Thematic Mapper Bumper Mode Scan Mirror Correction Algorithm Theoretical Basis

Background

The Thematic Mapper instruments on Landsat 4 and Landsat 5, as well as the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) instrument, achieve their 185-kilometer cross-track ground swath by using a bi-directional scan mirror to traverse the instrument line-of-sight through a 15-degree cross-track field of view. On descending passes, the mirror alternately scans west-to-east (forward scan) and then east-to-west (reverse scan). The mirror direction is reversed between scans by a set of mechanical bumpers and magnetic torquers designed to maintain a constant scan velocity. The geometric characteristics of the resulting scanning pattern must be carefully controlled and measured in order to ensure adequate coverage of the ground target area and to provide accurate knowledge of the sensor line-of-sight as a function of time for purposes of image geolocation.

To achieve the required level of scan mirror angular position knowledge and control the Thematic Mapper scan mirror assembly includes a device, known as the scan angle monitor (SAM), that provides timing pulses to the scan mirror control electronics at the beginning, middle, and end of each Earth-view active scan [1]. The SAM is an electro-optical device attached to the back of the scan mirror, that reflects the signal from a light emitting diode (LED) off of a three-facet wing mirror. The wing mirror is oriented so that as the scan mirror rotates, the three facets reflect the LED signal onto a detector when the scan mirror is at the desired scan start, midscan, and scan end angles. The SAM detector sends a timing signal to the scan mirror control electronics in response to each optical pulse from the wing mirror. Thus, three timing pulses are generated for each active scan.

The primary function of the SAM timing pulses is to initiate and halt the collection of Earth-view image data during the active scan time. In accomplishing this, these pulses drive the Thematic Mapper major frame data collection cycle. The SAM timing pulses are also used by the scan mirror control electronics to monitor the active scan time and to modulate the magnetic torquer outputs, applied to the scan mirror at the beginning and end of each scan, controlling the scan mirror velocity so as to maintain the desired active scan time. Finally, the timing pulses are used to compute the deviations from the ideal scan start to midscan and midscan to scan end times for each active scan. These first half and second half scan errors are encoded and downlinked in the wideband data stream for subsequent use in geometric correction during ground processing.

Over the life of the Thematic Mapper instruments the mechanical bumpers used to reverse the mirror direction have been found to wear, resulting in gradual growth in the length of time required to turn the mirror around. In the baseline SAM operating mode, this turnaround time growth causes a corresponding increase in total scan time since it is the active scan time that is monitored by the SAM. This gradual growth in the time between scans can ultimately lead to problems maintaining synchronization between the scan mirror and other Thematic Mapper components including the scan line corrector and the calibration shutter. Although designed to accommodate some variation in the scan mirror cycle time, the operating ranges of these devices have finite limits. In particular,

the Thematic Mapper calibration shutter has a maximum cycle period beyond which it cannot maintain synchronization with the scan mirror. This synchronization threshold was exceeded for the Landsat 5 mission in early 2002, leading to an inability of the Thematic Mapper to keep the calibration shutter out of the optical path during the active scan time. These shutter incursions are the source of the so-called "caterpillar tracks" anomaly described elsewhere [2].

The Thematic Mapper series instruments were provided with an alternate scan mirror operating mode to guard against the eventuality of a failure of the (non-redundant) SAM device. This backup "bumper" mode makes use of timing signals from magnetic pickoffs installed in the mechanical bumpers used to reverse the mirror direction, to control the time between bumper impacts, thus effectively controlling the total, rather than the active, scan time. Since the SAM pulses are no longer available to drive the Thematic Mapper data collection cycle, simulated pulses are generated by the scan mirror electronics to mark the beginning and end of the active scan period. These pulses are generated at fixed time offsets from the bumper pickoff signal. Thus, each major frame (active scan) is exactly the nominal length when operating in bumper mode.

Controlling the total scan time resolves the internal synchronization issues in the Thematic Mapper allowing the active scan imagery to once again be free of calibration shutter incursions. On the other hand, the loss of the SAM timing signals based on the scan mirror position means that the active scan start/stop field angles are no longer controlled, constant, or measured. Lacking the on-orbit mirror timing telemetry provided by the SAM mode, bumper mode operations rely upon stable and repeatable scan mirror behavior. Since the mechanical bumpers can be expected to continue to wear, bumper mode data should be expected to exhibit (hopefully slowly) time varying scan angles and scan velocities as the scan mirror control logic compensates for increased turnaround time by increasing the active scan velocity. If the bumper variations are slowly varying, the scan start/stop field angles can be inferred from image data, and monitored over time through an ongoing ground calibration activity. Bumper mode data collection will become problematic when and if the fixed major frame collection time window becomes shorter than or misaligned with the period of linear mirror scanning motion. Additional measures to artificially truncate the active scan during ground processing may be required in this case.

