SCS_Reference_Detector_1 = (7,7,1)
SCS_Reference_Detector_2 = (7,7,1)
SCS_Reference_Detector_3 = (7,7,1)
SCS_State_Mask_Parameters = (0.000007113387, 601, 2.15, 0.05, 0.05)
B1_SCS_Magnitudes = (1.1569804e-02,-1.5625911e-01,3.2996424e-02,-1.1304116e-01,1.4710412e-02,-1.6058411e-01,7.2760472e-02,-1.2827364e-01,1.8843410e-02,-3.3344272e-01,1.8333317e-02,-1.9159730e-01,-3.9324667e-02,-3.4885825e-01,-3.9938065e-02,-2.5303062e-01)
B2_SCS_Magnitudes = (7.2098294e-01,3.7425930e-02,3.6839192e-01,-5.9152038e-02,2.5968120e-01,8.3694987e-02,2.8259830e-01,9.5723345e-02,1.6736335e-01,1.2281209e-02,2.2465824e-01,3.5409573e-02,3.6006368e-01,1.6311572e-01,3.0721359e-01,6.7545385e-01)
B3_SCS_Magnitudes = (5.2192020e-01,1.3320758e-01,5.4508526e-01,4.0118462e-01,4.0680130e-01,5.6667455e-01,3.1066546e-01,1.7622443e-01,4.7273162e-01,3.3055915e-01,4.6439925e-01,3.9249319e-01,3.6471880e-01,2.7372833e-01,3.8050369e-01,2.4974505e-01)
B4_SCS_Magnitudes = (4.4828032e-01,8.9812094e-02,7.5109591e-02,2.4592970e-01,3.4749578e-02,8.6333297e-03,1.4461188e-02,-3.4450797e-02,6.4423982e-02,-1.6255673e-04,7.4066195e-02,-1.4154289e-02,1.5053092e-01,-1.4437600e-02,3.8741075e-02,-9.7693635e-02)

B5_SCS_Magnitudes = (1.7000721e-01,-1.6055916e-02,2.4704872e-01,-5.2022618e-02,-5.3244174e-02,-1.4390805e-01,8.3640852e-02,-1.3654846e-01,1.0964904e-01,7.5864344e-02,1.2969957e-01,-1.5621545e-01,6.0418422e-02,-9.2451386e-02,-7.0901081e-02,-1.5514363e-01)
B6_SCS_Magnitudes = (0.0,0.0,0.0,0.0)
B7_SCS_Magnitudes = (7.1424251e-02,-6.9256432e-02,-2.3865368e-02,-1.7026510e-01,5.1228012e-02,-1.5863398e-01,2.6906569e-01,-2.4568812e-01,2.1776210e-01,-2.4221505e-01,1.6413804e-01,-1.1843650e-01,8.0542090e-02,-8.8635934e-02,7.5825711e-02,-1.5623075e-01)
END_GROUP = SCAN_CORRELATED_SHIFT

For the subentries *SCS_Reference_Detector_X* (X=1, 2, 3), the first number represents the reference band, the second number represents the reference detector, and the third number represents the phase relationship to Detector 1 of Band 2—a '1' indicates the reference is in-phase, while a '-1' indicates the reference is out-of-phase. For the sub-entry *SCS_State_Mask_Parameters*, the first and third numbers represent the estimated slope and intercept, respectively, of a linear model of the bias state (obtained through regression analysis). The second number represents the Days-Since-Launch (DSL) of the 27-scene 1985 data set. The fourth and fifth parameters represent, respectively, the high and low 'delta' values determine a 'valid' range of detector bias levels.

For the typical processing scenario involving SCS correction of scenes acquired during the day, the default reference detector should be set to Detector 7 of Band 7. This information is immune to corruption from the Memory Effect (ME) artifact that has long been observed to affect the detectors in Bands 1-4.

10.5 Outputs

- SCS-corrected reflective band image data (floating point)
- SCS-corrected reflective band calibration data (floating point)
- SCS scan bias states are recorded in the database L0R_SCS_Scan table

10.6 Algorithm

1. Calculate the average reference detector bias level for each scan of the input scene / sub-interval from the shutter region of the uncorrected calibration data. Data samples flagged in LMASK as being IN should be excluded from the data population used to compute average shutter bias.
2. Calculate the average reference detector bias level over the entire input scene / sub-interval. This is the mean value of the reference detector bias levels obtained in step 1.
3. Using the *SCS_State_Mask_Parameters* values obtained from the CPF, calculate the following DSL-specific threshold values representing the 'nominal' bias level and the maximum and minimum limits on the estimated bias level:

$$t_{mDSL} = bias\_slope \times (DSL - testdata\_DSL) + bias\_offset \quad \text{(1a)}$$

$$t_{hDSL} = t_{mDSL} + high\_delta \tag{1b}$$
$$t_{lDSL} = t_{mDSL} - low\_delta \tag{1c}$$

The CPF values are tightly coupled to a single reference detector, and should not be expected to work for an arbitrary reference detector. Hence, although out-of-phase reference detectors are allowed within the logic and CPF, it is doubtful they will be used.

4. Generate the SCS state mask for the input scene / sub-interval from the following tests. The expression 'mean' represents the average shutter-region bias value for the reference detector across the entire input scene / sub-interval calculated in step 2, and the expression 'avgs[scan]' represents the average shutter-region bias value for the current scan of the input scene / sub-interval calculated in step 1. The expression 'State[scan]' represents the estimated SCS state of the current scan given as '0' for the 'high' state and '1' for the 'low' state.

    a. IF((t_{lDSL} < mean) AND (mean < t_{hDSL}) AND (avgs[scan] < mean)) THEN State[scan] = 1
    b. IF((t_{lDSL} < mean) AND (mean < t_{hDSL}) AND (avgs[scan] >= mean)) THEN State[scan] = 0
    c. IF((mean <= t_{lDSL}) OR (mean >= t_{hDSL}) AND (avgs[scan] < t_{mDSL})) THEN State[scan] = 1
    d. IF((mean <= t_{lDSL}) OR (mean >= t_{hDSL}) AND (avgs[scan] >= t_{mDSL})) THEN State[scan] = 0

    Tests 4(a) and 4(b) compare the scan-based shutter-region bias estimate to the scene / sub-interval estimate for the reference detector. In general, these tests are applicable to SAM mode data. Tests 4(c) and 4(d) are called if tests 4(a) and 4(b) fail due to the estimated reference detector bias level falling out of the 'valid' range defined by t_{lDSL} and t_{hDSL}. In general, this situation occurs with bumper mode data.
5. Based on the CPF phase-toggle variable, logically flip the state mask if necessary.
6. For those scans determined to be in the 'low' SCS state (based on the reference generated state mask), add the appropriate SCS correction factors for each detector to the corresponding input image and calibration data. The correction factor is a signed number, with positive values indicating an in-phase correction, and negative values indicating an out-of-phase correction. All phase information is with respect to the selected reference detector. If the reference detector is already in the 'high' state for a given scan, no corrections are applied to any data from the other detectors within that scan.

10.7 References

D. Helder et al. Short Term Calibration of Landsat TM: Recent Findings and Suggested Techniques. IGARSS '96. May 27-31, 1996. Lincoln, Neb.

M.D. Metzler and W.A. Malila. Characterization and Comparison of Landsat-4 and Landsat-5 Thematic Mapper Data. Photogrammetric Engineering and Remote Sensing. Vol. 51, No. 9. pp. 1315-1330.

Helder, D.L, Ruggles T.A. Landsat Thematic Mapper Reflective-Band Radiometric Artifacts. IEEE Transactions on Geoscience and Remote Sensing. Vol. 42, No. 12. December 2004. pp. 2704-2716.

Section 11 Scan-Correlated Shift Correction (L4-TM)

11.1 Introduction

The correction algorithm discussed herein corrects L4 TM reflective band data (image and calibration file) for sudden bias shifts (up to two DN in magnitude). These bias level shifts (characterized into four unique levels or states) are assumed to be random, phase locked for all detectors, occur during the scan mirror turnaround interval, and persist throughout the duration of a scan.

11.2 Background

As compared to two bias states in L5 TM, historical investigation shows that four bias states exist for L4 TM data sets (Metzler and Malila, 1985). To discriminate four SCS states, two reference detectors are chosen, each of which has a high and low bias state (relative to a threshold defined by the reference detector scene level shutter bias mean). Historical studies show that some detectors exhibit clearly separated and stable bias levels. For the correction algorithm implemented in the IAS, Band 1 Detector 4, and Band 5 Detector 10 establish the four bias states exhibited by the TM sensor. The bias level phase relationships between the detectors are thought to remain constant in all images. Band 7 Detector 7 is a good alternative to the reference detector Band 5 Detector 10. Similarly, Band 1 Detector 8 and Band 1 Detector 12 are also good alternatives to the first reference detector (i.e., Band 1 Detector 4).

SCS characterization was initially performed in 1985, resulting in a set of SCS magnitude estimates obtained using one scene [1]. Helder, et. al. later estimated detector-specific SCS correction magnitudes for L4 from multiple scenes [2]. An investigation based on processing 20 contiguous night scenes from the 4120205008303710 interval to the 4120205008303710 interval resulted in the updated CPF SCS amplitude factors used in the IAS.

11.3 Inputs

- L0R day and night images and calibration data (floating point)
- LMASK

11.4 Parameters Obtained From the CPF

For a complete set of current values, refer to CPF. Sample CPF numbers and the Object Description Language (ODL) format are shown in the following for reference.

GROUP = SCAN_CORRELATED_SHIFT
SCS_Reference_Detector_1 = (1, 4, 1)
SCS_Reference_Detector_2 = (5, 10, 1)
SCS_Reference_Detector_3 = (0, 0, 0)
B1_SCS_Magnitude_LL-LH = (1.85050e-01, 1.74160e-01, 1.44980e-01, -1.02070e-01,
1.61400e-01, 4.37700e-02, 9.31100e-02, 1.02260e-01, -2.73000e-02, 5.19400e-02,
8.14500e-02, 1.36900e-02, 5.09000e-02, 1.024600e-01, 7.59900e-02, 8.75900e-02)

B1_SCS_Magnitude_HL-LH = (4.3742e-001, 1.6449e-001, 2.1753e-001, 1.7537e+000,
2.7651e-001, 9.5620e-002, 1.8624e-001, 6.7883e-001, 1.1108e-001, 9.2173e-001,
2.4288e-001, 1.6298e+000, 3.4915e-001, 1.8622e-001, 2.3190e-001, 6.8420e-002)
B1_SCS_Magnitude_HH-LH = (2.5066e-001, -2.9820e-002, 8.1310e-002, 1.8579e+000,
1.1249e-001, 4.1480e-002, 8.3570e-002, 5.6983e-001, 1.3665e-001, 8.5401e-001,
1.5290e-001, 1.5843e+000, 2.9142e-001, 7.9250e-002, 1.4548e-001, -2.7110e-002)

Three SCS magnitudes exist for each detector of each band. Because 'low-high' is regarded as the correct state, each of these three SCS magnitudes correspond to the SCS correction factor for one of the remaining three SCS states with respect to the low-high state.

11.5 Outputs

- SCS corrected day and night reflective band images and calibration data (floating point)
- SCS scan bias states are recorded in the database L0R_SCS_Scan table

11.6 Algorithm

1. Assign Band 1 Detector 4 as the first reference detector and Band 5 Detector 10 as the second reference detector.
2. Calculate the reference detector's average bias level for each scan of the input scene from the shutter region (middle 550 samples) of L0R calibration data. Data samples flagged in LMASK as artifacts should be excluded from the data population when computing the reference detector scan averages.
3. Calculate the reference detector's mean bias over the entire input scene. To perform this step, take the mean of all valid average bias values from all scans as computed in step 2 for each reference detector.
4. To generate the state mask, use the mean bias value computed in step 3 for each reference detector. The value assigned to the state mask is one of the SCS states:
   i. '0' represents the 'low-low' state
   ii. '1' represents the 'low-high' state
   iii. '2' represents the 'high-low' state
   iv. '3' represents the 'high-high' state

   ref1_avgs[scan] represents the average value of the shutter bias region of the first reference detector for the given scan as computed in step 2 and ref1_mean[scan] represents the mean of the entire scene for reference Detector 1 as computed in step 3. Similarly, ref2_avgs[scan] and ref2_mean[scan] correspond to the second reference detector.

   The following are the four tests performed to estimate the four states:

a. if((ref1_avgs[scan] < ref1_threshold) && (ref2_avgs[scan] < ref2_threshold))
   State[scan] = 0;
b. if((ref1_avgs[scan] < ref1_threshold) && (ref2_avgs[scan] > ref2_threshold))
   State[scan] = 1;
c. if((ref1_avgs[scan] > ref1_threshold) && (ref2_avgs[scan] < ref2_threshold))
   State[scan] = 2;
d. if((ref1_avgs[scan] > ref1_threshold) && (ref2_avgs[scan] > ref2_threshold))
   State[scan] = 3;

All four tests compare the average bias estimate of the scan-based shutter-region to the threshold (mean shutter bias estimate of the entire scene) of the entire scan-based shutter region for two reference detectors.

The historical investigation by Helder, et. al. suggests that the “low-high” SCS state is the optimal target bias state, resulting in detector bias levels (after SCS correction) that are within the nominal dynamic range (i.e., the data typically does not assume negative values or exceed the upper saturation level for any detector). The SCS correction is applied to image and calibration data for scans determined to be in the “low-low”, “high-high” and “high-low” states by subtracting the respective CPF differential amplitude factors from the data, thus forcing all scan bias levels to the “low-high” state.

For the L4 TM sensor, the IAS database SCS table records bias state information in the following format:

i. ‘-1’ represents the ‘low-low’ state
ii. ‘2’ represents the ‘low-high’ state
iii. ‘0’ represents the ‘high-low’ state
iv. ‘1’ represents the ‘high-high’ state

Note 3/30/2009: In keeping with the philosophy established for L7 and L5, the SCS correction algorithm as implemented in R9.0 “adds” the CPF SCS correction factors rather than subtracting them for L4 TM as discussed. The “subtraction” is implemented as a ± sign change for all L4 TM SCS CPF correction factors, rather than as a subtraction in the code.

11.7 References

Metzler, M.D. and Malila, W.A., "Characterization and Comparison of Landsat-4 and Landsat-5 Thematic Mapper Data," Photogrammetric Engineering and Remote Sensing, Vol. 51, No. 9, September, 1985, pp. 1315-1330.

D. Helder et. al., “Landsat Thematic Mapper Reflective-Band Radiometric

Artifacts", IEEE Transactions on Geoscience and Remote Sensing, Vol. 42, No. 12, December 2004, pp. 2704-2716.

Section 12 Coherent Noise (CN) Characterization

12.1 Introduction

The TM instruments exhibit complex and dynamic noise effects that often intercouple with other artifacts and system states (i.e., SCS, mirror scan direction, etc.). The following discussion details IAS algorithms and system requirements to study the assumed coherent (i.e., frequency locked or pseudo-locked) sinusoidal noise components in TM reflective imagery and calibration shutter data, via Fast Fourier Transform (FFT) analysis. Three stages of analysis are implemented as follows:

1. Generate the FFTs from L0R data
2. Analyze L0R FFT information to determine average spectral peak locations for a scene based on both night image and day / night calibration data
3. Track drifting frequency components, based on the analysis of night image data

Significant results are stored in the IAS database to allow subsequent trending analysis, and summary results are written to Coherent Noise (CN) Report Files. In addition, the capability is provided to output extensive L0R raw FFT data (thus allowing the analyst to further investigate complex noise scenarios outside the IAS environment).

12.2 Inputs

- L0R night image data (floating point)
- L0R day and night calibration data (floating point)
- LMASK
- SCS State Mask (derived from the SCS Correction algorithm, IDSCSState processing module)

12.3 Inputs from CPF

- GROUP = CHAR_CN_FFT_GENERATION
    Forward_Scan_IC_Offset = 23
    Reverse_Scan_IC_Offset = 25
  END_GROUP = CHAR_CN_FFT_GENERATION

  Note: The CPF parameters listed can be over-ridden by a work order parameter (CHAR_CN_IC_OFFSETS = [fwd, rev]) at the time of the work order creation. Positive values override the CPF defaults.
  Starting with R9.1, the reverse scan offset is not utilized.

12.4 Optional Output Products

- L0R FFT normalized amplitude and phase data (floating point, non-Hierarchical Data Format (HDF))

12.5 Process Flow Considerations

The CN analysis routine discussed herein occurs logically at several unique locations in the process flow. First, the FFTs are generated from L0R data immediately before SCS Correction. Next, the Scene Average calculations are performed after the SCS Correction, thus allowing the SCS State Mask to sort the results. Finally, the Frequency Tracking calculations are performed on night image data after the Scene Average results are known, allowing the Scene Average spectral information to initialize search parameters. In summary, once the L0R FFTs are generated and the SCS State Mask is available, all CN Characterization processing occurs outside the primary data product flow in IAS. Because the CN Characterization processing does not modify the image and calibration file products, ME Characterization / Correction and subsequent processing are not dependent on the completion of the Average Spectral Processing or Frequency Drift Analysis.

12.6 FFT Generation

The IAS generates normalized 4096-point Fourier Transforms from L0R imagery for each of the 96 Band 1-5 and Band 7 detectors present in the TM sensor. For characterization analysis, it is anticipated that only night scene image data will be utilized, along with both day and night shutter bias data from the calibration file. When selecting the appropriate night image region for each scan, the center 4096 valid minor frames of each scan are utilized, wherein valid data are defined as those falling within the boundaries of the left- and right-side telemetry codes contained in the LACS L0R image files. Similarly, the IAS generates radix-2 512-point FFTs for each detector in the system based on night and day shutter bias data. The 512-point regions are selected to avoid encountering the calibration pulses, and a dual line artifact present on the left side of the calibration file, as shown in Figure 12-1. Failure to avoid the two vertical lines results in an undesirable ringing effect in the FFT amplitude data, as shown in Figure 12-2; care must be taken to ensure the proper region is selected. The rxx_get_dark_region function, along with CPF pulse offset parameters and an optional work order override, control the location of the 512 samples extracted from the calibration file.

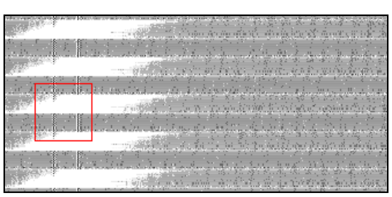

Figure 12-1. Dual Line Artifact

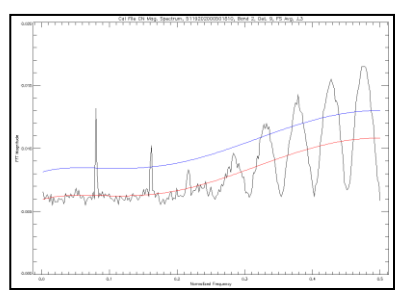

Figure 12-2. Resulting FFT Ringing

The resulting L0R FFT values for amplitude are scaled in a normalized fashion. Assuming implementation is via the GNU Scientific Library (GSL), radix-2 function calls for processing real data, the amplitude data returned from the subroutine needs to be scaled by 4096 or 512, respective of the data, source to achieve proper normalization. Using the LMASK is limited during this processing, and is only used to skip dropped lines. FFT output products have the dropped lines / scans zero filled for both amplitude and phase. The IAS supports output of the FFT amplitude and phase information into flat data files in a floating point format. By default, generation of these output products for use external to the IAS is disabled unless selected during work order generation. The output files, if generated, contain normalized FFT amplitude and radian phase information, in scan sequence, for individual detectors. Amplitude and phase file specifications include 4096x5984 for the image FFT, 512x5984 for the cal-shutter FFT, and are stored as double precision floating point values.

Because the windowed regions are anticipated to move within the total data volume of a scan, a reference location is recorded in an attempt to establish a physical spatial / temporal reference for FFT phase information. Ideally this reference is absolute, and maintains the same representation from scan to scan. Uncertainty exists in the optimal way to establish this reference; however, the R8.1 IAS implementation saves to the IAS database on the left location of the FFT windows, with respect to the left SLO location (i.e., the left side of “valid” scan data) for calibration file analysis. Similarly, for night image FFT windows, the left SLO location serves as the zero reference for storing the beginning sample number of the window subset. In order to maintain consistent phase results for both forward and reverse scan FFT calculations, the reverse scan image data must be flipped end-to-end to orient the data time sequence consistent with forward scan image data. In processing the calibration file scans, no data sequence flipping is required, as both forward and reverse scan bias information are stored in the file in the same time order (i.e., advancing time from left to right).

When selecting the 512 point IC regions from the calibration file, the starting locations are defined by the following equations and incorporate CPF parameters:

Forward_Scan_IC_Offset and Reverse_Scan_IC_Offset to allow some adjustment of the region location, if necessary, to avoid systematic artifacts in the IC data.

F_start = (Pulse Center) – ((Pulse Width)/2) – (Forward_Scan_IC_Offset) – IC_FFT_Size

R_start = (Pulse Center) + ((Pulse Width)/2) + (Reverse_Scan_IC_Offset)

12.7 Average Spectral Amplitude Processing

After the SCS correction module of the process flow is complete, the SCS state mask is available for use in subsequent analysis. For the CN characterization routine, the SCS state mask, along with mirror scan direction and the detector number, form the fundamental parameter set used to sort the L0R-derived FFT data and extract meaningful information regarding system noise. The Average Spectral Processing routine creates average amplitude spectra for each detector and each scan direction, broken down by two SCS bias states for L5 TM (and four SCS bias states for L4 TM). The resulting set of average spectra (L5:384, L4:768) is produced after scans have been removed that are known to contain Dropped Lines, Saturated Data, and IN, as flagged within the LMASK. Computations are performed on both the night image (4096 point FFTs) and night / day calibration shutter (512-point FFTs) derived data sets. The resulting number of average spectra produced for a typical night scene total L5:768, L4:1536, and for a typical day scene total L5:384, L4:768. No computations are performed using the phase information as part of the Average Spectral Processing data reduction. The IAS database record retains a count of the number of valid scans used to create each averaged spectra.

Once the average amplitude spectra are available, automatic identification of spectral peaks rising above the noise floor is attempted. The following processing steps are applied: median filter, noise floor characterization, threshold determination, and determination of the noise frequency corresponding to each significant spectral peak detected. Elaborating the first processing step applies a one-dimensional median filter (default length of seven samples, user adjustable in odd increments from 5 to 13 samples during work order generation) to each average spectral profile. This processing effectively removes the peaks, leaving a smooth noise floor. The noise floor characterization step performed next uses a polynomial function created via linear regression (explicitly removing the 0-frequency term) of the median filtered noise floor amplitude data. The fit parameters (slope, intercept, R^2, 1-σ) are saved to the IAS database (referenced to band and detector number, along with SCS state, and scan direction) to allow later analysis. It is anticipated that the noise floor amplitude is dependent on both SCS bias state and scan direction. The significant CN noise components, and 0-frequency term, are also believed to vary in amplitude with respect to the noise floor as a function of the SCS bias state. The next computational step creates a threshold used to search for spectral peaks. This threshold is defined as the sum of the noise floor function, and PeakStdDev (default value of 5; adjustable during work order creation from 1 to 10) times the standard deviation of the smoothed noise floor data after a linear frequency dependent trend is removed (i.e., the noise floor function is subtracted from the median filtered data). **Note:** This method was implemented in IAS R9.1. The detection threshold is the noise floor linear regression function shifted upwards by 5σ. Next, the spectra data points exceeding the detection threshold are identified. Figure 12-3 presents a typical result.

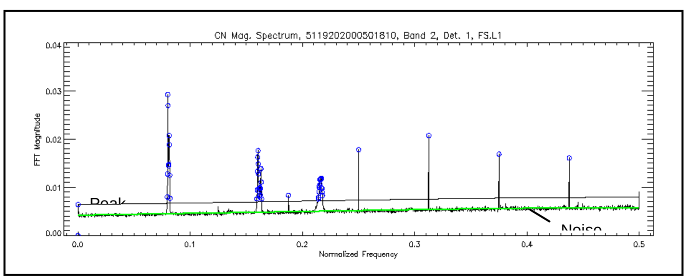

Figure 12-3. Thresholded Spectra

The next processing step decides where each peak is located and determines the corresponding frequency of up to 10 peaks, in order of descending amplitude. The resulting frequencies (in units of Hertz (Hz)) are recorded to the IAS database and CN Report File.

The IAS logic searches the average spectra profiles (neglecting the 0-frequency term) for consecutive samples that exceed the detection threshold (i.e., noise floor), and attempts to cluster the data into windows that have, at most, [MaxPkGap=1] gaps (i.e., below threshold samples) in the consecutive pattern. The MaxPkGap parameter (in effect a detection sensitivity parameter) is set to a default value of 1, but is adjustable in a range from 1 to 5 during work order creation. Examples include the following:

<u>…….</u> No spike detection
<u>…|…</u> Single spike detection
<u>.||.|…</u> Three spikes in a pseudo consecutive sequence, containing < MaxPkGap=1 gaps, hence considered one peak
<u>.||..|..</u> Three spikes are considered two unique spectral components because the gap > MaxPkGap=1

Once the spectra profile decomposes into windowed groups (defined by the left and right frequency boundaries in the consecutive pattern), each region is examined to determine the following parameters: maximum normalized amplitude value, frequency (in Hz) corresponding to maximum amplitude location, minimum and maximum frequencies (in Hz) corresponding to the edges of the window, and the value of the noise floor at the maximum peak location (computed from the noise floor regression function). The ten resulting data sets with the most significant normalized amplitude values (above the noise baseline) are stored to the IAS database (Note: Fewer than ten resulting detections may exist, depending on the detector under analysis), and detailed in the CN Report File. For each scene averaged spectra, the average normalized amplitude of the 0-frequency term is stored to the database, and listed in the CN Report File. IAS reported frequency values assume the Instantaneous Field Of View (IFOV) dwell time for each pixel is held constant at 9.611 µsec throughout the lifetime of the instrument. The corresponding frequency resolution (i.e., bin increments) is 203.218 Hz and 25.402 Hz, respectively, for 512 and 4096 point transformations.

Note: Beginning with IAS R9.1, the peak search algorithm skips the first 20 FFT bins in the IC-based transform data in order to avoid a pulse induced low frequency sync function often mischaracterized as CN. This frequency filter effectively disables any search of CN peaks below 4064 Hz. During R9.1 system test, the night scene based analysis was also modified to establish a low frequency cutoff (bin 20, ~508 Hz) similar to what was implemented for the IC data. The cutoff frequencies are tentative and subject to future change.

Following the completion of the Average Spectral analysis, the IAS generates graphs, similar to that shown in Figure 12-4. These graphs present summary information about detected CN frequencies for each band and SCS state for both image and calibration file derived results. The resulting graphs are output by default to the current IAS work order directory (this capability may be disabled at the time of work order creation). The frequency axis should be scaled in units of Hz, with 16 detectors represented on the vertical axis. Both forward and reverse scan data are plotted for a single SCS bias state in a single graph for the reflective bands.

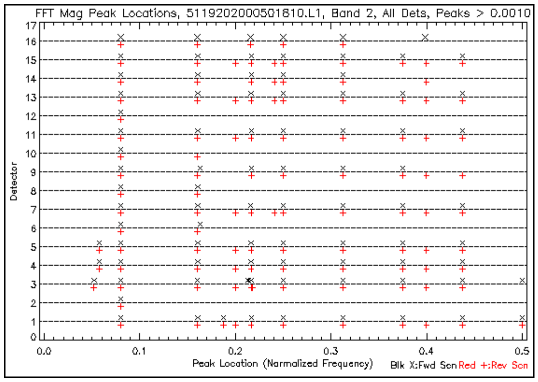

Figure 12-4. CN Component Peak Locations for Landsat 5, Band 2

12.8 Frequency Drift Analysis

CN is typically thought of as having one or more locked frequency components that act in a superimposed sense with the acquired imagery and calibration data. In the case of Landsat instruments (specifically L5 TM), frequency components may drift slowly over time, and occasionally make rapid jumps from scan to scan. These effects are often only observable over long periods (typically multi-scene in duration), and appear to be fixed over the short term. The IAS CN Drift Analysis routine attempts to extract frequency drift information from the 4096-point FFT data (derived from night scene data) and record results to the IAS database and CN Report Files. The approach implemented, beginning in IAS R8.1, is outlined in the following.

First, the normalized spectral peaks detected during the Average Spectral Processing analysis are examined to see if the average absolute peak value is at least CN_Scale times the noise floor estimate at the frequency of interest (CN_Scale=2 by default, adjustable from 1 to 5 during work order creation). Spectral peaks meeting this criteria are then further processed to track potential frequency drift by creating an analysis window CN_Bins wide (CN_Bins=21 by default; adjustable in odd increments from 1 to 41 during work order creation) centered on the Average Frequency peak locations. For each scan, the window is exhaustively searched to determine the peak normalized amplitude location detected during the scan. If the window width intrudes into an adjacent spectral spike window (as determined by the minimum and maximum frequency boundaries determined during the Average Spectral Processing), then the window is dynamically reduced in size (one-sided or two-sided nonsymmetrical reductions are possible) to contain the exhaustive search to a region extending 50 percent of the frequency range to the adjacent window edge. Once the spectral peaks are localized for each scan, the frequency estimates and peak amplitudes are recorded into the IAS database and CN Report File along with the scan number, scan direction, and SCS bias state. In addition, the search window widths utilized for each peak are recorded in the database and noted in the CN Report File. Additional summary information is also computed and stored as follows: minimum frequency, maximum frequency, and a histogram of scan-to-scan frequency jumps, for each spectral spike studied.

An assumption is made during this analysis that the “significant” CN noise components are present during all scan directions and SCS states. The L5 TM Drift Analysis routine is initialized by default with frequency spike events from the High SCS State, Forward Scan, and Average Spectral Analysis results for each detector. During L5 TM work order creation, the IAS supports options to select High SCS State-Reverse Scan, Low SCS State-Forward Scan, and Low SCS State-Reverse Scan as the Drift Analysis initialization. Selected scenes may not exhibit all SCS states; initialization frequency information may not be available for the analyst’s initialization choice. In this case, the IAS attempts to select another initialization by cycling through the options, which include High SCS-Forward Scan, High SCS-Reverse Scan, Low SCS-Forward Scan, and Low SCS-Reverse Scan. The IAS database and CN Report File indicates which option was ultimately used during the calculations. If no valid search initialization parameters exist, the IAS issues a warning and gracefully aborts the calculations. Similarly for L4 TM, the Drift Analysis routine is initialized with High-High SCS State, Forward Scan Average Spectral analysis results for each detector. During work order creation and potential initialization cycling discussed previously, the system allows a total of eight options, which include High-High Forward Scan, High-Low Forward Scan, Low-High Forward Scan, Low-Low Forward Scan, and High-High Reverse Scan, High-Low Reverse Scan, Low-High Reverse Scan, and Low-Low Reverse Scan. The IAS database and CN Report File indicate which options were ultimately used during the calculations.

12.9 Issues

None

Section 13 Memory Effect Characterization

13.1 Algorithm Description

This algorithm determines the parameters required to construct a convolution filter that corrects the ME artifact found in L4 / L5 TM data. This algorithm is intended to be implemented in two stages. The first processing stage is implemented within the IAS, and is intended to create detector-specific, scene-specific concatenated ‘profiles’ of forward scan IC data and reverse scan image data from SCS-corrected night scenes; these profiles are created for all IC lamp states for all reflective bands. The second processing stage is an offline analysis, and is intended to create and model a detector-specific ‘average’ calibration data / image data profile for a user-specified lamp state, obtained from the previously extracted scene-specific profiles for that lamp state. In the default processing scenario, profiles from lamp state [111] data are used in the modeling, as the ME characterization parameters were historically derived from this state. For the context of this document, only IAS stage 1 processing is discussed in detail.

13.2 Background

ME (also known as ‘Bright Target Recovery,’ ‘Bright Target Saturation,’ or ‘Scan Line Droop’) has been observed in TM image data since the launch of L4 in 1982. ME can be observed as alternating lighter and darker scans that are most prominent near significant changes in along-scan intensity, such as at cloud / water boundaries. The ‘source’ of ME has been traced to a first-order Resistor-Capacitor (RC) network within the detector pre-amplifier circuits, with a time constant of approximately 10 milliseconds (ms), directly corresponding to time constants of approximately 1100 pixels derived from the analysis of night scenes. Historically, ME has been the cause of significant errors in radiometric calibration, particularly because the magnitude of the effect is highly scene-dependent.

ME has been most visible in Band 1-4 imagery. In Band 5 and Band 7, Detector 16 and Detector 15 on reverse scans and Detector 2 and Detector 1 on forward scans have also been observed to exhibit an ME-like suppression and recovery of response in low DN regions. The character of these responses, however, differs from that observed in the primary focal plane detectors in that the recovery tends to be much faster (i.e., ~100 pixels instead of ~1100 pixels).

ME characterization is most easily accomplished for scenes in which the detectors are stimulated by known inputs and allowed to respond without further stimulus. Thus, only night scenes are used for ME characterization on L4 / L5, where the calibration pulse provides the known stimulus. Detector response from a single pulse is noisy; consequently, reasonable ME characterization uses an average of detector responses obtained from as many night scenes as possible.

13.3 Inputs

- Reflective band SCS-corrected L0R image data from night scenes (floating point)

- Reflective band SCS-corrected L0R IC data from night scenes (floating point)
- Starting scan indices for each lamp state, as determined with the IAS Internal Calibrator Pulse (IASICP) algorithm (integer)
- Detector-specific pulse width for each lamp state, as determined with the IASICP algorithm (floating point)
- User-specified maximum number of allowed impulse noise pixels for calibration data (integer)
- User-specified maximum number of allowed impulse noise pixels for image data (integer)
- LMASK information

13.4 Required CPF Information for IAS Processing

- Operable detector listing

13.5 Processing Outputs Trended to IAS Database

- Scene ID
- Worldwide Reference System-2 (WRS-2) row / path
- Scene acquisition date
- Detector-specific averaged 'profiles' comprised of forward scan calibration data and reverse scan image data (concatenated in time order) for all reflective bands of each night scene processed, for each lamp state (floating point)
- Number of valid scans used to construct each detector-specific profile (integer)
- Number of pixels used from each reverse scan image data for each band, for each lamp state (integer)
- Number of pixels used from each forward scan calibration data for each band, for each lamp state (integer)
- Number of maximum pixels truncated from a reverse scan image data for each band, for each lamp state (integer)
- Number of maximum pixels truncated from a forward scan calibration data for each band, for each lamp state (integer)
- Number of maximum shifted pixels to align detector profiles of all selected scans for each band, for each lamp state (integer)
- Band averaged summary statistics (mean and standard deviation) derived from image data, corresponding to each lamp state (floating point)

13.6 Reported Outputs

- Scene ID
- WRS-2 row / path
- Scene acquisition date
- Number of valid scans used to construct each detector-specific profile (integer)
- Number of pixels used from each reverse scan image data for each band, for each lamp state (integer)
- Number of pixels used from each forward scan calibration data for each band, for each lamp state (integer)

- Number of maximum pixels truncated from a reverse scan image data for each band, for each lamp state (integer)
- Number of maximum pixels truncated from a forward scan calibration data for each band, for each lamp state (integer)
- Number of maximum shifted pixels to align detector profiles of all selected scans for each band, for each lamp state (integer)
- Summary statistics (mean, standard deviation, and signal-to-noise ratio) derived from image data corresponding to each lamp state, for each night scene processed (floating point)

13.7 Algorithm

This algorithm requires knowledge of the starting scan indices for each lamp state, and an estimated IC pulse width for each detector. This information is assumed available from the IAS database through running the IASICP (IASICP_RPS1) algorithm prior to performing the first-stage characterization processing for each scene. In addition, this algorithm is intended to run only on 'complete' scenes (those scenes with the full number of image and calibration data scans).

This algorithm performs characterization in two stages. The first stage generates and trends detector-specific 'profiles' comprised of forward scan calibration data and the following reverse scan image data, concatenated in time sequence, from each night time SCS-corrected scene. To generate these profiles, perform the following steps for each lamp state:

1. Locate the first 'complete' occurrence of the lamp state data. This occurrence ensures that data for the same lamp state are not duplicated between consecutive scenes. The number of consecutive scans for each 'complete' lamp state in a typical TM lamp sequence are defined as follows: LS [000] -- 43 scans; LS [100] -- 40 scans; LS [110] -- 37 scans; LS [010] -- 43 scans, LS [011] -- 40 scans; LS [111] -- 37 scans, LS [101] -- 40 scans; LS [001] -- 40 scans.
2. Skip the first five to six calibration data scans from the desired lamp state (from the starting scan) to exclude those scans most potentially corrupted from transient effects resulting from turning on/off an individual lamp.
   Note: The previous IASICP processing identified and recorded 'Transition' scans that indicate changes between lamp states, with a flag value of '1' indicating a transition scan and '0' indicating a non-transition scan. To maintain consistency with historical analysis of calibration data, the IASICP algorithm identifies the first 12 scans and the last 4 scans of calibration data as transition scans. For the purpose of this characterization, skipping the first five to six scans should minimize any transient effects.
3. Starting from the first forward scan after the first 5 to 6 skipped scans, extract the next 30 scans of calibration data and image data (15 forward scans of calibration data and the corresponding 15 reverse scans of image data). Check for and exclude 'corrupted' scans (i.e., those scans where any of the following conditions occur):

a. The pulse width for a detector, as determined from the IASICP algorithm applied to L5 TM data, is less than 40 pixels or greater than 55 pixels for Bands 1, 2, 3, and 7, and less than 30 pixels or greater than 55 pixels for Bands 4 and 5. This check should only be applied to non-LS [000] data.
b. Dropped lines are determined from earlier LMASK processing. More total impulse noise artifacts, as determined from earlier LMASK processing, exist in the forward scan calibration data than the maximum number specified by the user. A default value for an allowed number of impulse noise pixels in the calibration data should be set to 10, with a user-selectable range from 0 to 20.
c. More impulse noise artifacts, as determined from earlier LMASK processing, exist in the reverse scan image data than the maximum number specified by the user. A default value for an allowed number of impulse noise pixels in the image data should be set to 3, with a user-selectable range from 0 to 20.
d. The INVALID_PULSE_EDGE flag is set.
e. The INCOMPLETE_PULSE_PROFILE flag is set.
f. The IASICP_MAX_NPV (i.e., pulse contains saturated samples) is set.

4. Trend the number of 'valid' (i.e., not corrupted according to step 3) forward scan calibration data / reverse scan image data pairs to the database. Ideally, this number should be 12-13; however, elimination of corrupted scans reduces this count. If the number of valid scans is less than five, skip all scans, set the valid scan count to '0,' issue a warning message, and exit from processing the current lamp state.
5. Use LMASK information to replace the impulse noise pixels with a linear interpolation of the two adjacent valid pixels of current detector data. It is possible that a contiguous sequence of impulse noise-affected pixels occurs at the very edge of a scan; however, it is expected that this condition rarely occurs, if ever. If this condition occurs, modify the interpolation process according to whether the occurrence is observed in the image or calibration data.
    a. In image data, replace the affected pixels with the average value of 'valid' pixels immediately following (Left-Hand Side (LHS)) or prior to (Right-Hand Side (RHS)) the affected data ('valid' referring to those pixels free of impulse noise artifacts as determined in the LMASK). The number of pixels used in averaging should be the same as the maximum number of impulse noise-affected pixels allowed for image data.
    b. In the shutter region of calibration data (LHS or immediately prior to the calibration pulse), replace the affected pixels with the average value of LMASK-defined 'valid' pixels immediately following (LHS) or prior (before the calibration pulse). The number of pixels used in averaging should be the same as the maximum number of impulse noise-affected pixels allowed for calibration data.
    c. In the 'post'-calibration pulse region, do nothing. The LMASK tracking of impulse noise artifacts does not exist in this region of calibration data. A significant part of the change in response due to ME is observed in this region.

6. If the number of pixels in the reverse scan image data varies from scan to scan, then take the same number of pixels from all selected scans by truncating extra pixels from the left end of the image data. Similarly, take the same number of pixels from all selected forward calibration scans by truncating extra pixels from the left end of the forward scan calibration data. Store the maximum number of pixels truncated from the reverse scan image data and forward scan calibration data.
7. Time-reverse the reverse scan image data. Append the time-reversed image data to the corresponding forward scan pulse data. Assume there is no 'gap' (i.e., missing data) between the pulse data and the image data. After this step is complete, 'profiles' of concatenated forward-scan calibration data and reverse-scan image data exist for the current lamp state for each detector.
8. Compute band averaged summary statistics (mean and standard deviation) and estimated Signal-to-Noise Ratio (SNR) (defined as the ratio of the mean to the standard deviation) from the last 1000 samples of image data in all extracted profiles, across all normally operating detectors (as determined from the CPF listing). This method serves as a check on the overall 'quality' of the data. Trend the mean and standard deviation results to the database and write all summary statistics (including the SNR) to a summary report file.
9. If the current lamp state is LS [000], determine an 'average' pulse data / image data profile for each detector for the scene being processed, using all valid profiles created in step 6. Trend these detector-specific LS [000] profiles to the database for the second characterization stage performed offline.
10. If the current lamp state is not LS [000], align all valid calibration data / image data profiles created in step 6 for each detector using the following procedure:
    a. Select the responses from the first scan to represent 'reference' pulse locations for each detector.
    b. Compare the pulse location in the scans to the reference, using a cross-correlation analysis, to determine how many pixels the subsequent scans should shift (right or left) to maximally align with the reference. If the maximum correlation value is found at multiple shift values, take the smallest shift value for alignment. When a detector profile is required to shift on the left end by 'n' pixels, then exclude 'n' pixels from the left and add 'n' pixels with '0' fills on the right end. Similarly, when a detector profile is required to shift on the right by 'n' pixels, then exclude 'n' pixels from the right end and add 'n' pixels with '0' fills on the left end.
    c. Determine the maximum number of pixels to shift from the 'worst-aligned' scan. Store this maximum number of pixels shifted on the database and include it in the report file.
    d. Obtain an 'average' pulse data / image data profile. The maximum number of shifted pixels at both ends of this average profile is corrupted by adding '0's during the alignment process in steps 10(b) and 10(c). Mark these pixels at both ends of the profile with a value of '1000.' These pixels are excluded from consideration in the regression analyses performed during the offline characterization stage. Store the average profiles to the database for future processing.

The second characterization stage is performed offline, outside the normal IAS radiometric processing flow. In this stage, the final ME characterization parameters are derived from the profile information stored during the first stage processing. In the default processing scenario, the parameters are derived from LS [111] profiles; however, parameters can be derived from any non-zero lamp state profiles, thus providing an opportunity to study ME across the instrument dynamic response range.