The operating state of the scan mirror assembly is identified in the spacecraft telemetry in serial words E and L of the payload correction data (PCD) [3]. Bits 6 and 7 of serial word E indicate whether the primary (SME1) or redundant (SME2) scan mirror electronics are being used to control the scan mirror. Throughout its lifetime, the Landsat 5 Thematic Mapper has operated using the primary SME. This is indicated in serial word E by having bit 6 set to 1 (SME1 on) and bit 7 set to 0 (SME2 off). There is no expectation that this will change in the future. Bit 6 of serial word L indicates which SME is using input from the scan angle monitor. If bit 6 is set to 1 (SME1 select SAM) then the primary SME and, hence, the Thematic Mapper, is operating in SAM mode. If bit 6 is set to 0 (SME2 select SAM) then the redundant SME is using SAM input and the primary SME and, hence, the Thematic Mapper, is operating in bumper mode. The PCD serial word bit settings for

SAM and bumper mode are summarized in table 1. Note that bit 6 of serial word L provides the critical information used to determine the scan mirror control mode. Bits 6 and 7 of serial word E would only change if there were a failure in the primary SME.

Mirror Mode	Serial Word	Bit	Setting
SME1 SAM	E	6	1
	E	7	0
	L	6	1
SME1 Bumper	E	6	1
	E	7	0
	L	6	0

Table 1: Mirror Mode PCD Serial Word Settings

Scan Angle Monitor Mode Correction Model
An overview of the SAM mode scan mirror model will provide a context for the subsequent discussion of the bumper mode models. The SAM mode algorithm is described in detail on pages 42-48 of reference 4. A summary will be provided here. Although that description was written for the Landsat 7 ETM+ it is also valid for the Landsat 4/5 Thematic Mappers.

The scan mirror is modeled using a linear motion with adjustments for repeatable nonlinear behavior, high frequency jitter, and scan time variations. Fifth-order polynomials, determined through both prelaunch and on-orbit calibration, model the repeatable along- and across-scan deviations from linearity of the scan mirror. Angular displacement sensors mounted on the instrument provide a continuous record of high frequency jitter so that vibration effects can be compensated. These jitter observations; packaged in the spacecraft PCD, contribute to both the attitude component of the instrument pointing model and the scan mirror model. As the scan mirror is operating, the SAM measures the mirror position at the start of scan, mid-scan, and end of scan. The SAM data are output in counts, measuring the deviation from the nominal start-to-mid (first half) and mid-to-end (second half) scan times. The counts are in units of 0.18849 microseconds per count. The measured counts are included in the wideband data stream and are recorded in the level 0 mirror scan correction data (MSCD).

The parameters used in the SAM mode mirror model are listed in table 2. This list includes fixed, slowly varying (calibrated), and rapidly varying (measured) parameters.

Parameter	Description	Source
$b_{j=0,5}$	The forward along-scan fifth-order polynomial coefficients	Ground Calibration
$d_{j=0,5}$	The reverse along-scan fifth-order polynomial coefficients	Ground Calibration
$e_{j=0,5}$	The forward across-scan fifth-order polynomial coefficients	Ground Calibration
$g_{j=0,5}$	The reverse across-scan fifth-order polynomial coefficients	Ground Calibration
A_{smF}	The forward start to middle angle	Ground Calibration
A_{meF}	The forward middle to end angle	Ground Calibration
A_{smR}	The reverse start to middle angle	Ground Calibration
A_{meR}	The reverse middle to end angle	Ground Calibration

T_{fhf}	The forward nominal first half scan time	Fixed by TM
T_{shf}	The forward nominal second half scan time	Fixed by TM
T_{fhr}	The reverse nominal first half scan time	Fixed by TM
T_{shr}	The reverse nominal second half scan time	Fixed by TM
T_n	The nominal scan time	Fixed by TM
T_{unit}	The conversion factor from counts to time	Fixed by TM
$FHSERR_i$	The measured first half scan error for each scan	MSCD
$SHSERR_i$	The measured second half scan error for each scan	MSCD
$Aprofile_{i,j}$	The corrected along-scan mirror polynomial for each scan	Computed per Scan
$Xprofile_{i,j}$	The corrected across-scan mirror polynomial for each scan	Computed per Scan