Note: Earlier characterization analyses observed difficulties in generating ME amplitude parameters that produce consistently reliable correction. The ME amplitude parameter, κ_{ME}, needs to be adjusted with a detector-specific 'scaling' factor. At the time this document was written, these scaling factors were determined through a 'trial-and-error' iterative process of applying various 'perturbation' values to κ_{ME}, performing the correction, and qualitatively and quantitatively assessing the results. This determination of scaling factors is NOT necessary for ME characterization performed with this algorithm; it is important for improving the correction.

As currently conceived, this algorithm was historically run under the assumption that the characterization parameters are derived from a sequence of consecutively acquired night time scenes from a single orbit. This assumption is not strictly true; in principle, the characterization parameters could be derived from a sequence of individual night time scenes. This is perhaps a more realistic processing scenario, as there are more single-scene night time data acquisitions than extended single-orbit night time acquisitions. However, at the time this document was written, this approach had not been attempted.

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Section 14 Memory Effect Correction

14.1 Introduction

This algorithm performs ME correction on L4 / L5 TM image and calibration data. ME has been modeled as a simple first-order linear system, and the ME characterization identifies the model parameters. Correction of ME is carried out by a convolution operation of the image and calibration data, with restoration filters derived from the inverse of the ME pulse response function. This function is determined from the current set of ME model parameters contained in the CPF. Currently, the correction of ME is required only for image and calibration data from Bands 1-4.

14.2 Input Data

- SCS-corrected reflective band image data (day / night) (floating point)
- SCS-corrected reflective band IC data (day / night) (floating point)
- LMASK

14.3 Input Parameters Obtained from CPF

- Detector-specific ME magnitude (floating point)
- Detector-specific ME time constant (floating point)
- Detector-specific ME amplitude 'scaling' factor (floating point)

14.4 Output Data

- ME-corrected image data (floating point)
- ME-corrected IC data (floating point)

14.5 Algorithm Description

For each band of image and calibration data to correct, perform the following:

1. Obtain the ME amplitude k^d_{ME}, time constant τ^d_{ME}, and scaling factor s^d parameters for each detector from the CPF.
2. Construct restoration filters for each detector of the following form:

$$w^d_{scene}(t) = \left(\frac{1}{1-s^d k^d_{ME}\tau^d_{ME}}\right)\left[\delta(t) - \frac{s^d k^d_{ME}}{1-s^d k^d_{ME}\tau^d_{ME}}\exp\left(-\left[\frac{1}{\tau^d_{ME}} + \frac{s^d k^d_{ME}}{1-s^d k^d_{ME}\tau^d_{ME}}\right]t\right)\right] \quad (1a)$$

$$w^d_{calibration}(t) = \left(\frac{1}{1-s'^d k^d_{ME}\tau^d_{ME}}\right)\left[\delta(t) - \frac{s'^d k^d_{ME}}{1-s'^d k^d_{ME}\tau^d_{ME}}\exp\left(-\left[\frac{1}{\tau^d_{ME}} + \frac{s'^d k^d_{ME}}{1-s'^d k^d_{ME}\tau^d_{ME}}\right]t\right)\right] \quad (1b)$$

where s'^d is equal to 1 when s^d is greater than 1 and equal to s^d when s^d is less than 1. This form represents an 'infinite' impulse response; this form can be converted to a more efficient computational form with a total filter length of 3000 (representing approximately three ME time constants) through approximation into a series of 'steps;' a larger number of steps tend to approximate the 'true' filter response more accurately. To maintain a reasonable computational burden, set the number of steps equal to 30. The step widths for this filter size correspond to {1, 19, 25, 25, 50, 50, 50, 75, 75, 75, 75, 100, 100, 100, 100, 100, 130, 130, 130, 130, 130, 130, 150, 150, 150, 150, 150, 150, 150, and 150.}. The coefficient value for a given step is the average of all coefficient values within that step.

3. Read and arrange the image and calibration data for each detector in the time sequence. 'Stitch' data together in the following fashion: forward scan image data, forward scan calibration data, reverse scan image data (reversed to account for proper time flow), and reverse scan calibration data.
4. Convolve the restoration filters obtained in step 2 with the 'stitched' detector data sequence obtained in step 3. If the current pixel to filter is within the day input image data, use the filter represented by (1a); if the current pixel to filter is within the input calibration data or night image data, use the filter represented by (1b). For convolution purposes only, pixels flagged in the LMASK with impulse noise artifacts are replaced with a value resulting from interpolation of neighboring pixels, up to a maximum of 10 consecutive pixels; for more than 10 consecutive pixels or for dropped scans / lines, the pixel values are replaced with 0s.
5. Rearrange the filtered detector data sequence to form the ME-corrected image and calibration data outputs. Remember to reverse the filtered reverse scan image data to restore their 'proper' image order.

14.6 Issues

1. The correction algorithm implemented in IAS 8.0 does not account for 'gaps' observed between the 'stitched' image and calibration data (during the scan mirror turnaround periods). It is assumed that these gaps are small, with minimal temporal effect. Future enhancements of this algorithm may need to explicitly account for these gaps.
   Note 4/4/2008: Examining the initial L5 TM ME characterization profiles that IAS produced shows the gap to be near zero. Several detectors that exhibit significant CN were examined, and upon visual inspection, it is clear that the sinusoidal noise pattern is not missing samples where the image and calibration file data are concatenated. Occasional outlier samples were noted near the concatenation point, but it is not known if these are due to missing data from gaps or are simply random noise events.
2. As currently implemented, ME correction is only performed on Bands 1-4 image and calibration data. Recent analysis of currently acquired and historical data suggests an ME-like response variation in Detectors 1, 2, 15, and 16 of Bands 5 and 7. Analysis of these data suggests that the response time constant is much less than that historically observed in the primary focal plane detectors (generally ~100 pixels or less). A scan direction dependence is influencing the manifestation of this effect (i.e., Detector 1 and Detector 2 are affected in forward scans, while Detector 15 and Detector 16 are affected in reverse scans). Future enhancements of this algorithm may need to explicitly account for these effects as well.
3. **Note 4/4/08:** As currently implemented, it is possible for the ME correction algorithm to induce significant shutter bias shifts when processing a day scene with extreme cloud cover content. Shutter bias values in the range from 3 to 8

DN have been observed, and can exceed the bias subtraction failover thresholds (currently set at 0.5 to 6 DN), resulting in a subtraction of scan bias values defined in the CPF, rather than dynamic values as calculated in IASICP_RPS. Usage of mixed bias sources can result in detector stripping within a scan. This issue is currently under investigation.

14.7 References

D. Helder et al. Landsat TM Memory Effect Characterization and Correction. Canadian Journal of Remote Sensing. Vol. 23, No. 4. pp. 299-308. December 1997.

USGS/EROS. LS-IAS-02. Landsat 7 (L7) Image Assessment System (IAS) Radiometric Algorithm Theoretical Basis Document (ATBD). Version 1.0. June 2003.

Section 15 Debanding

15.1 Introduction

This algorithm calculates pixel-specific ‘correction factors’ representing the amount of banding present in daytime Landsat TM image data. When called by the ‘Assess Memory Effect’ algorithm, the correction factors are generated from pre-ME and post-ME image data to estimate the amount of banding removed following the application of the ‘Correct Memory Effect’ algorithm. When applied to radiometrically corrected L1R image data, the correction factors can be used in a ‘cosmetic’ processing step to remove residual banding.

In this document, ‘banding’ is considered a manifestation of the ME artifact observed in TM image data. Consequently, the terms ‘banding,’ ‘memory effect,’ and ‘ME’ are considered interchangeable.

15.2 Background

After scanning past a bright target, such as cloud or snow, detector response is significantly reduced due to ME. Subsequent targets imaged after the bright target in the affected scans measure ‘darker’ pixel values than on the next scans in the opposite direction (which have yet to image the bright target). In general, the ME banding pattern tends to have low amplitude, with typical differences of approximately 1-2 DN between consecutive scans. However, if not corrected, ME can cause potentially significant radiometric errors of approximately 5-10 DN or more (depending on various factors, such as the affected band, the nature of the target, etc.).

This algorithm applies a separable, computationally efficient, spatial domain 2D Wiener filter optimized for detection of the banding pattern. Because of the low amplitude inherent in banding, the filter operates only on those portions of the image where it is more easily detected (i.e., in relatively homogeneous regions following an intensity change). Application of the filter to an input image can produce one of two outputs. These outputs are an image with banding removed or a correction factor image,’ indicating locations where the banding pattern is most observable and its amplitude is recorded. From the CF image analysis, a metric can be derived to assess the effectiveness of ME correction.

15.3 Inputs

To derive correction factors for ‘cosmetic’ residual banding removal, the following inputs are required:

- L1R daytime image data (floating point)
- LMASK
    - Used to avoid processing image data affected by dropped lines, impulse noise, or saturated pixels
- Banding detection threshold, TOLR, in units of DN (floating point)
    - Expected to range between 3.0 DN and 8.0 DN

    - Default value of 5.0 DN
- Band-average absolute gain obtained from CPF (floating point)
    - Scales the banding detection threshold TOLR to the corresponding radiance-level threshold value

At this time, banding due to ME has been observed only in Bands 1-4 image and calibration file data; consequently, banding removal correction factors are derived only for image data for these bands by default. If banding artifacts are discovered in Bands 5-7 data (as another form of ME or as an unrelated artifact), it is necessary to incorporate the relevant processing for these bands as well. All image data bands should be considered as potential inputs.

To derive correction factors for assessing the results of the 'Correct Memory Effect' algorithm, the following inputs are required:

- Level 0 Reformatted Corrected (L0Rc) daytime image data prior to ME correction (floating point)
- L0Rc daytime image data following ME correction (floating point)
- LMASK
- Banding detection threshold, TOLR, in units of DN (floating point)
    - Expected to range between 3.0 and 8.0 DN
    - Default value of 5.0 DN

All bands should be considered as input to account for the potential discovery of banding artifacts in Bands 5-7. By default, processing involves only Bands 1-4 of artifact-corrected daytime image data (either SCS corrected, or both SCS and ME corrected).

15.4 Outputs

For cosmetic banding removal in L1R daytime image data:

- L1R banding-corrected daytime image data (floating point)

As input to the 'Assess ME Correction' algorithm:

- 'Correction factor' image *CF(x, y)* (floating point)

15.5 Algorithm

As mentioned earlier, the debanding filter is a separable, 2D Wiener filter. Application of the filter in the vertical direction generates initial estimates of correction factors that represent initial estimates of the banding amplitude. Adjacent scans are assumed to be aligned; if scan lines are not aligned, the image data should be processed to eliminate / reduce the offsets (offset requirements are <= 2 pixels).

Extensive use of functions from the GPS is made in the Deband algorithm to compute scan offsets and linear adjustment factors. These parameters either create a pseudo-scan aligned image (for local use only, (i.e., never propagated in the process flow)) or directly as scan-to-scan pixel index adjustments when comparing image data between adjacent scans. The general process for achieving a scan alignment is as follows:

1. The geometric model is built. The geometric model is created from the Landsat PCD, MSCD, and the CPF. The geometric model combines the data available within these files such that for any input line and sample location, a corresponding geographic latitude and longitude can be found. For more information on how the PCD, MSCD, and CPF create the geometric model, see LS-IAS-01 Landsat 7 (L7) Image Assessment System (IAS) Geometric Algorithm Theoretical Basis Document (ATBD).
2. To calculate the alignment difference between adjacent scans within an L0R image file, the same methodology used in creating extended scans for resampling image data is employed. This process works by taking the mapping for one scan and determining how it affects another scan or an adjacent scan. These steps allow one scan to map geometrically into another scan. LS-IAS-01 Landsat 7 (L7) Image Assessment System (IAS) Geometric Algorithm Theoretical Basis Document (ATBD) contains a more thorough explanation of the process and steps involved.
3. Statistics for along-scan displacements are calculated from the values generated in step 2, giving the offset and trend needed to map one scan into the adjacent scan.
4. The statistics from step 3 are accumulated from the second scan down to the last scan such that all scans are mapped to the first scan of the image data.
5. The accumulated statistics from step 4 resample each scan to a common relative position, or the first scan. Nearest neighbor resampling creates each new scan. Under this scenario, pixels may be thrown out in order to align a scan.

The following sequence of steps generates the correction factors for each band of aligned image data. The sequence is identical whether the input image data have been scaled to radiance units (L1R) or not. However, if the input image data are in radiance units, the TOLR parameter must be divided by the band-average absolute gain to obtain the corresponding radiance-level threshold value.

1. For each 'valid' pixel (any not flagged in the LMASK as part of dropped lines / scans or having saturation or impulse noise artifacts), find the absolute value of the difference between the current pixel value in the input image, *I(x, y)*, and the pixel value one scan above, *I(x, y-16).*
    a. If this difference is less than or equal to the threshold value *TOLR*, set the 'Upper Data Point' (UDP) to the pixel value *I(x, y-16)*. For the first scan in the input image, no UDP values are available (because there is no scan 'above' the first scan); in this case, assign a flag value to the UDP to indicate an invalid value.
    b. If this difference is greater than *TOLR*, calculate the absolute values of the differences between the current pixel value *I(x, y)* and pixel values *I(x+10*n, y-16)*, where n=-2, -1, 1, 2. If any of these differences are less

than or equal to *TOLR*, set the UDP as the average of those pixel values *I(x+10*n, y-16)* satisfying the condition. If all differences are greater than *TOLR*, no UDP values are available at the current location *(x, y)* in the input image; therefore, set the UDP value to the invalid flag value.
If the current pixel *I(x, y)* is flagged in the LMASK, set the UDP value to the invalid flag value. If *I(x, y)* is 'valid' but *I(x, y-16)* is flagged in the LMASK, use step 1(b) to determine an appropriate UDP value. In this case, exclude from consideration those pixels in the above scan flagged in the LMASK.

2. For each 'valid' pixel, find the absolute value of the difference between the current pixel value in the input image *I(x, y)* and the pixel value one scan below, *I(x, y+16)*.
    a. If this difference is less than or equal to *TOLR*, set the 'Lower Data Point' (LDP) to the pixel value *I(x, y+16)*. For the last scan in the input image, no LDP values are available (because there is no scan 'below' the last scan); in this case, assign the invalid flag value to LDP.
    b. If this difference is greater than *TOLR*, calculate the absolute values of the differences between the current pixel value *I(x, y)* and pixel values *I(x+10*n, y+16)*, where n=-2, -1, 1, 2. If any of these differences are less than or equal to *TOLR*, set the LDP as the average of those pixels *I(x+10*n, y+16),* satisfying the condition. If all differences are greater than *TOLR*, no LDP values are available at the current location *(x, y)* in the input image; set the LDP value to the invalid flag value.
    If the current pixel *I(x, y)* is flagged in the LMASK, set the LDP value to the invalid flag value. If *I(x, y)* is 'valid' but *I(x, y+16)* is flagged in the LMASK, use step 2(b) to determine an appropriate LDP value. In this case, exclude from consideration those pixels in the below scan flagged in the LMASK.

3. Calculate an initial estimate of the correction factor, Initial Correcection Factor (*ICF*), for the current pixel location (x, y) as follows:
    a. If there is only a UDP value, *ICF(x, y)* = 0.5**(I(x, y)* – UDP)
    b. If there is only an LDP value, *ICF(x, y)* = 0.5**(I(x, y)* – LDP)
    c. If there are UDP and LDP values, *ICF(x, y)* = 0.5*([*I(x, y)* – 0.5*[UDP+LDP]])
    d. If both UDP and LDP values are flagged with the invalid flag value, *ICF(x, y)* = 0.0

4. Application of the filter in the horizontal direction refines the ICF estimates generated in steps 1-3. For each scan line with ICF information, apply a 35-point Finite Impulse Response (FIR) moving average filter centered about the current pixel location *(x, y)*. For each pixel location not flagged by LMASK, calculate the final estimated CF at the current pixel location as:

$$CF(x,y) = \frac{\sum_{k=-17}^{17} ICF(x+k,y)}{35} \quad (1)$$

If 35 ‘valid’ (i.e., nonzero) ICF values are not available, average over as many nonzero ICF values as are available, making sure to adjust the limits in the summation and the total number of ICF values accordingly. For example, at the first / last pixel locations on a scan line, and assuming there are 16 nonzero ICF values in either horizontal direction, take the average of 17 ICF values (the current value and the 16 other values). For the pixel locations flagged by LMASK, set *CF(x,y)* = 0.0.

5. When the algorithm is called for ME assessment, return the CF image to the ME Assessment algorithm for further processing. When the algorithm runs for residual banding correction, subtract the CF image from the input image to generate banding-corrected image and store this banding-corrected image.

15.6 References

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D. Helder, T. Ruggles. Landsat Thematic Mapper Reflective-Band Radiometric Artifacts. IEEE Transactions on Geoscience and Remote Sensing. Vol. 42, No. 12. December 2004. pp. 2704-2716.

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Section 16 Assess Memory Effect Correction

16.1 Introduction

This algorithm assesses the performance of ME correction on Landsat TM daytime imagery. The assessment procedure uses a CF image, which the 'Deband' algorithm generates when applied on a pre-ME corrected image. The assessment procedure automatically detects and characterizes three relatively homogeneous subregions in images that exhibit a significant ME-induced banding pattern. Application of this algorithm to the same three regions in the 'Debanding' algorithm generated ME-corrected CF image estimates the correction efficacy in terms of a relative percentage change in local ME amplitude before and after the correction.

For the remainder of this section, the terms 'memory effect,' 'ME,' and 'banding' are used interchangeably. These terms refer to the memory effect artifact, whether uncorrected or residual following application of the 'Correct Memory Effect' algorithm.

16.2 Background

ME is a prominent artifact present in L4 / L5 TM imagery. It is most visible in homogenous regions exhibiting a sudden significant change in radiant intensity, such as at a cloud / water boundary. ME appears as alternating bright and dark scans, and is currently believed to affect Bands 1-4 image and calibration data. If uncorrected, ME can be a significant source of radiometric error. An inverse-filter based correction algorithm applicable to both image and calibration data is available within the IAS radiometric process flow. See Section 14 for more information.

The 'Debanding; algorithm, developed prior to the ME correction algorithm currently implemented within the IAS, is an adaptive 2D Wiener filter designed to remove banding from the TM image data (see Section 15 for additional details regarding its construction and application). The algorithm estimates pixel-specific banding amplitude as a CF image, and subtracts this amplitude from the banding-affected input image. Analysis of the CF image revealed that the correction factors are generally random in nature, except in regions where ME is the most significant (see Figure 16-1). The correction factors at any pixel location (x, y) in these regions tend to follow the general ME banding 'pattern'(i.e., the correction factors are equal in magnitude but opposite in sign) with the correction factors at pixel locations ($x, y\pm16$), one scan below (+) and/or above (-).

The ME assessment algorithm calls on the 'Debanding' algorithm only to generate the CF image from the pre-ME corrected image. Once generated, the assessment algorithm searches the image to identify three subregions where the banding pattern is the most significant (as in the examples shown in Figure 16-2 and Figure 16-3). Once these regions are identified, statistics are calculated that indirectly represent the local ME banding amplitude. Following the application of the ME correction algorithm, the assessment algorithm is applied a second time to calculate the same statistics as in the pre-ME correction application, using the post-ME corrected CF subregions corresponding to the most affected subregions, as determined from the pre-ME CF image.

The overall effectiveness of the ME correction in these subregions is estimated as a relative percentage change in the statistics between the two applications. If fewer than three CF image subregions are found to exhibit 'significant' banding prior to ME correction (i.e., if at least 60 percent of the banding correction factors within each of at least three subregions are not determined 'valid'), the post-correction application is not performed.

16.3 Inputs

- Daytime image data prior to ME correction (floating point)
  By default, this algorithm is applied only to Bands 1-4 SCS-corrected image data in floating point format. If Bands 5-7 show an ME-like artifact, the algorithm can be expanded to allow processing.
- Daytime image data following ME correction (floating point)
  Bands 1-4 image data are processed by default. Processing these data occur only when application of the algorithm to the non-ME-corrected image detects three regions with 'significant' ME (i.e., the percentage of 'valid' correction factors for the three most affected regions is 60 percent or greater).
- LMASK
  Used to avoid processing image data affected by dropped lines, impulse noise, or saturated pixels.

16.4 Input Parameters to Set

- User-specified banding detection threshold value, *TOLR* (floating point), required for the call to the 'Debanding' algorithm. The default value of *TOLR* is set to 5 DN, with a permissible variation between 3 and 8 DN. This parameter can be selected through a Graphical User Interface (GUI) prior to the start of Radiometric Processing System (RPS) processing.
- User-specified threshold value, *K* (floating point), representing the maximum allowable percentage of deviation from the characteristics of the 'ideal' banding pattern (the 'ideal' banding pattern occurs when the final correction factor estimate at pixel location (x, y) is of equal magnitude as, but opposite sign to, the correction factors at pixel locations one scan immediately above and/or below (i.e., $(x, y\pm16)$). The default value for *K* is set at 0.1, indicating that there can be as much as 10 percent variation between banding correction factors at the pixel locations (x, y) and $(x, y\pm16)$, and still be considered 'valid' correction factors. An acceptable range of values for this parameter, *K*, is empirically determined to be between 0.0 and 0.4, and can be set during work order creation.
- A window dimension defining an image subregion 'square' used for ME assessment (integer). It can be selected from the GUI interface used to select the other options for this algorithm. Acceptable values for this parameter range between 128 and 512, in increments of 32. This user-specified value should be checked to ensure that it is a multiplicative value of 32 in order to account for an equal number of forward and reverse scans in the vertical direction (1 forward

and 1 reverse scan pair are 32 pixels wide). By default, the value is set to 384, representing 12 forward-reverse scan pairs.

16.5 Outputs to Trend to a Database and Written to a Report

- Starting (*x, y*) coordinates of three subregions that possess significant ME amplitude (integer). These coordinates are extracted only from the pre-ME-corrected imagery; these coordinates also locate the assessed regions in the ME-corrected imagery. If the algorithm runs on the corresponding ME-corrected imagery, these coordinates function as an additional input obtainable from the database. The upper-left corner of the input image is utilized as the origin of these coordinates.
- Total count of correction factors within the selected subregions (integer)
- Total count of 'valid' correction factors used in calculating the subregion ME amplitudes (integer)
- Percentage of correction factors used to estimate the subregion ME amplitudes (floating point)
- Overall banding amplitude estimates for the three selected subregions (floating point)
- Status flag, '0' or '1,' for each of the three subregions, where '0' indicates ME is not significant (% accepted CF < 60 percent) and '1' indicates ME is significant (% accepted CF >= 60 percent).
- 'Correct Memory Effort' (floating point) estimated percentage of ME amplitude correction. The data are estimated only when the algorithm processes ME-corrected imagery.

16.6 Algorithm

Note: It is assumed that all scans in the input image data are aligned to within one to two pixels. If this is not the case, the image data must be processed prior to applying this algorithm in order to eliminate / reduce observed SLOs. This is especially important for image data acquired during bumper mode operation, but can also be an issue for image data acquired during SAM mode operation, especially during its later stages. See Section 15 for further details regarding how scan alignment is implemented in the IAS for TM.

Figure 16-4 shows a schematic diagram of the algorithm process flow. The algorithm is intended to run before ME correction for all day scenes. As indicated earlier, this flow is intended to run after ME correction only on those scenes where significant ME has been identified before ME correction.

A. Perform the following steps on image data prior to the application of the 'Correct Memory Effect' algorithm:

    1. Call the 'Debanding' algorithm to generate a correction factor 'image' *CF*, and use the available LMASK information to exclude dropped lines / scans, saturated pixels, and impulse noise artifacts from consideration. See Section 15 for additional details on this procedure.

2. Compare the correction factor for the current pixel location, $CF(x, y)$, with the correction factors one scan above and below (denoted by UCF and LCF, respectively; in other words, $UCF = CF(x, y-16)$, and $LCF = CF(x, y+16)$. For the first scan, no corresponding UCF estimates exist; perform the comparisons to the LCF estimates. Similarly, for the last scan, no corresponding LCF estimates exist; perform the comparisons to the UCF estimates. Flag $CF(x, y)$ as 'invalid' for the purposes of future analyses (with a value of -50) if the current pixel location (x, y) is either flagged in the LMASK or if any of the following three conditions are met:
    a. $UCF*CF(x, y) > 0$ **AND** $LCF*CF(x, y) > 0$
    b. $|CF(x, y)| < (1 - K)*|LCF|$ **AND** $|CF(x, y)| < (1 – K)*|UCF|$, where K is the threshold value indicating the maximum acceptable deviation from the characteristics for 'ideal' banding.
    c. $|CF(x, y)| > (1 + K)*|LCF|$ **AND** $|CF(x, y)| > (1 + K)*|UCF|$
3. Divide the correction factor 'image' into square subregions (as shown in Figure 16-2) according to the dimension chosen prior to running the algorithm (for default processing, 384x384 pixels). Each subregion contains an equal number of forward and reverse scans (12 forward and 12 reverse) and starts on a forward scan. Subregions that are not of these dimensions (such as those occurring near the image edges) are not considered for analysis.
4. Count the total number of 'valid' correction factors within each subregion. Select the three subregions with the largest number of 'valid' correction factors. Make sure that the starting line coordinate for each subregion corresponds to Detector 16 of a forward scan.
5. Compute an overall ME amplitude for the three selected subregions:
    a. Compute the average correction factors over each line by considering the valid correction factors only. If a valid correction factor does not exist, then assign '0' to this value.
    b. Compute the average correction factor for each forward scan, A_f, using the nonzero absolute average correction factors of the 16 lines corresponding to the forward scan.
    c. Compute the average correction factor for each reverse scan, A_r, using the nonzero absolute average correction factors of the 16 lines corresponding to the reverse scan.
    d. Compute a banding amplitude BA for each consecutive pair of forward and reverse scans as:

$$BA = \frac{A_f + A_r}{2} \tag{1}$$

    e. Compute the overall banding amplitude as the average of the absolute values of the banding amplitudes obtained from step 5(d).
6. For all three selected subregions (as in Figure 16-3), record in the database and report the following summary information to the report file:

    - Position of the subregion

- Total number of correction factors in the subregion
- Total number of 'valid' correction factors used to calculate the average ME amplitude in the subregion
- Percentage of valid correction factors in the subregion
- Status flag '0' or '1'
- The average ME amplitude of the subregion

B. Perform the following steps to apply the algorithm following ME correction. Only those scenes where significant ME has been identified before correction are processed. The scene being processed is considered to have significant ME before correction only if **all** three identified subregions have a percentage of 'valid' correction factors at 60 percent or greater.

1. For each band, retrieve from the database all values trended in step A6 when the algorithm ran prior to ME correction. If the percentage of valid correction factors in at least one subregion is less than 60 percent, inform the user that ME assessment cannot be performed for the current band, and continue checking the other bands. If all bands are found to have at least one subregion with a valid correction factor percentage less than 60 percent, inform the user that no ME assessment is possible for the current scene, then exit from the algorithm.
2. Repeat the calculations contained in steps A1, A2, A3, and A5. The starting and ending line and sample coordinates of the three subregions required to perform step A5 should be available from step B1.
3. Using the banding amplitude before and after ME correction, compute the percentage change in ME amplitude before and after correction in each subregion:

$$\% Change = 100 * \frac{(\overline{BA_{preME}} - \overline{BA_{postME}})}{\overline{BA_{preME}}} \quad (2)$$

4. Record the percent change in ME amplitude for each subregion to the database. Report the percent change to the report file.

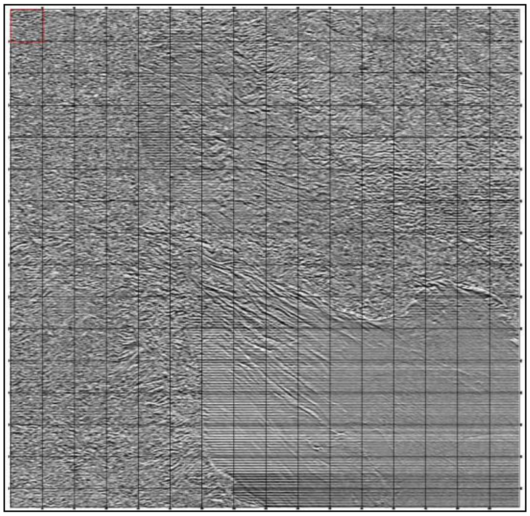

Figure 16-1. CF Image Divided into 384x384 Subregions

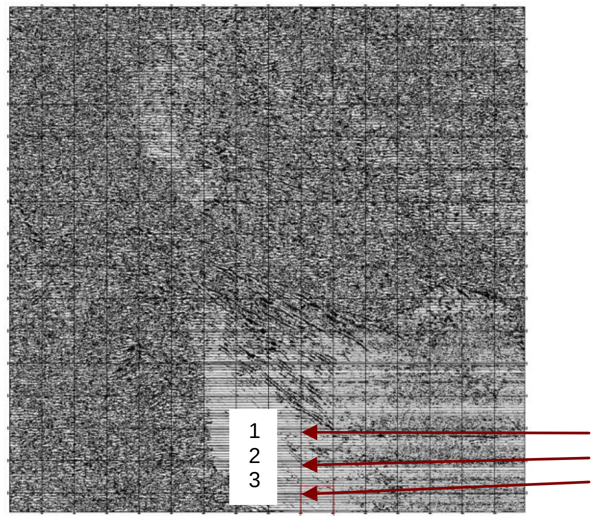

Figure 16-2. Three Subregions (1, 2, 3) with Largest Number of 'Valid' Correction Factors

Figure 16-3. Region '1' at Full Resolution (384x384 pixels)

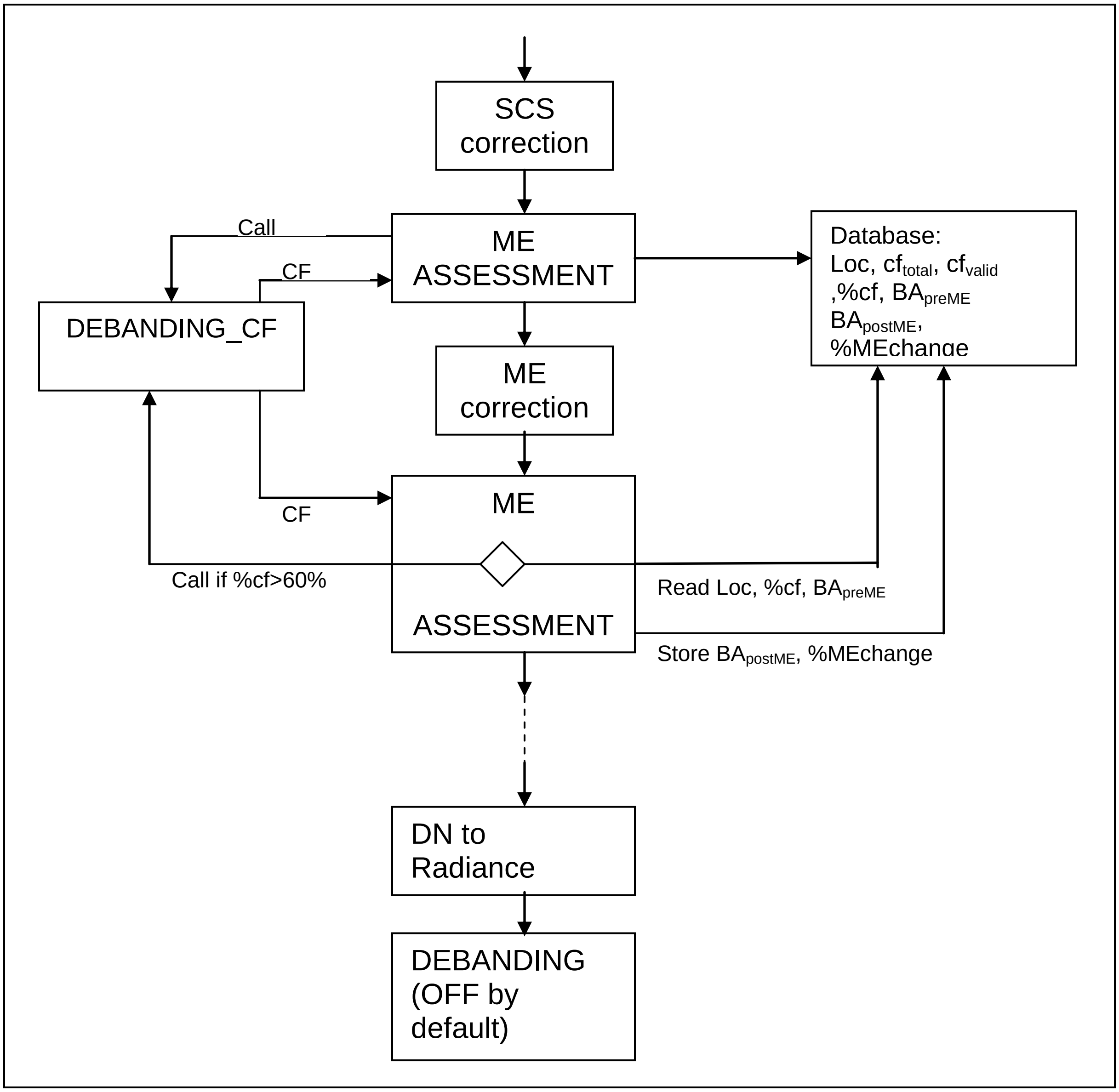

Figure 16-4. Process Flow for ME Assessment and Debanding

16.7 References

D. Helder. Debanding Thematic Mapper Imagery. PhD Dissertation. Electrical and Electronics Dept. North Dakota State University. 1990.

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Section 17 Histogram Analysis

17.1 Introduction

This algorithm extracts the relevant first- and second-order detector statistics from image data. Depending on the processing level of the input data, these statistics can determine the following:

- Data points for the generation of relative radiometric calibration models based on time-dependent detector response
- Relative radiometric calibration specific to the given image

17.2 Background

In general, this algorithm provides a level of functionality similar to the corresponding algorithm in the current L7 IAS. However, two differences in functionality specific to the TM version must be noted. First, the TM version is intended to run at more stages within the main radiometric processing flow. As in the L7 version, it runs on Level 0 Correcterd (L0c) and daytime L1R reflective band / night time thermal band image data to obtain the necessary information for relative gain correction and 'cosmetic' striping removal. It is also intended to run on night time L0c reflective band image data before and after each artifact correction step to provide information for assessment purposes. Second, the TM version is intended to run on daytime and night time reflective band L0R image data. In addition, for night time L0R image data, detector-specific histograms can be generated for use in enhanced noise characterization analyses (TBD).

As currently conceived, this algorithm description is based on the concept of processing data 'levels' in use with the current L7 IAS. Alternatively, this algorithm can be presented independent of the RPS processing level; in this manner, modules incorporating specific functionality can be designed, implemented, and called whenever necessary in the process flow. At the time this document was written, the algorithm could be more cleanly described relative to processing levels. To determine the exact 'correlation' between specific modules and processing levels, examine the process flow diagrams.

In the L7 IAS, the image and calibration data are typically handled as scaled (100x) integer values, and the histograms are computed using unity bin widths. For the TM-IAS, the use of floating point numbers with no scale factor impacts the required bin widths to achieve sufficient resolution in the histogram statistical calculations. Beginning with R8.0.2, the initial implementation (using unity bin widths) was changed to support 1/100 the DN and radiance bin widths for the histograms, subsequent statistical calculations, and derived relative gain values. Effective with R8.0.3, the histogram calculation dynamic range was extended to 450 counts from 255 to better match the dynamic range of the images throughout the process flow. Histogram results are typically reported as aggregated unity bin width values in the report files and database. In addition, the analog saturation algorithm searches on aggregated unity bin width values to determine potential saturation points on both the low and high ends of the dynamic range.

17.3 Inputs

- Daytime / night time L0R (for raw histograms and detector saturation information) (floating point)
- Daytime L0c artifact-corrected (for relative gain estimation) (floating point)
- Night time L0c artifact-corrected reflective band (for artifact correction assessment) (floating point)
- Daytime L1R (for image-specific ‘cosmetic’ striping removal) (floating point)
- IASICP function extracted scan line bias levels (for estimation of relative gain from daytime L0c image data) (floating point)
- LMASK

17.3.1 Input Parameters from CPF

- Dead / degraded detector information
- Detector noise levels (floating point)
- Number of scans in the window used for calculation (between one and three total scenes) (integer)
- Number of scans to overlap between windows (i.e., in a window of length >1 scans do not overlap; by default set to 0) (integer)
- Starting pixel for calculation (from SLO information) (integer)
- Number of pixels for each calculation (refers to the total number of scans)
- Reference detector (integer)
- Saturation bin threshold (integer)
- Adjacent bin threshold (integer)
- Number of adjacent bins to test (integer)

17.4 Outputs

Database trending of daytime L0R image data (all bands) and night time thermal band image data:

- Detector saturation bins (floating point)
- Band average, detector level, summary statistics (mean and standard) for all detectors, including the reference detector (floating point)

Database trending of daytime L0c / L1R image data (all bands) and night time thermal band image data (can also be used as inputs for scene-specific relative gain correction):

- Detector-specific relative gain ratios to individual reference detector and band-average, per scan direction--forward, reverse, and the ratio of forward to reverse (floating point)
- Ratio of standard deviations (floating point)
- Ratio of bias-corrected means (floating point)

- Relative bias-calculated with respect to the reference detector and the band-average of all operative detectors (floating point)
- Number of pixels (integer)
    - Total number used per detector
    - Numbers excluded at both the high-end and low-end of the detector-specific histogram
- Summary histogram statistics for each band, per scan direction—forward scans, reverse scans, and all scans together (floating point)
    - Detector means and standard deviations
    - Mean and standard deviation of all operative detectors in the band

Database trending of night time L0R / L0c reflective band image data:

- Detector-specific histograms (floating point)
- Summary histogram statistics
    - Minimum, maximum, mean, and standard deviation (floating point)
    - Number of pixels (integer)

Summary reporting:

- Daytime / night time L0R, L0c, and L1R histograms (floating point)
    - Detector-specific
    - Band average (across all operative detectors)
- L0c / L0R scene statistics (floating point)
- Unweighted / weighted by detector noise (daytime and night time image data)
- Unweighted (night time reflective band image data only)
    - L0c / L0R detector-specific summary statistics before bias correction, per scan direction—forward scans, reverse scans, and all scans together (daytime reflective band and night time image data) (floating point)
    - L0c / L0R detector-specific summary statistics after bias corrections, per scan direction—forward scans, reverse scans, and all scans together (daytime reflective band and night time thermal band image data) (floating point)
- Number of high and low brightness pixels excluded (daytime reflective band and night time thermal band image data) (integer)
- Number of pixels used in calculations (integer)
- L0c / L1R computed gain ratios per detector (floating point)
    - Four sets per window (reference and average, based on mean and standard deviation ratios) (daytime reflective band and night time thermal band image data)
- L0c / L1R computed relative biases per detector (floating point)
    - Two sets per window (reference and average) (daytime reflective band and night time thermal band image data)
- L0c / L1R differences of gains calculated between the mean ratio and standard deviation ratio (daytime reflective band and night time thermal band image data) (floating point)

- L0c / L1R differences in relative bias between forward and reverse scans (daytime reflective band and night time thermal band image data) (floating point)
- L0c / L1R ratios of relative gains between forward and reverse scans (daytime reflective band and night time thermal band image data) (floating point)
- L0R saturation bins applicable to L0c image data (daytime reflective band and night time thermal band image data) (byte)
- Temperatures (daytime / night time thermal band image data) (floating point)

17.5 Algorithm Description

For night time L0R reflective band image data:
Within each 'window' of image data that the CPF window parameter defines, perform the following steps:

1. Using the available LMASK information (to exclude pixels due to dropped lines / scans, impulse noise, and 0/255 saturation events), generate detector-specific histograms on the L0R image data. At this stage, histograms should be generated for all forward scans only, all reverse scans only, and all scans together. The amount of data considered varies depending on the CPF-defined window size mentioned earlier (the default value for this parameter is 1, which effectively represents an individual scene), as well as the starting pixel location obtained from the SLO data. Center the histogram bins at the integer DN values, and make the bins 1/100 DN in width. As the data to be histogrammed have been converted from 8-bit unsigned integer to floating point, the bin limits are approximately (DN)-0.5 to (DN)+0.49. Given that the DN values are at essentially bias level, only 11 aggregated bins (ranging from 0 to 10 DN) are required for a complete characterization.
2. From the detector-specific histogram information, generate a band-level histogram for all normally operative detectors (obtained from the dead / degraded detector information from the CPF).
3. From the available histograms, compute summary first- and second-order statistics (i.e., mean and standard deviation) for each detector and for the band as a whole. These calculations should be performed for data from all forward scans only, all reverse scans only, and all scans considered together. The resulting data are written to the report file, and trended to the database.

For daytime L0R image data (all bands) and night time thermal band image data:
Within each 'window' of image data that the CPF window parameter defines, perform the following steps:

1. Using the available LMASK information to exclude pixels from dropped lines / scans and detector saturation (0/255 DN) artifacts, generate detector-specific histograms, as well as a band-level histogram over all normally operative detectors. Center the bins at (integer) DN values, and make the bins 1/100 DN in width.
2. From aggregated histogram information, determine whether analog saturation artifacts are present. To perform this assessment, start from the highest bin

below 255 DN, and find the first bin with a count of Saturation_Bin_Threshold_Bx or greater. From this bin, check the number of adjacent lower bins (defined by Adjacent_Bin_Number_Bx) to see if their total count is below the adjacent bin threshold (defined by Adjacent_Bin_Threshold_Bx). If this condition is met, then the bin with the saturation bin threshold is considered analog saturated high. If the condition is not met, record a default high saturation value of 255 into the database and terminate the search. Repeat this test at the low end, only this time look for the first bin above 0 DN at the Saturation_Bin_Threshold_Bx or greater, and search the number of adjacent higher bins to see if the total count is below the adjacent bin threshold. If this condition is met, then the bin with the saturation bin threshold is considered analog saturated low. If the condition is not met, record a default low saturation value of 0 into the database and terminate the search.

3. After counting the total number of analog saturated pixels (excluding the pixels from further histogram calculations), determine the 'gross' mean and standard deviation ('gross' referring to the fact that these data have not been bias corrected). Record the summary statistics to the appropriate report file and trend to the database.

For night time L0c reflective band image data:
Within each 'window' of image data that the CPF window parameter defines, perform the following steps:

1. Following SCS correction (implemented in the "Correct SCS" function) and using the available LMASK information to exclude dropped lines / scans and detector saturation artifacts, generate detector-specific histograms. From this stage of radiometric processing onward, it is possible that negative DN values were created due to artifact correction. Center the bins at (integer) DN values and set the bin widths to 1/100 DN. It is expected that the bin values range from approximately -5 DN to 10 DN (requiring about 16 aggregated bins for a full characterization). From this high resolution histogram information, calculate and trend the following summary statistics: minimum, maximum, mean, standard deviation, and total number of pixels. Also, record in the trending database that the statistics came from image data that were only corrected for SCS.
2. Following CN correction (if enabled in the processing flow), generate detector-specific histograms. Calculate and trend summary statistics. In addition, record in the database that these statistics came from image data that have been SCS and CN corrected.
3. Following ME correction (implemented in the "Correct ME" function), generate detector-specific histograms. From this high-resolution information, calculate and trend the minimum, maximum, mean, standard deviation, and total number of pixels statistics. In addition, record in the database that the statistics came from image data that have been SCS, CN, and ME corrected.

For daytime L0c image data (all bands) and night time thermal band image data: Within each 'window' of image data that the CPF window parameter defines, perform the following steps:

1. Using the available LMASK information to exclude dropped lines / scans and detector saturation artifacts, generate detector-specific histograms for forward scan data only, reverse scan data only, and all scans together. Due to the artifact correction, negative DN values can occur. As the amount of correction could be greater than expected for L0c night time image data, estimate bin limits in the following manner. At the lower end, find the most negative DN value and convert it to the nearest (negative) integer. At the higher end, find the largest DN value and convert it to the nearest (positive) integer. As with the other histograms generated according to this algorithm, center the bins at (integer) DN values, and set the width to 1/100 DN.
2. For a normally operative detector where L0R analog saturation limits were detected and recorded earlier in the LMASK, remove from consideration all pixels below the low analog saturation level and above the high analog saturation level. This step removes all pixels with negative DN values due to artifact correction.
3. For the remaining detectors in the scan, remove an equal number of the brightest and darkest pixels. This step is necessary in order to force all detectors to be equally sampled. Calculate and trend the unweighted summary statistics for all forward scans only, all reverse scans only, and the ratios of forward to reverse scans, and write the results to the appropriate report file and database tables.
4. Subtract the detector bias for each scan line determined by the IASICP function run on L0c calibration data. Due to potential errors in bias estimation, potential negative DN values can occur.
5. Regenerate detector-specific histograms on the bias-corrected image data. Structure bin centers and widths as previously described (centered on integer DN values and 1/100 DN in width). Calculate and trend the summary statistics for all forward scans only, all reverse scans only, and the ratios of forward to reverse scans, and write the summary statistics to the appropriate report file and database table.
6. For each detector, calculate the relative gain defined as the ratio of the bias-corrected mean value to the selected reference source (both the band average and the selected individual reference detector) according to the following:

$$g_i = \frac{\overline{m_i}}{\overline{\overline{m}}} \qquad \text{(1a)}$$

$$g_i = \frac{\overline{m_i}}{m_{ref}} \qquad \text{(1b)}$$

where *ref* indicates the mean of the reference detector and $\overline{\overline{m}}$ indicates the band average histogram mean.

7. For each detector, calculate the relative gain defined as the ratio of the detector standard deviation to the standard deviation of the reference source (both the band average and the selected individual reference detector) according to the following:

$$g_i = \frac{s_i}{\bar{s}} \qquad (2a)$$

$$g_i = \frac{s_i}{s_{ref}} \qquad (2b)$$

   where *ref* indicates the standard deviation of the reference detector and $\bar{s}$ indicates the band average histogram standard deviation.
8. Trend the relative gain results generated in steps 6 and 7. These estimates can also generate lifetime models of relative gain response for each detector.
9. Calculate and trend estimates of relative bias based on the 'gross' summary statistics calculated in step 3. These estimates are calculated according to the following:

$$b_{rel} = \overline{m} - \bar{s}\,\frac{m_i}{s_i} \qquad (3a)$$

$$b_{rel} = m_{ref} - s_{ref}\,\frac{m_i}{s_i} \qquad (3b)$$

10. Weight the band average bias-corrected mean and standard deviation calculated in step 5 with the detector noise level (which is the standard deviation of the L0c calibration shutter region). Do not include dead / degraded detectors in this calculation. Write the results to the appropriate report file.
11. Calculate the ratios and differences of relative gains and biases for both mean-based and standard deviation-based ratios, and write the results to the appropriate report file.

For L1R day and night image data (all bands):
As currently conceived, this is a 'cosmetic' step for residual striping removal, and is by default turned 'off.' If activated, perform the following steps:

1. For each window of calibrated image data defined according to the CPF window parameter, generate detector-specific histograms.
2. For each window of calibrated image data, calculate relative gains and biases as described in steps 6 through 9 for L0c daytime reflective band and night time thermal band image data. In step 7, calculate and trend the relative bias estimates calculated from the bias-corrected detector, reference means, and standard deviations. Write the relevant summary statistics and relative gain estimates to the appropriate report file.

17.6 Issues

In R8.1 prior issues with the low-high saturation detection algorithm (involving adjacent bin locations) have been resolved. As of 4/11/08, the saturation algorithm only searches 150 unity width histogram bins when detecting potential low-high saturation points. For data with a dynamic range of 0-255, this seems reasonable (i.e., L0R); however, in the IAS implementation, the 150 bins searched must be considered in context with how many histogram bins exist. In the R8.0.3 timeframe, the histogram dynamic range was set from -20 to +450. The consequence is that the high-end search only executes starting at 450, moving down 150 bins. This may not be enough to accurately characterize all scenes. Similarly, the low-end search executes from -20 and moves up 150 bins. An algorithm revision was implemented in IAS R8.2 (CCR5374), forcing the search to execute from hist-min to 130 and from hist-max to 130. The 130 numerical value is expressed in absolute DN and/or radiance units depending on where in the process flow the saturation search is executed.

17.7 References

USGS/EROS. LS-IAS-02. Landsat 7 (L7) Image Assessment System (IAS) Radiometric Algorithm Theoretical Basis Document (ATBD). Version 1.0. June 2003.

Helder, D.L., Ruggles, T.A, Dewald, J.D., Madhavan, Sriharsha. Landsat-5 Thematic Mapper Reflective-Band Radiometric Stability. IEEE Transactions on Geoscience and Remote Sensing. Vol. 42, No. 12. Dec. 2004. pp 2730-2746.

Section 18 Band 6 Trending

18.1 Introduction

The calibration of the TM thermal band, Band 6, is different from that of the reflective bands. Due to the nature of the thermal environment, the shutter is not the system offset, and the instrument gain is calculated for every scan from the shutter and blackbody responses. The offset is calculated based on a prelaunch model from the shutter, gain, and CPF coefficients. This routine extracts shutter and blackbody pulse information from artifact-corrected reflective thermal band calibration data and calculates the per-scan gain and offset. All four of these parameters (shutter, pulse, gain, and offset) are recorded in the database on a per-scan and per-scene basis.

18.2 Background

The Hughes algorithm, developed at the Santa Barbara Research Center, determines the average count from the blackbody pulse and the shutter. The pulse and shutter are used in a model developed during prelaunch testing to calculate the instrument gain and offset.

18.3 Inputs

- L0R Band 6 IC data (floating point)
- Dead / degraded detector information
- Detector noise levels (floating point)
- Number of scans in the window used for calculation (between one and three total scenes) (integer)
- CPF coefficients

18.4 Outputs

For trending (per detector, per scan direction):

- Per-scan shutter average and stdev
- Per-scan net integrated pulse
- Per-scan pulse center location
- Per-scan pulse width
- Per-scan pulse minima
- Per-scan pulse maxima
- Per-scan gains
- Per-scan offsets
- Scene average gain and stdev of the per-scan gains
- Scene average offset and stdev of the per-scan offsets

For the report file (per detector, per scan direction):

- Per-scan shutter average and stdev
- Per-scan net integrated pulse

- Per-scan pulse center location
- Per-scan pulse width
- Per-scan pulse minima
- Per-scan pulse maxima
- Per-scan gains
- Per-scan offsets
- Scene average gain and stdev of the per-scan gains
- Scene average offset and stdev of the per-scan offsets
- Temperature and radiance of blackbody and shutter

18.5 Algorithm Description

1. The Hughes algorithm determines the average count from the blackbody pulses and the shutter. Figure 18-1 shows a sample Band 6 calibration scan for one detector in one direction.

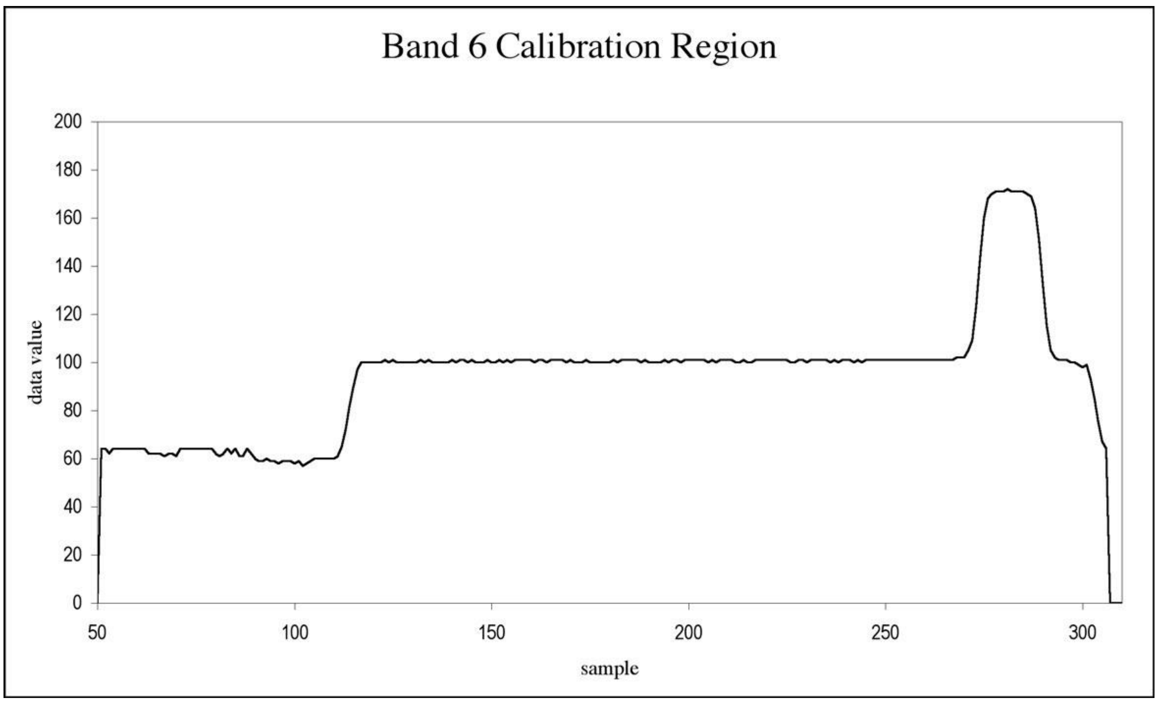


Figure 18-1. Band 6 IC Response and Pulse Location

The average count of the blackbody pulse is calculated using the Hughes algorithm (see Figure 18-2). The following steps summarize the Hughes algorithm:

a. Find the location of the blackbody pulse (pulse maximum) peak.
b. Find the pulse "shoulders" location on either side of the peak; the location of the shoulder points is where the DN is 95 percent of the peak value.
c. Find the pulse center location; the center is the location midway between the shoulders.

d. Average the data ±3 pixels about the center location (seven pixels total) to determine the scan average pulse value, also called the Integrated Pulse Value (IPV) or Q_{bb}.

Find the pulse maximum and pulse minimum, which are the maximum and minimum values in the region ±3 pixels about the center location. Write the pulse maximum, pulse minimum, center location, and pulse width (number of pixels between the shoulders) to the database.

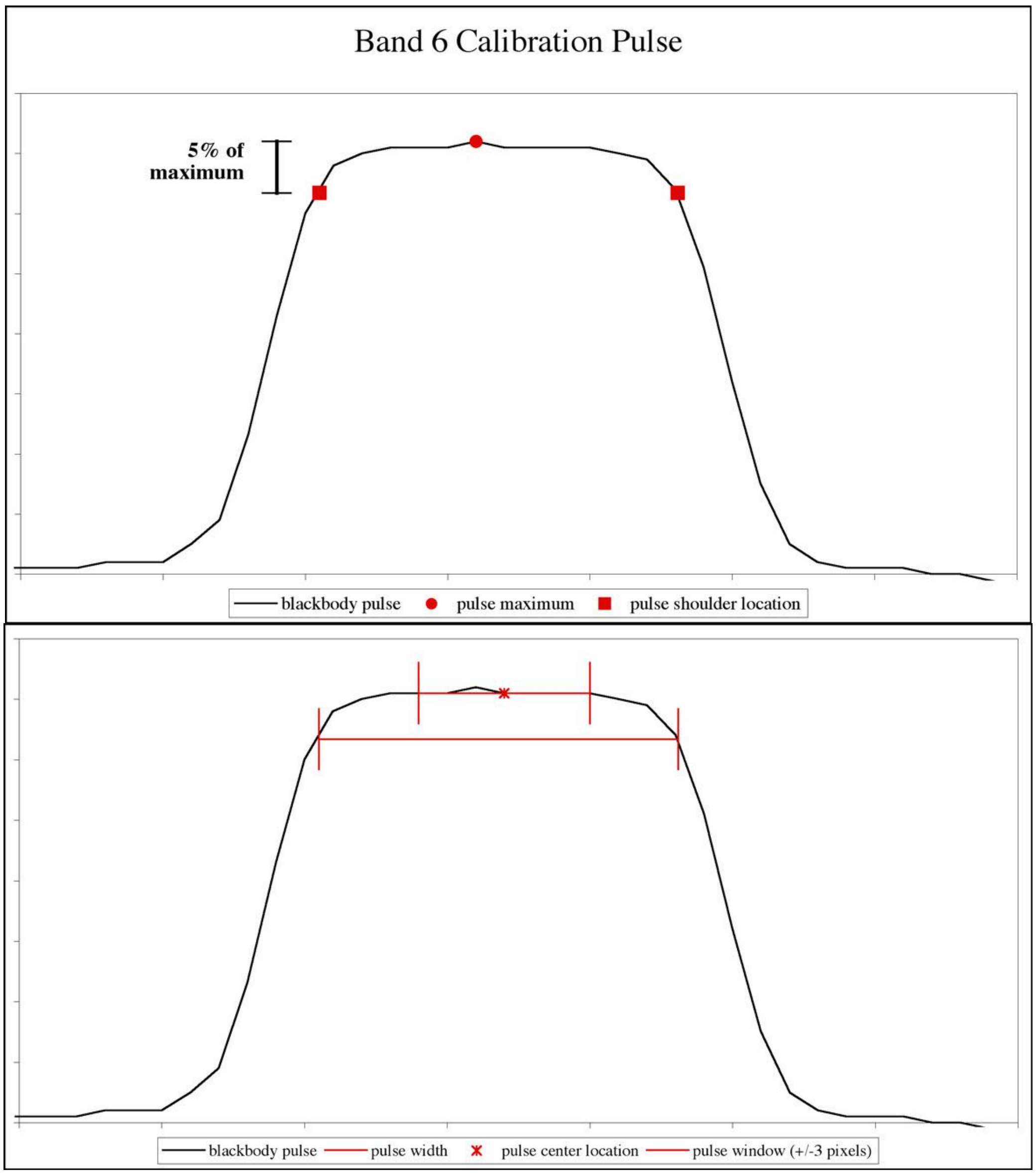


Figure 18-2. Band 6 Blackbody Pulse Calculation

2. Integrate the shutter data over the calibration shutter window for a scan. The window width is hard coded to 101 (consensus between Julia Barsi and Esad Micijevic, August 2007). The window center is hard coded to 78, a location halfway between the reverse and forward pulses. Calculate the mean shutter value in this window, which is the integrated shutter value (Q_{sh}) per scan. Write the shutter value to the database.

3. Calculate the Net Pulse Value (NPV) from the IPV and the shutter value. Write NPV to the database:

$$NPV = Q_{bb} – Q_{sh}$$

4. Calculate the scan-based gains from the integrated pulse and shutter data.

$$G_{in} = (Q_{bb} – Q_{sh}) / (L_{bb} – L_{sh})$$
$$G_{ext} = a \times G_{in}$$

Where:
Q_{bb}-Q_{sh} is L0RC_IC_SCAN.IC_NPV
Q_{sh} is L0RC_IC_SCAN.IC_SHUTTER_MEAN.
L_{bb} is the scene average of PCD_MAJOR_FRAMES.TEMP_BLACKBODY_ISO (in Kelvin) converted to radiance.
L_{sh} is the scene average of PCD_MAJOR_FRAMES.TEMP_CAL_SHUTTER_FLAG (in Kelvin) converted to radiance. Spectral radiance, L, can be extracted from Blackbody (T_{bb}) and Shutter Flag temperatures (T_{sh}) as:

$$L_{bb} = (d_1 \times T_{bb} - d_2) \times T_{bb} + d_3$$
$$L_{sh} = (d_1 \times T_{sh} - d2) \times T_{sh} + d_3$$

where d_1, d_2, and d_3 are the first, second, and third value from the CPF parameter Temp_To_Rad, respectively.
a is a per-detector constant, given in the CPF.

Calculate the scene-average G_{in} for use in step 5. Write the per-scan G_{ext} to the database. Calculate the scene average G_{ext} and write it to the database.

5. Compute the per-scan offsets based on scene-averaged gains and per-scan integrated shutter values:

$$Q_0 = Q_{sh} - G_{in} (b \times L_{sh} - c)$$

Where b and c are per-detector constants given in the CPF and G_{in} is the per-detector scene average from step 4.

Write Q_0 to the database per-scan. Calculate the scene average Q_0 and write it to the database.

18.6 Issues

The IAS 8.0.1 Configuration Change Request (CCR) covering this issue does not include any outlier rejection for the shutter average, pulse average, or the per-scene averages. For example, a known problem exists when impulse noise occurs in the pulse region. (CCR 5139) addresses this issue.

Note 5/16/2008: It has been observed while implementing / testing the L5 TM IAS, that L4 TM Band 6 calibration pulses may be narrower in width than their L5 TM equivalents. During L4 TM code development (R9.0), efforts should be given to studying this situation and potentially modifying hardcoded parameters.

18.7 References

USGS/EROS. LS-IAS-02. Landsat 7 (L7) Image Assessment System (IAS) Radiometric Algorithm Theoretical Basis Document (ATBD). Version 1.0. June 2003.

Barsi, J.A, Chander, G., Markham, B.L., Higgs, N. Landsat-4 and Landsat-5 Thematic Mapper Band 6 Historical Performance and Calibration. Proceedings of SPIE, Vol. 588206-01.

Chander, G., Helder, D.L., Boncyk, W.C. Landsat 4/5 Band 6 Relative Radiometry. IEEE Transactions on Geoscience and Remote Sensing. Vol. 40, No. 1. Jan. 2002. pp 206-210.

Hook, S.J., Chander, G., Barsi, J.A, Alley, R.E., Abtahi, A., Palluconi, F.D., Markham, B.L., Richards, R.C., Schladow, S.G., Helder, D.L. In-Flight Validation and Recovery of Water Surface Temperature with Landsat-5 Thermal Infrared Data using an Automated High-Altitude Lake Validation Site at Lake. IEEE Transactions on Geoscience and Remote Sensing. Vol. 42, No. 12. Dec. 2004. pp 2767-2776.

Section 19 IASICP

19.1 Introduction

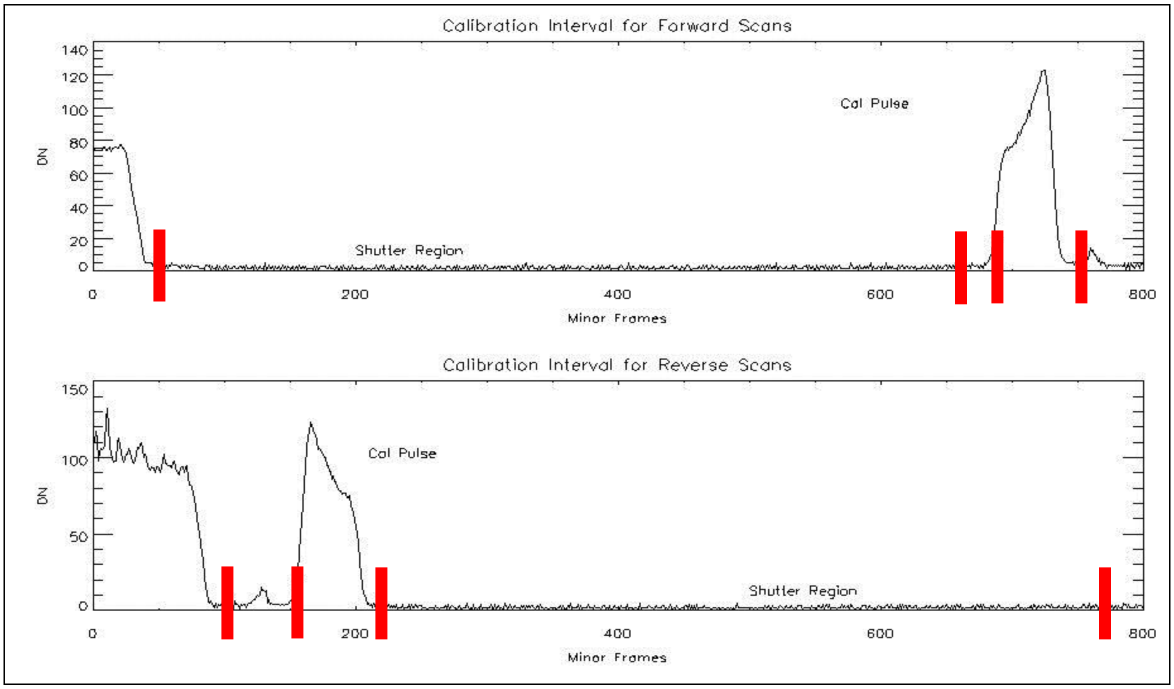
This routine extracts line-by-line, detector-averaged bias, and pulse information from artifact-corrected reflective band calibration data, and records this information in the IAS database. The detectors record these data during the scan mirror turnaround time, when the IC shutter flag passes in front of the detectors. Similar extraction and trending of Band 6 (thermal band) calibration data are provided in an independent algorithm, described in Section 18.

The IASICP algorithm runs on artifact-corrected calibration (L0c) data. Another instance of this algorithm, 'IASICP_RPS1,' runs on non-artifact-corrected L0R calibration data acquired from all IAS processed night and selected day scenes. This 'version' of the IASICP algorithm provides all of the bias level / pulse value information required for SCS artifact characterization, as well as pulse lamp state / parameter information (i.e., width) required for ME artifact characterization. The major difference between these algorithm versions is that the algorithm runs on non-artifact-corrected data obtained by line-by-line bias information from a smaller 'window' within the shutter region. In addition, the IASICP_RPS1 algorithm instance provides shutter bias location information to allow FFT generation as a component of the CN characterization routine.

19.2 Background

The IC system on the L4 / L5 TM is located between the SLC and the primary focal plane [1]. For the reflective bands, three tungsten lamps are individually filtered to produce non-attenuated, 25 percent attenuated, and 50 percent attenuated outputs covering eight distinct radiance levels. The lamp outputs are directed to the primary focal plane with fiber optic cables and a system of focusing lenses / prisms attached to a black-painted shutter flag. The relay optics system directs a portion of this output to the cold focal plane.

Three calibration data 'segments' are produced during every scan turnaround period following the acquisition of the image data. This action is due to the motion of the shutter flag across the focal planes at the same operating frequency as the main scanning mirror (~7 Hz). For forward scans, the first segment consists of an extended record of the bias level acquired when the detector arrays are completely obscured. The second segment consists of a calibration 'pulse' from the lamp outputs produced as the flag motion across the focal planes gradually exposes and re-obscures the detector arrays. The final segment is a shorter record of the bias level as the detector arrays are again completely obscured. For reverse scans, these segments are acquired in reverse order as the flag moves in the opposite direction across the focal planes (i.e., the shorter bias level record is acquired first, then the calibration 'pulse,' and finally the extended bias level record). Figure 19-1 shows a sample plot of the forward and reverse scan calibration data sequences.



The thick lines approximately designate the data segments acquired within a scan.

Figure 19-1. Sample Forward and Reverse Scan IC Data

During a typical image acquisition, the IC lamps are cycled through eight brightness 'states' to produce the desired radiance levels; each state is produced when any one of the lamps is turned on or off. The state occurring when all lamps are turned off (represented by the notation '[000]') is followed by the other states in the order '[100],' '[110],' '[010],' '[011],' '[111],' '[101],' and '[001],' finally returning to the state '[000]' to repeat the cycle. Each 'state' is sampled approximately 20 times in each scan direction.

19.3 Input Data

- Reflective band IC data (floating point)
- LHS and RHS SLO data—for RHS fill information
- MSCD—for scan direction / timestamp information
- LMASK

19.4 Input Parameters

- None

19.5 Data Trended to IAS Database

Scene specific:

- Band number
- Detector number
- Bias information:

- Forward scan mean bias and standard deviation (floating point)
  - Reverse scan mean bias and standard deviation (floating point)
  - Overall mean bias and standard deviation (floating point)
  - Scan direction (0-All scans, 1-Forward scan, 2-Reverse scan) (integer)
- IC Pulse information:
  - Lamp state (integer), given by values ranging from 0 to 7, in order of increasing brightness (i.e., 0 maps to the '000' state, 1 maps to the '001' state, 2 maps to the '010' state, 3 maps to the '011' state, 4 maps to the '100' state, 5 maps to the '101' state, 6 maps to the '110' state, and 7 maps to the '111' state)
  - Forward scan pulse width mean and standard deviation (floating point)
  - Reverse scan pulse width mean and standard deviation (floating point)
  - Forward scan pulse center mean and standard deviation (floating point)
  - Reverse scan pulse center mean and standard deviation (floating point)
  - Forward scan pulse peak mean and standard deviation (floating point)
  - Reverse scan pulse peak mean and standard deviation (floating point)
  - Forward scan pulse minimum mean and standard deviation (floating point)
  - Reverse scan pulse minimum mean and standard deviation (floating point)
  - Forward scan bias-corrected NPV mean and standard deviation (floating point)
  - Reverse scan bias-corrected NPV mean and standard deviation (floating point)
  - Forward scan IPV mean and standard deviation (floating point)
  - Reverse scan IPV mean and standard deviation (floating point)

Scan specific:

- Band number (integer)
- Detector number (integer)
- Line-by-line detector bias statistics (floating point)
  - Mean and standard deviation
- Line-by-line calibration pulse information:
  - Estimated pulse width (floating point)
  - Estimated pulse center (floating point)
  - Estimated pulse peak (floating point)
  - Estimated pulse minimum (floating point)
  - Estimated bias-corrected or (NPV) (floating point)
  - Estimated bias-corrected or NPV sample standard (floating point)
  - Estimated IPV (floating point)
  - Estimated IPV sample standard (floating point)
  - Estimated lamp state (integer), which range from 0 to 7 in order of increasing state brightness, as described for the scene-level information.
  - Estimated lamp state transition status, 0-normal, 1-in transition (integer)
- Line-by-line band number (integer)
- Line-by-line detector number (integer)

- Line-by-line scan number (integer)
- Line-by-line scan direction, 1-Forward scan, 2-Reverse scan (integer)
- Line-by-line scan time (date / time?)
- Line by-line status flag (integer)

19.6 Data Written to Report

For each reflective band, this routine also generates a report, which includes the following:

- A summary scene and processing information 'header' with:
  - Scene ID
  - WRS path and row
  - Acquisition date / time in calendar year format and days since launch
  - IAS processing version
  - Processing date / time in calendar year format
- Detector-specific bias and pulse information summarized according to scan direction (i.e., 'forward,' 'reverse,' and 'both')
- Line-by-line bias / pulse information trended to the IAS database (excluding the scan time information)

For both summaries, the presented detector order corresponds to the top-to-bottom order in a scan (i.e., Detector 16 first, followed by Detector 15, then Detector 14). For a given detector, the pulse information is further sorted according to lamp state.

19.7 Algorithm Description

1. Determine the scan number (1-based) corresponding to the first scan of the '[000]' lamp state, using reverse scan data for a combination of Detector 15 and Detector 13, Detector 15 and Detector 11, and Detector 13 and Detector 11. Use the calibration data from the current band being processed for this step. If both detectors for any pair 'agree' (i.e., return the same index), the starting scan number is considered 'valid.' If none of the detectors agree, do not attempt to extract calibration pulse information; extract and trend the line-by-line and detector-specific bias information according to the procedure for each band described in step 3.

2. If a 'valid' starting scan number for the '[000]' state has been determined, determine the starting and ending scan numbers (again, 1-based) for each lamp state, according to the following approximate TM lamp state sequence definition:

   - '[000]': 43 scans
   - '[100]': 40 scans
   - '[110]': 37 scans
   - '[010]': 43 scans
   - '[011]': 40 scans

- ‘[111]’: 37 scans
- ‘[101]’: 40 scans
- ‘[001]’: 40 scans

For example, if the starting scan number for the ‘[000]’ state is 100, then the starting scan for lamp state ‘[100]’ is 144, the starting scan for lamp state ‘[110]’ is 184, etc.

Note: From scene-to-scene, the scan counts are known to vary a small amount (typically one to two counts).

Given the total number of scans in this sequence (320) and the total number of scans in a calibration data set (374), a ‘partial’ lamp state sequence is typically located at the top and/or bottom of the input calibration data set. Determine starting and ending scan locations for these as well. Flag the first 12 scans and the last 4 scans within each lamp state to indicate that they are ‘transition’ scans whose data are to be excluded in later calculations in order to avoid the effects of lamp turn on / off transients. This flagging should also account for any variation in the number of scans actually recorded for each lamp state.

The computational logic of IASICP is designed to produce summary statistics (mean and standard values) from scans located in “full” lamp state sequence regions of the calibration file, and ignore underlying data from “partial” regions located at the top / bottom of the calibration file. While small improvements in numerical results could be achieved using all scans for a given LS, the additional code complexity was deemed not worth the effort. Given the way the TM sensor’s IC lamp repeat cycle works and the 374 scans length of a WRS-2 scene for one given lamp state (which varies from scene to scene), either one or two full region occurrences may occur; for all other lamp states, only one full region should occur. Thus, the IASICP code logic is designed to seek for, at most, one lamp state executing a full repeat. Filtering above and beyond the application of the LMASK is performed using localized statistics, tracing its heritage to prototype code from South Dakota State University (SDSU) that did not utilize LMASK. For the one full repeating lamp state region, this implies filters are/can be applied without producing a joined data population.

Note 10/30/08: During IAS R8.1 system testing, a scene was processed wherein one or more lamp states occurred for two full cycles. It was thought that only scans from the first full lamp cycle would compute band level statistics; however, calculations indicated that all valid scans in both complete cycles were used. After extensive discussion, this result was accepted as valid. For lamp states exhibiting one full cycle plus a partial, only the scans from the full cycle were used to compute band level results (as expected).

For each band of calibration data, perform the following steps:

3. Calculate line-by-line bias statistics (mean and standard deviation) according to the following steps:

   a. Calculate an initial mean value and standard deviation from the samples within a 550-pixel window centered in the middle of the shutter region (well away from the calibration pulse). Exclude those samples flagged in the LMASK as having impulse noise. If the entire line / scan is flagged as 'dropped' in the LMASK, go to the next scan line. Retain the cumulative sum and squared sum 'counter' values used in the statistics calculations.
   b. If the window standard deviation is greater than 3.3 (the ratio of an expected upper valid data bound of 10.0 DN to a 'nominal' bias value of 3.0 DN following a DC-restore operation), check each 'valid' (nonimpulse noise affected) bias sample within the window to see if its value is greater than the initial mean value + 10.0 DN. For those valid samples where this condition occurs, subtract the corresponding values from the cumulative sum and squared sum counters, and increment an initial outlier counter.
   c. Recalculate the mean and standard deviation using the adjusted sum / squared sum counters and reduced 'valid' pixel count (the difference between the original sample count in the window and the initial outlier count).
   d. Calculate the lower and upper outlier threshold values from the adjusted statistics generated in step 3c as follows:

$$
\begin{aligned}
L &= \mu - 3\sigma \\
U &= \mu + 3\sigma
\end{aligned}
\tag{1}
$$

   e. Search through the window again. For the remaining 'valid' samples, if their value is greater than the upper outlier threshold value or less than the lower outlier threshold value, subtract the corresponding values from the accumulated sum / squared sum counters and increment a 'final' outlier count. From these outlier-reduced values, recalculate the mean and standard deviation. Make sure to subtract the final outlier count from the current 'valid' sample count (the count obtained in step 3c) prior to recalculating the mean and standard deviation.
   f. From the line-by-line bias statistics obtained in steps 3a through 3e, calculate detector-specific bias statistics for all forward scans, all reverse scans, and all scans together.
   g. Trend the line-by-line and detector-specific bias estimates to the IAS database, and record the values in the summary report.

Perform steps 4 through 6 if a 'valid' lamp state sequence assignment could be performed according to steps 1 and 2 above.

4. Perform a line-by-line extraction of the peak, width, minimum, and NPV parameter values, according to the following procedure:
   a. Starting in the center of the shutter region, locate the pulse 'edge,' which is the first in a sequence of five consecutive samples where the DN value is

above a minimum threshold value of 12.0 DN. This threshold value is currently applicable to all reflective bands. For forward scans, the edge to locate is the ‘left’ or ‘leading’ edge, while for reverse scan pulses, the edge is the ‘right’ or ‘trailing’ edge.

b. Initialize the peak value to the DN value of the starting edge sample, as well as an ‘index’ value representing its location.
c. Test subsequent samples in the pulse up to the first sample whose DN value falls below 40 percent of the peak value. Update the peak value and its location accordingly, and keep track of the location where the DN value first falls below 40 percent of the peak value. For forward scans, this location defines the ending sample of the region over which pulse integration occurs; for reverse scans, this location defines the starting sample of the region over which pulse integration occurs. Perform a linear interpolation between the ending (starting) sample and the sample immediately before (after) to obtain a final ending (starting) location estimate.
d. From the index location defined in step 4b, search the pulse region in the opposite direction to find the starting (ending) sample. Perform a linear interpolation between the starting (ending) location and the sample immediately after (before) it to obtain a final starting (ending) location estimate.
e. Obtain initial estimates of the pulse width and center from the starting and ending location estimates obtained in steps 4c and 4d as follows:

$$width = end - start + 1.0 \tag{2a}$$

$$center = \frac{end + start}{2.0} \tag{2b}$$

f. Obtain initial estimates of the starting and ending pulse integration limits (positions) and an estimate of the fractional interpolation width, Δ, as follows:

$$start\_mf, S = trunc(center) - 15 \tag{3a}$$

$$end\_mf, E = trunc(center) + 16 \tag{3b}$$

$$\Delta = center - (double)(trunc(center)) \tag{3c}$$

trunc(center) in (3a) through (3c) represent the conversion of the floating point value *center*, to its integer representation through truncation. The last equation determines the fractional part of the floating point value, *center*.

g. Perform linear interpolation to obtain pulse value estimates f(S+Δ) and f(E-1+Δ) at the (sub-pixel) starting (S+Δ) and ending (E-1+Δ) integration limits (positions), using the observed pulse sample values f(S), f(S+1), f(E-1) and f(E) from the discrete pixel locations S, S+1, E-1, and E, respectively:

$$f(S+\Delta) = f(S) + \Delta \times \{f(S+1) - f(S)\} \tag{4a}$$

$$f(E - 1+\Delta) = f(E - 1) - \Delta \times \{f(E -1) - f(E)\} \tag{4b}$$

h. Calculate the area under the pulse within the final starting and ending integration limits obtained in step 4g using trapezoidal integration (see Figure 19-2). As this area is being 'integrated,' keep track of the minimum observed pulse value within the integration region.

$$\begin{aligned} area &= \frac{(1-\Delta)}{2}\{f(S+\Delta)+f(S+1)\}+\frac{1}{2}\{f(S+1)+f(S+2)\}+\frac{1}{2}\{f(S+2)+f(S+3)\}+\ldots.. \\ &+\frac{1}{2}\{f(E-3)+f(E-2)\}+\frac{1}{2}\{f(E-2)+f(E-1)\}+\frac{\Delta}{2}\{f(E-1)+f(E-1+\Delta)\} \qquad (5) \\ &= \sum_{X=S-2}^{X=E-2} f(X)+\frac{1}{2}\left\{f(S+1)\times(2-\Delta)+f(E-1)\times(1+\Delta)+f(S+\Delta)\times(1-\Delta)+f(E-1+\Delta)\times\Delta\right\} \end{aligned}$$

i. From the integrated value obtained in step 4h, obtain the bias-corrected or 'net' pulse value NPV over the total number of samples, *N*, within the integration region:

$$\begin{aligned} N &= (E - 1+\Delta) - (S+\Delta) = E - S - 1 \\ &= \{(trunc(center)+16\}-\{trunc(center)-15\}-1 \\ &= 30 \end{aligned}$$

$$NPV = \frac{area}{30.0} - bias[scan][\det] \qquad (6)$$

The integration region of the observed pulse profile covers 31 discrete pixels (as defined by (3a) and (3b)). However, the observed pulse values on the left between S and S+Δ and on the right between E-1+Δ and E are excluded from the integration. Consequently, the effective number of discrete pixels within the 'true' integration region (as determined in step 4g) is 30.

5. Calculate detector-specific statistics (mean and standard deviation) for each pulse parameter according to the following procedure:
   a. Calculate an initial mean and standard deviation estimate using information from those scans in each lamp state not flagged as transition scans. Keep track of the cumulative sum / squared sum values used in the statistics calculations.
   b. Determine upper and lower outlier rejection limits as defined in (1) of step 3d.
   c. For those scan-specific estimates that fall outside the outlier limits defined above, subtract the corresponding values from the sum and squared sum totals, and increment an outlier counter.
   d. Recalculate the statistics, using the outlier adjusted cumulative sum / squared sum values and an adjusted 'valid' count (the difference between the initial data count and the outlier count).

6. Trend all line-by-line and detector-specific pulse parameters to the IAS database, and record the results in the report.

7. Determine the status of line-by-line bias and extracted pulse information and set this information in the status flag. The status flag is an 8-bit value representing validity conditions on the calibration data. The bit ordering is from right-to-left starting in bit 1 (the 'least significant bit') and ending at bit 8 (the 'most significant bit'):

    - Bit 1: flag representing a dropped line condition. This information is collected from the LMASK. '0' indicates the line was not dropped, '1' indicates the line was dropped.
    - Bit 2: flag representing the validity of the estimated detector bias. '0' indicates a valid bias estimate, '1' indicates an invalid bias estimate.
    - Bit 3: flag representing the validity of the estimated 40 percent pulse edge locations. '0' indicates that the estimated 40 percent edge locations are valid, '1' indicates that the estimated locations are invalid, which occurs if the estimated locations are at the pixel locations containing the first LHS or last RHS calibration data values.
    - Bit 4: flag representing the 'completeness' of the observed pulse profile for the given scan line. A pulse profile is considered 'complete' if the pulse extends at least 1.25 times the estimated width beyond the estimated 40 percent edge location on the RHS for forward scans, and beyond the estimated 40 percent edge location on the LHS for reverse scans. '0' indicates a 'complete' pulse profile; '1' indicates an incomplete pulse profile. This flag ultimately selects 'complete' pulse profiles for ME characterization.
    - Bits 5-7: reserved for Band 6 use.
    - Bit 8: indicates the use of saturated (i.e., ≥255DN) pixels during pulse integration calculation.

```
 8 7 6 5 4 3 2 1
[][][][][][][][]   : 1 byte
         \ \ \ \
          \ \ \ `-------- dropped line
           \ \ `--------- invalid bias
            \ `---------- invalid 40% pulse edge
          `----------- incomplete pulse profile
   \ \ \ `------------ pulse too narrow (B6)
    \ \ `------------- pulse too wide (B6)
     \ `-------------- pulse invalid peak (B6)
      `--------------- saturated pulse mf
```

8. Trend the line-by-line status flag of bias and pulse information to the IAS database, and record the results in the report.

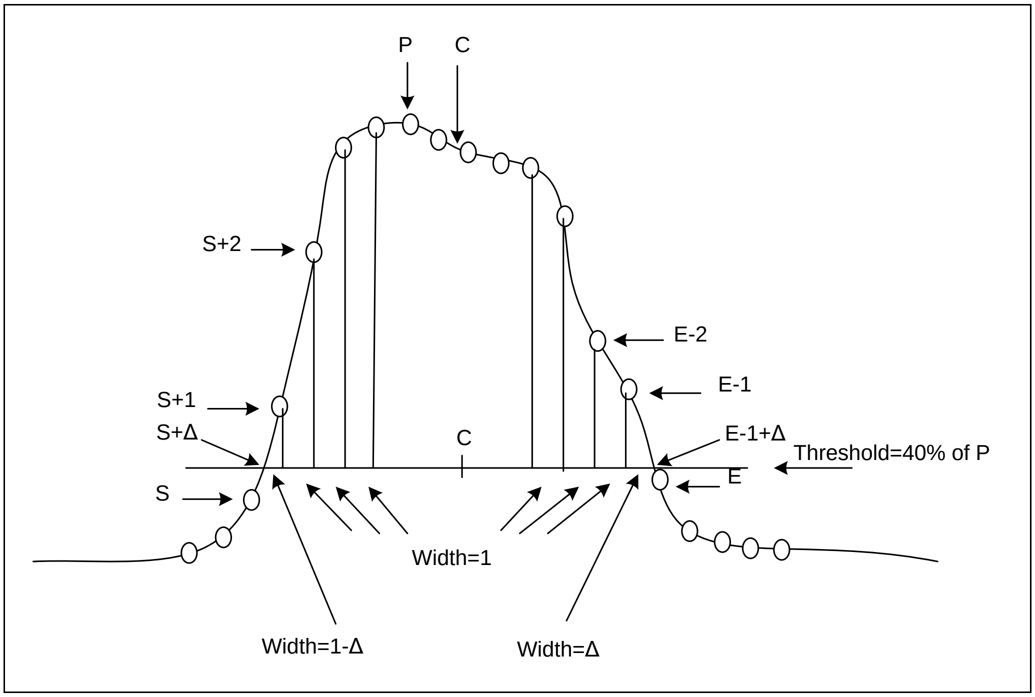


Figure 19-2. IC Pulse Showing Important Pixel Locations Used in Trapezoidal Integration

19.8 Issues

1. The leading (trailing) pulse edge is determined as the first location in a consecutive series of five samples where the DN value is above a 12.0 DN threshold. For forward scans, this method works reasonably well. However, issues may occur with a 'light leak' effect in the narrow shutter region preceding the pulse in reverse scans where an additional signal can be observed. If the calibration pulse amplitude is quite low, as in the transition between the '[001]' and '[000]' states, it is possible that the edge of this pulse would be detected, with the result that 'invalid' pulse parameter estimates would be generated. Fortunately, flagging the last four scans in this lamp state as in a transition should prevent their use in determining detector-averaged pulse statistics.
2. It is possible for IC pulse samples to be saturated and used in calculating IPV and NPV results. Starting with IAS R8.1, bit 8 of the pulse status flag is set on a line-by-line basis when saturated pixels are used in calculations. This flag should enable analysts to filter out such data. In addition, the flag is used in the IAS to remove potentially suspect data from band-level statistical calculations. The flag is set based on L0R IC data processing using IASICP_RPS1. The results of this test are carried forward and maintained for flags set by IASICP_RPS during processing of artifact-corrected IC data. This rather convoluted approach was implemented after noting that the IAS detected saturated pulse samples in L0R data, set the flag, and then failed to detect the same pulse samples in artifact corrected data. The root cause of this behavior was traced to pulse samples that were no longer exactly 255 DN; therefore, the saturation test failed and made it appear that the IPV and NPV results were valid, when in fact they were not.

3. It is possible for bias samples to record values of 0 DN, particularly in Bands 5 and 7. Due to the outlier rejection filters used in the bias calculations, this is not considered a serious issue.
4. As currently implemented, the IC status flags representing valid 40 percent pulse edge locations and/or complete pulse profiles may not properly set for those scans transitioning between LS [001] and LS [000]. Further investigation is required to determine the cause of this failure. This issue is important only for those analyses requiring valid extracted data in these transition scans.

19.9 References

Helder, D.L., Ruggles, T.A., Dewald, J.D., Madhavan, S. Landsat-5 Thematic Mapper Radiometric Stability. IEEE Transactions on Geoscience and Remote Sensing. Vol. 42, No. 12. Dec. 1984. pp. 2730-2746.

Section 20 Bias Subtraction

20.1 Introduction

This routine removes TM detector bias from artifact-corrected image data. In a typical processing scenario, line-by-line detector shutter bias values for the scene to be processed are assumed to be previously extracted from the corresponding calibration data using the IASICP or Band 6 Trending routine and stored in the IAS database. In the absence of 'valid' values that IASICP extracts, detector bias estimates are obtained from the CPF. For Band 6, CPF defaults would also be applied in the absence of a valid bias; however, no test exists for validity of the thermal band bias data.

Bias subtraction shall be performed prior to relative gain characterization / correction and absolute radiometric calibration. Bias removal from artifact-corrected calibration data (as required for determination of 'net' integrated pulse values) is performed within IASICP, and is not considered further in this document.

20.2 Input Data

- Artifact-corrected image data, all bands (floating point)
- Line-by-line detector bias estimates obtained from IASICP and Band 6 Trending (floating point)
- CPF failover bias estimates (reflective bands) (floating point)
- Validity information for scan bias estimates
- LMASK information

20.3 Input Parameters

- None

20.4 Output Data

- Bias-corrected image data, all bands (floating point)

20.5 Algorithm Description

- For the reflective bands, test the validity of the bias estimate. An IASICP-derived bias estimate for any detector is considered 'valid' if the following condition is satisfied:

$$B^i_{lower} \leq b^i_{scan} \leq B^i_{upper}$$

  where B^i_{lower} and B^i_{upper} are detector-specific minimum and maximum bias limits obtained from the CPF, and b^i_{scan} is the IASICP-derived estimate for the current scan line.

  CPF bias values are intended, as a last resort, for bias removal in subsequent radiometric processing / analysis of daytime image data whenever any of the following extreme conditions occur:

- An entire line / scan of bias data is dropped, as determined from previous LMASK preprocessing of the calibration data.
- The IASICP determined a line-by-line bias value is less than the detector-specific lower bias limit or greater than the detector-specific upper bias limit.

Currently, no validity check exists for Band 6 bias. Due to the contaminant on the cold focal plane, the Band 6 bias and gain vary by tens of DN. A small range threshold would not be appropriate for these biases.

- For each line of image band data, subtract either the corresponding ‘valid’ mean shutter bias value or the appropriate detector-specific mean bias value obtained from the CPF to generate the final bias-corrected output image data.

20.6 Future Considerations

1. It is possible that image data pixels can possess negative DN values following bias correction. Such pixels should be flagged and counted on a detector-specific basis; the counts should be stored in the IAS database. ‘Excessive’ negative DN counts (greater than five percent of the total number of pixels) should be reported to the IAS Operator for offline Evaluation and Analysis (E&A).
2. As mentioned earlier, the detector-specific limits indicating a ‘valid’ IASICP bias estimate are obtained from the CPF. The initial default limits of 0.5 DN and 6.0 DN were chosen based on an analysis of band-average bias levels for Bands 1-4. These limits for Bands 5 and 7 were set to 0.5 DN and 3.5 DN after the analysis of bias levels recorded in the IAS R8.0 database. A possibility exists that due to overall changes in bias level, the limiting values could change for each detector. An IAS Analyst should periodically monitor IASICP-derived bias levels over time and, if necessary, adjust the limits on a detector-specific basis.

20.7 References

None

Section 21 Relative Gain Correction (Lifetime Model)

21.1 Introduction

This algorithm performs DN relative gain (‘destriping’) correction on L4 / L5 TM reflective band day image data. By default, it is assumed that the data have been previously artifact-corrected (suggested) and bias-corrected (required).

Band 6 is not run through this module. The Band 6 relative gains are applied by adjusting the CPF calibration coefficients, the a, b, or c parameters in the BAND_6_CALIBRATION_COEFFICIENTS group.

21.2 Inputs

- Artifact-corrected, bias-corrected L0R day image data (reflective bands) (floating point)
- LMASK
- DSL value for the scene to process

21.2.1 Input Parameters from the CPF

- Lifetime model parameters (i.e., slope and intercept) for each detector (floating point)

21.3 Outputs

- Destriped L0R day image data (reflective bands) (floating point)

21.4 Algorithm Description

1. Acquire the correction model parameters from the CPF.
2. Use the CPF Relative Gain Slope and Intercept values to evaluate a simple linear model (function of DSL) for each detector’s relative gain.
3. Destripe the scene by multiplying bias-subtracted image data by the reciprocal value of the relative gain derived from the model for each detector.

21.5 Future Considerations

The Relative Gain (RG) CFs for L5 TM are obtained from the linear models for detectors characterized from 1984-2000. It would be necessary to update the model parameters in order to accurately correct for RG beyond 2000. The initial L4 TM CPF is initialized with RG factors derived outside the IAS environment at SDSU. When the L4 TM processing capabilities exist (R9.0), a remodeling effort should be undertaken.

21.6 References

D.L.Helder, T.Ruggles, J.Dewald, S.Madhavan. Landsat 5 Radiometric stability. IEEE Trans. Geosci. Remote Sensing. December 2004.

USGS/EROS. LS-IAS-02. Landsat 7 (L7) Image Assessment System (IAS) Radiometric Algorithm Theoretical Basis Document (ATBD). Version 1.0. June 2003.

Chander, G., Helder, D.L., and, Boncyk, W.C. Landsat- 4/5 Band 6 Relative Radiometry. IEEE Trans. Geosci. Remote Sensing. vol.40. pp 206-210. Jan 2002.

Schowengerdt, R.A. Remote Sensing, Models and Methods for Image Processing. pg 301. Second edition. Academic Press. 1997.

Helder, D.L., Micijevic, E., and, Ruggles, T.A. Landsat TM Radiometric Artifacts. IEEE Trans. Geosci. Remote Sensing. December 2004.

Helder, D.L., Boncyk, W., Morfitt, R. Landsat TM Memory Effect Characterization and Correction. Canadian Journal of Remote Sensing. vol.23. No.4. pp- 209. December 1997.

D. Helder. Comparison of MSS Relative Radiometric Calibration Methods. SPIEOE/Aerospace and Remote Sensing Symposium. April 12-16, 1993. Orlando, FL.

Section 22 Relative Gain Correction (Histogram Matching)

22.1 Introduction

This routine performs relative gain correction on artifact-corrected, bias-corrected Landsat TM reflective band image data. The relative gain estimates used in the correction process have been obtained directly from the scene being processed through prior generation of bias-corrected, 'adjusted' histograms (see Section 17 for additional details describing the procedures and the resulting relative gain estimates).

22.2 Background

This routine is an alternative method of performing relative gain correction available in the IAS. In the default processing scenario, this routine is not applied; instead, relative gain correction is performed using estimates obtained from lifetime models of detector response. However, once the relative gains are generated, the basic correction processing is identical between the two routines.

22.3 Inputs

- Artifact-corrected, bias-corrected L0R reflective band image data (floating point)
- Scene-specific relative gain estimates (floating point)

22.4 CPF Parameters

- Group = Striping
    - Correction_Reference_B1
    - Correction_Reference_B2
    - ….
    - Correction_Reference_B7

  End_Group = Striping

  Three options exist for setting the correction reference for each band as follows:
    - 0: Band Average Calculations
    - 1: Utilize Reference Detector
    - 2: No Correction is Applied

- Group = Histogram
    - Reference_Detector_B1
    - Reference_Detector_B2
    - ….
    - Reference_Detector_B7

  End_Group = Histogram

The reference detector for each band may be set for any valid detector from 1 to 16.

22.5 Outputs

- Relative gain-corrected image data (floating point)

22.6 Algorithm

The relative gain estimates derived from the scene being processed (through prior application of the histogram analysis routine) are extracted from the IAS database. The relative gain correction is then applied, on a per-detector basis, to the input image data according to:

$$DN_i^{output} = \frac{DN_i^{input}}{g_i}$$

where DN_i^{output} is the relative gain corrected DN value for detector i, DN_i^{input} is the input DN value for detector i (artifact-corrected and bias-corrected), and g_i is the detector relative gain. All parameters in the above expression are floating point numbers.

22.7 References

None

Section 23 Modulation Transfer Function Correction (L4-TM)

23.1 Introduction

The Modulation Transfer Function (MTF) is a fundamental imaging system design specification and system quality metric often used in remote sensing. MTF is defined as the normalized magnitude of the Fourier Transform of the imaging system's point spread function. [1]

This algorithm performs MTF correction, de-blurring on images with detectors exhibiting poor MTF performance. Some of these detectors have not been used since the launch of the instrument. The MTF correction models were derived from calibration file data. The correction is performed in the frequency domain by a complex division of the Fourier Transform of the image data with the MTF model for each detector. Currently, the correction is applied only to image data and not calibration data.

23.2 Input Data

- Reflective band relative gain-corrected scenes (floating point)
- Scan direction of each individual scan line
- SLO information to determine the starting and ending pixel locations for each valid scan line (integer)
- Forward scan (complex) MTF response model for each affected detector
- Reverse scan (complex) MTF response model for each affected detector
- Detectors flagged for correction in the CPF DETECOR_STATUS group

23.3 Outputs

- MTF-corrected image (floating point)

23.4 Algorithm Description

The correction is applied to the scenes immediately before the conversion to radiance.

Based on the scan direction and SLO information, valid image data for the detectors flagged in the CPF are extracted for each scan line.

For each valid scan line, the LHS and RHS boarder pixels are mirrored (select the range of pixels at the border and flip horizontally) and concatenated to the scan line data.

1. Determine the difference between the length of the scan line and the MTF model.
2. Add mirrored pixels to both sides of the image to make each line length equal to that of the MTF model.
3. If…
    a. The difference between the MTF model and the image line length is even, add an equal number of pixels (half of the difference) to both ends.
    b. The difference between the MTF model and the image length is odd, add one more pixel to the LHS than the RHS.

4. Compute the FFT of each concatenated scan line.
5. Divide the scan line data FFTs by the corresponding (forward or reverse) MTF model (complex division).
6. Take the Inverse Fast Fourier Transform (IFFT) of the divided scan line data.
7. Remove mirrored pixels from the LHS and RHS of the corrected scan line data.
8. Insert corrected scan line data back into the image.

The algorithm processes all valid scan lines (374) for each flagged detector, for scene data only.

23.5 Notes

At the time this document was written, the correction algorithm is only performed for Detector 2 and Detector 4 of Band 2 for L4 TM.

The correction models provided are in rectangular format. If required, the models can be provided alternatively in magnitude and phase (radian), whichever format makes the complex division easier.

Dropped lines are not altered if detected in the scene.

The MTF correction is in the form of a high-pass filter, and it increases noise in the data. Detailed information on this subject can be found in the following subsection.

23.6 MTF Correction Issues

Band 2 Detector 2 and Detector 4 are degraded, and are relatively noisy compared to other detectors. These degraded detectors also suffer from pixel bleeding, which results in a loss of feature contrasts within the detector’s scans (see Figure 23-1).

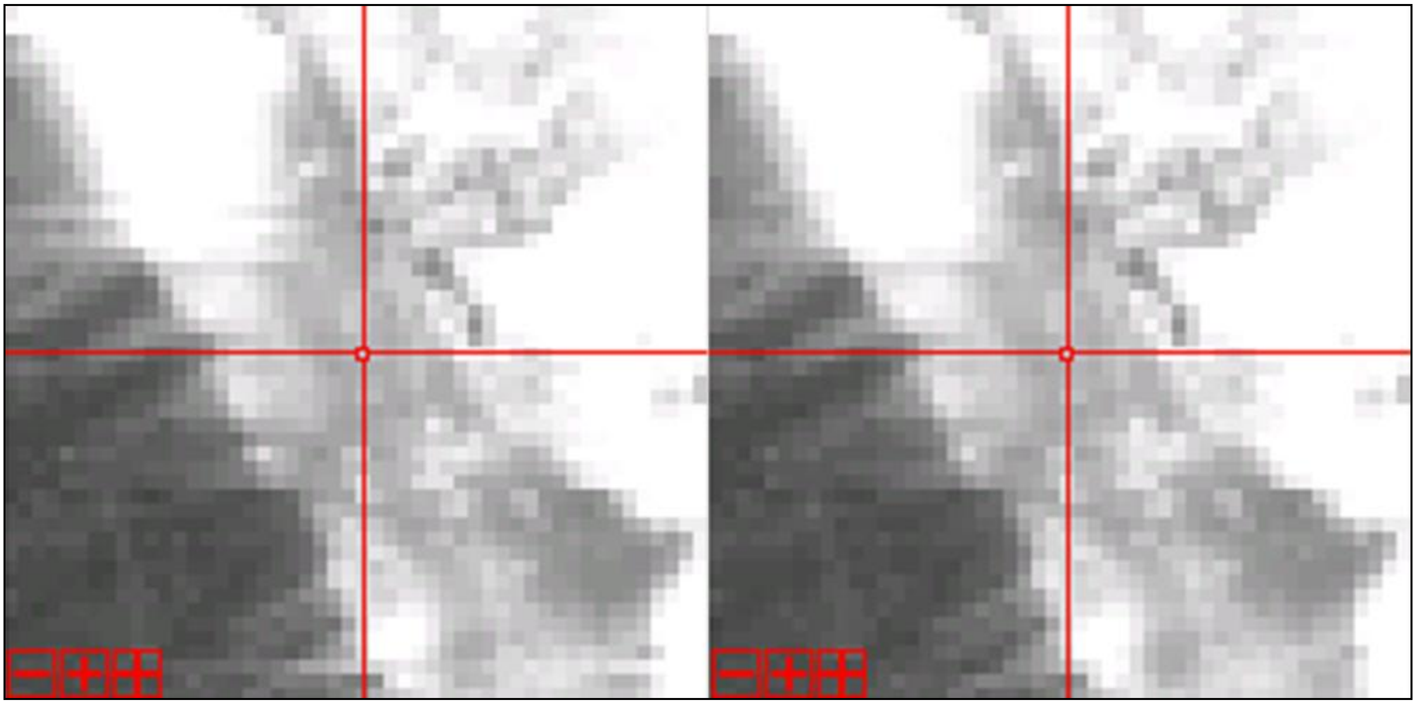


Figure 23-1. Comparison

Figure 23-1 is a comparison of bleeding pixels across an image feature (left) and the MTF corrected scan data (right).

The MTF correction filter is a high-pass filter coupled with a second order Butterworth filter that reduces the detectors' pixel bleed and restores the contrast of the image features. This correction uses the original acquisitioned data in place of the neighbor interpolated data used previous to this correction.

Some adverse effects accompany this correction. Due to the high-pass nature of the filter, the local extrema increases in magnitude causing high-reflectance pixels (such as clouds) to saturate, and a slight noise increase in homogeneous areas. Increasing the order of the Butterworth filter decreases some of the noise, but it also increases ringing in high-contrast areas. After checking several test-scenes, what is cleared up in noise reduction does not justify what is observed in the increased ringing effect. This group of nine test scenes shows the Butterworth filter to be optimized at an order of two.

23.7 References

K. Kohm, "Modulation Transfer Function Measurement Method and Results for the Orbview-3 High Resolution Image Satellite", ORBIMAGE, 1835 Lackland Hill Parkway, St. Louis

Section 24 Apply Radiometric Calibration

24.1 Introduction

To generate radiance-level products, this routine applies absolute radiometric calibration to TM image data. For the reflective bands, the gain applied to the data is based on time-dependent calibration models implemented in CPF as day-specific band average gains. The per-detector gains used to convert the thermal band DN images to spectral radiance are based on gains calculated in Band 6 Trending.

24.2 Background

Since May 5, 2003, the USGS processed and distributed L5 TM image data that have been radiometrically calibrated using a new procedure and revised calibration parameters. For reflective bands, the modified approach involves discontinuing the direct use of IC data and implementing time-dependent calibration gain LookUp Tables (LUT). The thermal band continues to make direct use of the IC data for radiometric calibration.

In March 2007, the calibration of L5 TM was updated a second time. Through analysis of pseudo-invariant desert sites and continued vicarious calibration data, it was determined that the calibration of the instrument was in error during the first 10 years of life, particularly in Bands 1 and 2. This effort resulted in a new LUT (referred to as LUT07) for all reflective bands.

For L4 TM data, conversion of DN to radiance has historically been based on the internal calibrator response. For IAS R9.0, a LUT was created (similar to that used for L5 TM processing) to hold the conversion gains. The underlying model for this LUT was developed from two absolute calibration points obtained from cross-calibration to L5 TM (using near-coincident acquisitions in 1987-1988 and 1990), and from the trend obtained from using the Libya 4 and Sonora pseudo-invariant calibration sites.

24.3 Input

- Artifact-corrected, bias-corrected, relative-gain corrected L0R image data (all bands) (floating point)
- Band 6 per-detector band-average gains from Band 6 Trending

24.4 Inputs Obtained From CPF

- Band-averaged day-specific absolute gain estimates for reflective bands, in units of DN / radiance (floating point)

24.5 Outputs

- L1R image data in absolute radiance units ($\frac{W}{m^2 sr \mu m}$) (floating point)

24.6 Algorithm Description

For reflective bands, given the day-specific calibration average gain estimates, *G(t)*, at time, *t*, radiance values are calculated as follows:

$$L(t) = \frac{1}{G(t)} DN_0 \, ,$$

where DN_0 represents artifact-corrected, bias-corrected, and relative-gain corrected image data.

For Band 6, given the scene-specific per-detector band average gains G_i for detector *i*, radiance values are calculated as follows:

$$L_i = \frac{1}{G_i} DN_{0i} \, ,$$

where DN_{0i} represents artifact-corrected, and bias-corrected thermal image data recorded by detector *i*.

In typical processing, this conversion is applied only to image data; it is not performed on calibration data or any type of ‘fill’ data.

24.7 References

Helder, D.L, Ruggles, T.A., Dewald, J.D., and Sriharsha Madhavan. Landsat Thematic Mapper Radiometric Stability. IEEE Transactions on Geoscience and Remote Sensing. Vol. 42, No. 12. December 2004. pg. 2730-2746.

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P. M. Teillet, D. L. Helder, B. L. Markham, J. L. Barker, K. J. Thome, R. Morfitt, J. R. Schott, and F. D. Palluconi. A lifetime radiometric calibration record for the Landsat Thematic Mapper. Proc. Can. Symp. Remote Sensing. Aug. 2001. pp. 17–25.

Section 25 Striping Correction

25.1 Introduction

The correct striping algorithm removes small residual offsets between detectors due either to small inherent detector sensitivity differences, or imbalances introduced in prior processing steps. This algorithm is executed on TM L1R floating-point radiance data. The applied correction factors are derived from histogram analysis executed immediately prior to this algorithm in the process flow; the applied correction factors are unique to the scene being processed, rather than being based on a lifetime sensor model or other extended characterization. This routine is skipped by default; however, the correction for individual bands (thermal and/or reflective) can be enabled if a final striping correction is desired on L1R data.

25.2 Background

In this algorithm, the L1R data are linearly adjusted to match the means and standard deviations of each detector to a reference detector, or an average of the detectors.

25.3 Inputs

- Scene Data - Normal Earth scenes (day or night) (all bands) (L1R) (floating point)
- Correction relative gains (floating point, unitless) and bias (floating point) from histogram analysis performed on L1R data. For relative gains, use the band average or reference detector for normalization. These values originate as outputs from the HistoAnalysisChar routine.

25.4 CPF Parameters

- Group = Striping
  - Correction_Reference_B1
  - Correction_Reference_B2
  - ….
  - Correction_Reference_B7

  End_Group = Striping

  Three options exist for setting the correction reference for each band as follows:
  - 0: Band Average Calculations
  - 1: Utilize Reference Detector
  - 2: No Correction is Applied

- Group = Histogram
  - Reference_Detector_B1
  - Reference_Detector_B2
  - ….
  - Reference_Detector_B7

  End_Group = Histogram

The reference detector for each band may be set for any valid detector from 1 to 16.

25.5 Outputs

- Destriped L1R image data (floating point)

25.6 Algorithm

This algorithm applies the relative gains and relative bias calculated by the HistoAnalysisChar_RPS2 analysis procedure. The relative gains are calculated by ratioing the standard deviations. The application procedure is similar to the standard destriping Land Analysis System (LAS) algorithm, "DESTRIPE," although the correction gains and bias are calculated slightly differently. (Note: "DESTRIPE" calculates and applies correction factors). The application of these gains and biases, per detector per band, is expressed as follows:

$$Q_{cor} = \frac{Q_{uncorr}}{GAIN_{rel}} + BIAS_{rel} \quad ,$$

Where

Q_{cor} is	the corrected quantized radiance
$GAIN_{rel}$	is the relative gain factor per detector, from the histogram analysis program based on the ratios of the individual detector standard deviations to the standard deviation of either the band average or reference detector,
Q_{uncorr}	is the uncorrected quantized radiance, and
$BIAS_{rel}$	is the relative bias per detector, determined by the histogram analysis program relative to either the average or reference detector.

25.7 Evaluation

Not applicable

25.8 References

USGS/EROS. LS-IAS-02. Landsat 7 (L7) Image Assessment System (IAS) Radiometric Algorithm Theoretical Basis Document (ATBD). Version 1.0. June 2003.

Section 26 Dead-Degraded Detector Data Replacement

26.1 Introduction

The L4 TM instrument historically exhibited several detectors that are either completely non-responsive or exhibit a degraded response. The RPS processing module discussed in this section details how replacement data are created and populated into the image (no changes are made to the internal calibrator data file) prior to handoff to the geometric processing routines.

26.2 Background

Two L4 TM detectors are known to have radiometric response issues. Band 5 Detector 3 is dead and locked out of processing via a flag set in the CPF Detector_Status group. Band 2 Detector 4 has a suspected degraded response and has historically been replaced in prior processing systems. In order to study the degraded response, this detector retained an active status during L4 TM IAS R9.0 system testing, after which a decision was made to replace its data due to a serious MTF degradation. IAS R10.5 implemented the MTF correction algorithm and this detector was set as operational.

26.3 Inputs

- Detector_Status list from CPF
- L1R image radiance product (floating pt)

26.4 Outputs

- L1R image radiance product (floating point)

26.5 Algorithm

Image data lines corresponding to detectors flagged as "dead" in the CPF Detector_Status group are replaced by a simple average of adjacent data lines. This methodology, while simple, was chosen because it is believed that historically all dead detectors are isolated (having valid neighbors) and do not lie on the scan boundary (i.e., are not Detector 1 or Detector 16 for reflective bands, nor Detector 1 or Detector 4 for the thermal band). If desired, a work order option exists to fill impacted data lines with "zero" rather than utilize interpolated data.

If a future study indicates a more complex interpolation routine is required, this routine will be addressed at that time. Possible issues include: 1) handling SLOs, 2) top and bottom lines in the image where only one-sided valid data exists, and 3) exclusion of random dropped lines (not well identified in the TM-IAS). Currently (from IAS R9.0), the L4-TMIAS code only reacts to the "dead" detector flag in the CPF. Other status conditions should be considered un-implemented placeholders.

26.6 Evaluation

Not Applicable

26.7 Reference

None

Section 27 Relative Gain Characterization

27.1 Introduction

This module assists in characterizing detector-specific relative gain response for the L4 / L5 TM and L7 ETM+ sensors, based on previously obtained scene-specific estimates of relative gain. The required functionality for this module is to be implemented within a standalone GUI application, which includes the capability to:

- Retrieve the currently available set of scene-specific relative gain estimates from a selected instance of the IAS database (i.e., 'production', 'test', or 'development') according to various user-specified conditions
- Display a trend plot of the data
- Apply any of three user-selected model types to the data and display the results
- Perform a 'first-order' model assessment via residual analysis and/or goodness-of-fit estimates and display the results
- Save relative gain model parameters and related information to an 'evaluation' database for future CPF processing
- Save selected outputs in formats compatible for reporting

Additional functionality, such as performing standalone relative gain correction and assessment using ordered L0R image products, is beyond the scope of this release.

27.2 Background

For whiskbroom sensors, such as the TM and ETM+, relative gain can be estimated for a specific image acquisition from the ratio of a detector's first- or second-order image statistics to the corresponding image statistics of a stable 'reference' source, typically either another detector within the array or the band average of all nominally operating detectors:

$$g_i^{rel} = \frac{\mu_i}{\mu_{ref}} \tag{1a}$$

$$g_i^{rel} = \frac{\sigma_i}{\sigma_{ref}} \tag{1b}$$

These estimates can perform a relative gain correction of the image they were derived from. For stable sensors, these estimates can also derive time-dependent models of relative gain response applicable at any point in the instrument's lifetime.

27.3 Inputs

From the IAS Database

- Scene-specific relative gain estimates. These estimates are assumed to have been previously obtained from the histogram analysis routine, as applied to artifact-corrected daytime imagery, and account for necessary saturation and bias adjustments. (floating point)

General Input Parameters

- IAS database instance (i.e., ‘production’, ‘test’, or ‘development’)
- Sensor
- Band (integer)
- Detector (integer)
    - Default setting makes all detectors characterized simultaneously

Required User-Selectable Parameters

- Maximum allowed Cloud Cover Assessment (CCA) score (integer)
    - Default condition represents 0 (less than ten percent cloud cover)
- Maximum / minimum solar elevation angle range (integer)
    - Default condition represents ‘all’
    - Both values selectable within one control ‘group’
    - For L7 ETM+, ‘all’ is the only option available
- Maximum / minimum solar azimuth angle range (integer)
    - Default condition represents ‘all’
    - For L7 ETM+, ‘all’ is the only option available
- Start / end date range (date/ time)
    - Entries are in the DD/MM/YYYY format, and should be converted into the DSL equivalents for use in database querying
- Start / end acquisition time (date / time)
    - Default condition represents ‘all’
- Maximum / minimum WRS path range (integer)
    - Default condition represents ‘all’
    - Both values are selectable within one control ‘group’
- Maximum / minimum WRS row range (integer)
    - Default condition represents ‘all’
    - Both values selectable within one control ‘group’
- Scan direction (values representing forward, reverse, or composite of ‘both’)
    - Default condition is ‘both’ (integer)
- Relative gain ratio type (i.e., ‘mean’ or ‘std’) (string)
- Reference detector
    - Choice between ‘band average’ and ‘single detector’
    - Default represents ‘band average’
- Flag indicating whether to perform outlier rejection prior to modeling
    - Default value represents no outlier rejection (i.e., ‘off’)
- Outlier rejection algorithm
    - Default for zero-order / linear models is “$\mu \pm k\sigma$”
    - Active only if the outlier rejection flag is set
    - Placeholder for other algorithms

27.4 Outputs

To 'Evaluation' Database

- IAS database instance (i.e., 'production', 'test', 'dev') (string)
- Unique 'Process ID' — autogenerated number
- Sensor (i.e., 'L5TM') (string)
- Band (integer)
- Detector (integer)
- Start and end modeled data DSL (same as start and end DSL range for the queried data only if the outlier rejection was not performed prior to modeling) (floating point)
- Flag indicating whether the outlier rejection was used (boolean)
- Applicable value of *k* used in the outlier rejection (integer)
- Ratio of input relative gain data (i.e., 'mean', 'std') (floating point)
- Date of model generation (date/time)
- Number of modeled scenes
- String indicating model type
- Final model coefficients (floating point)
- 1-σ uncertainty / standard error estimates for each model parameter (floating point)
- Single or 'invariant' site-based model flag (default value indicates a model derived from a multiple-site data set) (integer)
- WRS path / row information for single site models (integer)
- Applicable solar elevation / azimuth range (L4 / L5 TM) (integer)
- Applicable scene acquisition time range (date/time)
- Goodness-of-fit metrics generated from model assessment (floating point)
    - Variance / covariance matrix
    - Root Mean Square Error (RMSE)
    - R^2
    - Maximum / mean absolute deviation between the modeled relative gain data and the corresponding model estimates
    - Mean / standard development of residuals between the modeled data and the corresponding model estimates

'Other' Outputs for Reports, Etc.

- Relative gain trend / model plots
- Text displays of model parameters, goodness-of-fit estimates

27.5 Algorithm Description

27.5.1 Initialization

Through the appropriate controls in the main application interface, the user selects the sensor to model, an individual band to characterize, and a particular instance of the IAS database. By default, all detectors within the band are characterized. However, the user shall also perform characterization on a subset of one or more detectors within the chosen band. All detectors (reflective band, thermal band, and panchromatic band in the case of the ETM+) are considered potential candidates for characterization.

27.5.2 SQL Query Generation / Execution

The user shall generate and execute a Structured Query Language (SQL) query to obtain previously calculated scene-specific relative gain estimates from the selected instance of the IAS database, whether for all detectors in the band or a user-selected subset. Query generation is accomplished through dynamic script creation controlled by user selections of the following data constraints. Values for the scene location, solar geometry constraints (TM only), and acquisition time are assumed to have been extracted when the scene was initially ingested into the IAS.

- Sensor
- Start and end date of relative gain estimates in DSL
- WRS path and row ranges (to allow characterization of data from single or 'invariant' sites)
- Maximum acceptable CCA score (default value of 0)
- Acceptable scene acquisition time range
- Acceptable solar elevation angle range
- Acceptable solar azimuth angle range
- Scan direction
- Relative gain ratio type (i.e., 'mean' or 'std dev')
- Reference detector type. The default value represents the reference 'detector' as the band average of all nominally operating detectors. The user has the option of selecting estimates based on an individual reference detector.
    - **CAUTION**: The individual reference detector option assumes that the set of relative gain estimates returned from the query have been processed with the same reference detector, as listed in each scene's CPF. If possible, any query using this option should check the reference detector value recorded for each scene in the L0R_0RC_1R_HST_BAND table. If the reference detector numbers are different, the user is notified and given the option of resetting to the default 'band average' reference.

If relative gain estimates cannot be returned for a given band in a given sensor, the application notifies the user and allows the user to re-enter 'valid' band information.

Once the user enters the desired constraints, the application generates the SQL query to the IAS table containing the relative gain data. The SQL statement displays in a text window prior to its execution. Options are presented allowing the user to save the SQL statement to an American Standard Code for Information Interchange (ASCII) text file and 'confirming' whether to run the query; if the user elects to run the query, the query executes. Query results display in a text window and include the following information:

- IAS database instance
- Originate scene identifier (i.e., trend ID, etc.)

- Detector number (integer)
- DSL (floating point)
- Scene acquisition time (date / time)
- WRS path (integer)
- WRS row (integer)
- CCA score (integer)
- Scan direction
- Relative gain ratio (i.e., ratio of 'means ' or 'std devs') (string)
- Relative gain estimate (floating point)

All results are sorted according to increasing DSL. If less than ten data records are returned that meet the selected constraints, the user is notified and prompted to refine the constraint selection. At this point, the query is recreated according to the new selections and re-executed.

The user shall select an option to 'dump' the query results to a tabular formatted ASCII text file for other offline analysis. The results are sorted according to increasing DSL. Relative gain and DSL values are recorded to a minimum of six significant digits (DSL is assumed to be a fractional quantity). The output file contains the following information:

- A header section that includes:
    - 'Process ID'
    - IAS database instance
    - Sensor
    - Band
    - Query execution date
    - Selected path / row ranges
    - Selected solar elevation / azimuth ranges (L4 / L5 TM)
    - Selected starting / ending acquisition date range
    - Selected scene acquisition time range
    - Total number of scenes queried
    - Relative gain ratio type (i.e., 'mean' or 'std')
    - CPF 'reference' detector (i.e., 'band average' or 'single detector' — with an explicit detector number)
- DSL
- Scene identifier
- Scene CCA score
- Detector
- Relative gain estimate

27.5.3 Display of Queried Data

The user shall display relative gain data for the selected detector(s) in plot windows that include appropriate axis labels, titles, and legend information. A maximum of four detectors are plotted in any such window, with automatic selection of unique plot symbols and colors specific to each detector. Axes limits (both horizontal and vertical) are user adjustable if the data-dependent limits are not considered useful. For typical operation, DSL represents the horizontal (time) axis, and the vertical (relative gain) axis has a default lower limit of 0.95 and a default upper limit of 1.05. The user ‘saves’ the plot(s) in an appropriate output file format (i.e., JPEG).

In addition to the basic plot window(s), a window generates allowing simultaneous text display of all plotted information in an easily readable format.

27.5.4 Modeling of Queried Data

The user generates time-dependent models derived from the relative gain data, according to the selection from among three commonly encountered function types. In the following descriptions, “x” represents time in fractional DSL, and “y” represents the “final” set of relative gain numbers to model for a given detector (i.e., after any desired outlier removal processing).

- Polynomial, including zero-order (constant) and first-order (linear) functions, up to a maximum of a sixth order
- Exponential, of the form y=a*exp(b*x)+c
- Exponential+Linear, of the form y=a*exp(b*x)+c+d*x

The chosen model applies to all selected detectors.

The available model selections are presented to the user in a drop-down list (i.e., ‘Zero-order’, ‘Linear’, ‘Second Order Polynomial’, … , ‘Exponential’, and ‘Exponential+Linear’); by default, a linear function is modeled.

The user selects an option to perform an outlier rejection analysis; by default, this option is not set, indicating no outlier rejection is performed. If a zero-order or linear model is selected, and outlier rejection has been turned on, the analysis is performed on a detector-specific basis according to the following procedure:

a. Perform an initial zero (first) order fit using all the available relative gain data
b. Subtract the model estimates from the corresponding relative gain data to obtain a set of residuals to the fit
c. Calculate the mean of the residuals, μ
d. Calculate the standard deviation of the residuals, σ
e. Calculate lower and upper outlier threshold values as follows:

$$O_{lower} = \mu - k\sigma \tag{2a}$$

$$O_{upper} = \mu + k\sigma \tag{2b}$$

k ranges between 1 and 10. The user chooses the value from a control that is active only if outlier rejection has been selected. The default setting for *k* is 2.

- If a residual estimate is less than O_{lower} or greater than O_{upper}, flag the data point as an outlier

- Construct a 'final' modeling data set that contains DSL and relative gain information excluding all data determined to be an outlier

For any other models, the default outlier rejection method described likely produces 'unreliable' results. The user is notified of this possibility, and is prompted to reset the outlier rejection to 'off' or to continue. The user has the option of creating a tabular ASCII text file report listing all query information for those relative gain estimates deemed to be outliers. The report presents the following information:

- Header section with:
    - Process ID
    - IAS database instance
    - Satellite / sensor
    - Band
    - Generation date
    - Selected model
    - Outlier rejection status (i.e., 'enabled')
- Detector
- Lower outlier threshold value
- Upper outlier threshold value
- Relative gain value

The modeling process runs after the creation of the final modeling data set (i.e., for a second time on the reduced data set following the outlier rejection if that option was selected, or the full data set returned from the query if the outlier rejection was not selected).

The user over-plots the resulting model(s) on the full set of queried data in the plot window(s) previously generated. The model(s) are calculated according to the starting and ending DSL range contained in the full query; the DSL range of the modeled data, however, needs to be recorded along with the other model parameter information. The color of the plot curve(s) are the same as the plot color(s) of the queried data. The user saves the model plot(s) to an appropriate output file format.

An option allows the user to generate a tabular ASCII text file report summarizing the modeling results for all selected detectors. The report contains the following:

- A header section with the following information:
    - IAS database instance
    - Process ID
    - Sensor (i.e., L4 / L5 TM, L7 ETM+)
    - Band
    - Starting / ending DSL of modeled relative gains (outlier-reduced data set)
    - Type of relative gain ratio (i.e., 'mean' or 'std')
    - Starting / ending path / row information (if applicable)
    - Modeling date

    - Model type (i.e., 'first-order linear', 'exponential+linear', etc.)
- Detector number
- Number of iterations needed to reach the 'final' model parameter value
- Estimated model parameter values (to a minimum of six significant digits) +- corresponding 1σ uncertainty (to a minimum of three significant digits)

The capability of generating parameter uncertainty estimates should be part of the modeling process for implementations based on available scientific libraries (such as GSL).

27.5.5 'Assessment' of Modeled Data

The user 'assesses' the overall quality of the selected model(s), with respect to the queried data, through the following methods:

- Graphical and textual displays of the residual differences between the set of modeled data and the corresponding model predictions. A unique selection of plot symbols and colors specific to each modeled detector are available. In addition, the user rescales the plot axes to more useable ranges as necessary and saves the plot(s) to an appropriate output file format.
- Textual display of goodness-of-fit metrics:
    - Pearson's R^2 metric
    - RMSE
- Textual display of residual metrics:
    - Mean / standard deviation of the residuals
    - Maximum absolute deviation / mean absolute deviation between the model estimate and the corresponding modeled data value
- Textual display of 1-σ uncertainty and/or standard error estimates associated with all model parameters

The user saves all model assessment displayed in the text window to a tabular formatted ASCII text file. Alternatively, this information can be appended to the end of the summary modeling report.

27.5.6 Model Information Trended to Evaluation Database

The user trends the following model information to an evaluation database, with appropriate interfaces (TBD) to CPF generation tools:

- IAS database instance (string)
- Sensor
- Band (integer)
- Detector (integer)
- Start and end model DSL (same as starting and ending DSL range for the queried data only if the outlier rejection was not performed prior to modeling) (floating point)
- Flag indicating whether outlier rejection was used (boolean)

- Applicable value of *k* used in outlier rejection (integer)
- Ratio of input relative gain data (i.e., 'mean', 'std') (floating point)
- Date of model generation (date / time)
- List of modeled scenes (either by scene ID, trending ID, etc.)
- Number of modeled scenes
- String indicating model type
- Final model coefficients (floating point)
- 1-σ uncertainty / standard error estimates for each model parameter (floating point)
- Single or 'invariant' site-based model flag (default value indicates a model derived from a multiple-site data set) (integer)
- WRS path / row information for single site models (integer)
- Applicable solar elevation / azimuth range (L4 / L5 TM) (integer)
- Applicable scene acquisition time range (date / time)
- Goodness-of-fit metrics generated from a model assessment (floating point)
    - Coefficient of variation
    - Residual standard deviation
    - RMSE
    - R^2

In the current implementation of the IAS, relative gain model coefficients are stored in the CPF (the default model is assumed to be linear). Relative gain and its reciprocal, the destriping 'correction' factor, are calculated from this model for the specific scene acquisition date and applied internally within the correction routine. Given this architecture, the user has an option to query the evaluation database for a set of relative gain model coefficients to supply for a test CPF. When this option is selected, the user is prompted to enter a specific date / time, representing an image acquisition date / time in the MM:DD:YYYY HH:MM:SS format (to be internally converted to fractional DSL), as well as the following selectable "constraints," which include the following:

- IAS database instance
- Sensor (i.e., 'L5 TM')
- Relative gain ratio (i.e., 'mean' or 'std')
- Model generation date
- Specified scene acquisition date

The final query returns the following information:

- Process ID
- Band
- Detector
- Model coefficients
- Start and end acquisition dates of the scenes used to model a particular band set
- Start / end DSL

- Input relative gain
- Number of scenes used
- Standard errors on coefficients
- Coefficient of Var / Res Std Dev / RMSE / R_Square

An additional option allows the user to write the returned information directly to an ASCII text file report useable in offline analyses.

Current CPF holds only a linear model (i.e., slope and intercept for each detector of each band). A newly developed Relative Gain Characterization (RGC) tool offers a provision to model the detectors ranging from zero order constant models to sixth order polynomial, exponential, and exponential + linear models.

The present CPF has a placeholder for exponential model coefficients as well. In addition, model coefficients up to third order polynomial can also be stored. The model coefficients can be stored in the following format:

- If a detector is modeled using the linear model, the current method can store the intercept and slope.
- If a detector is modeled using second order model (i.e., $y= a + bx + cx^{2)}$, 'a' is stored as intercept, 'b' is stored as slope, and an additional part (i.e., AddPar1) stores c.
- For third order modeling (i.e., $y = a + bx + cx^2 + dx^{3)}$, 'a' is stored as intercept, 'b' is stored as slope, 'c' is stored as AddPar1, and 'd' is stored as AddPar2.
- Similarly, for fourth, fifth, and sixth order models, AddPar3, AddPar4, and AddPar5 can store the additional model coefficients.
- For exponential model (i.e., $y= ae^{bx)}$, 'a' is stored as ExpPar1 and 'b' is stored as ExpPar2.
- For exponential + Linear (i.e., $y = ae^{bx} + cx + d$), 'd' is stored as intercept, 'c' is stored as a slope, 'a' is stored as ExpPar1, and 'b' is stored as ExpPar2.

It is always possible that various detectors in a band are modeled using different modeling types. If a detector is modeled using exponential type, besides ExpPar1 and ExpPar2, the rest of the fields in CPF are filled with zero.

Note: The current relative gain correction code is not capable of handling CPF other than the linear format for all the bands. For future change in correction code, it is much easier to reference a formula, $Y = a + bx + cx^2 + dx^3 + fe^{gx}$, where x represents DSL.

This formula searches and replaces the model coefficients from the CPF text file and finally implements the model for the given detector.

27.6 References

Madhavan, Sriharsha, "Landsat 5 Relative Gain Analysis: Characterization of the Relative Radiometric Gain of All Reflective Channels of the Landsat 5 Thematic

Mapper", Masters Graduate Thesis, Dept. of Electrical Engineering and Computer Science, South Dakota State University, 2004.

References

Please see http://landsat.usgs.gov/tools_acronyms_ALL.php for a list of acronyms.