Table 2: SAM Mode Mirror Model Parameters

The SAM mode scan mirror algorithm generates scan-specific mirror correction profile polynomials. For each scan:

1. Compute the actual scan time--find true first half time (T_{fh}), true second half time (T_{sh}), and total scan time (t_s):

    For a forward scan:
    $T_{fh} = T_{fhf} - FHSERR_i * T_{unit}$ (The first half scan time)
    $T_{sh} = T_{shf} - SHSERR_i * T_{unit}$ (The second half scan time)
    $t_s = T_{fh} + T_{sh}$ (The total scan time)

    For a reverse scan:
    $T_{fh} = T_{fhr} - FHSERR_i * T_{unit}$ (The first half scan time)
    $T_{sh} = T_{shr} - SHSERR_i * T_{unit}$ (The second half scan time)
    $t_s = T_{fh} + T_{sh}$ (The total scan time)

2. Set the scan start (A_{sm}) and scan end (A_{me}) angles based on scan direction:

    For a forward scan: $A_{sm} = A_{smF}$ $A_{me} = -A_{meF}$

    For a reverse scan: $A_{sm} = -A_{smR}$ $A_{me} = A_{meR}$

3. Rescale the fifth-order polynomial coefficients to account for the difference between the actual and nominal scan time:

    For a forward scan: $b'_j = -b_j * (T_n / t_s)^j$ where j = 0 to 5
    $Xprofile_{ij} = e_j * (T_n / t_s)^j$ where j = 0 to 5

    For a reverse scan: $b'_j = -d_j * (T_n / t_s)^j$ where j = 0 to 5
    $Xprofile_{ij} = g_j * (T_n / t_s)^j$ where j = 0 to 5

4. Calculate the correction (A) to the linear model needed to make the mid-scan angle equal to the observed value (zero) at time T_{fh}.

    $A = -(A_{me}T_{fh} + A_{sm}T_{sh}) / t_s$

5. Calculate the contribution (B) to the correction quadratic due to the mirror's midscan nonlinearity by evaluating the rescaled fifth-order polynomial at time T_{fh}.

$$B = b'_0 + (b'_1 * T_{fh}) + (b'_2 * T_{fh}{}^2) + (b'_3 * T_{fh}{}^3) + (b'_4 * T_{fh}{}^4) + (b'_5 * T_{fh}{}^5)$$

6. Compute the net correction (D) to the mirror profile at the mid-scan time (T_{fh}):

$$D = A - B$$

7. Using the constraints $a(0) = a(t_s) = 0.0$, and $a(T_{fh}) = D$, the coefficients of the correction quadratic are:

$a_0 = 0.0$
$a_1 = -t_s * a_2$
$a_2 = -D / (T_{fh} * T_{sh})$

8. Interpolate the along-scan (roll) jitter values at the scan start (θ_s), midscan (θ_m), and scan end (θ_e) times.

9. Compute the coefficients of the jitter correction quadratic:

$c_0 = \theta_s$
$c_1 = (\theta_e-\theta_s) / t_s - [(\theta_e-\theta_m) T_{fh} + (\theta_s-\theta_m) T_{sh}] / (T_{fh} T_{sh})$
$c_2 = [(\theta_e-\theta_m) T_{fh} + (\theta_s-\theta_m) T_{sh}] / (t_s T_{fh} T_{sh})$

10. Compute the net along-scan mirror profiles:

$Aprofile_{i0} = b'_0 + a_0 - c_0$
$Aprofile_{i1} = b'_1 + a_1 - c_1$
$Aprofile_{i2} = b'_2 + a_2 - c_2$
$Aprofile_{i3} = b'_3$
$Aprofile_{i4} = b'_4$
$Aprofile_{i5} = b'_5$

Scan mirror angles are generated by applying the corrected mirror polynomial for the current scan to the nominal linear profile interpolated from the scan start and scan end angles. These mirror angles must be doubled when computing the corresponding object space lines-of-sight to account for the line-of-sight's reflection off the mirror surface.

Bumper Mode Correction Models
Two distinct models of the Thematic Mapper scan mirror's operation in bumper mode are described below. The first is a detailed model reflecting, as nearly as possible, the actual physical behavior of the scan mirror assembly. This "physical" model was developed to provide a best-case geometric correction capability demonstrating the achievable

geometric accuracy in bumper mode and to isolate the physical characteristics of the scan mirror assembly that may be changing with time.

The second model is a simplified version of the physical bumper mode mirror model designed to be easier to implement in Landsat image product generation systems. The goal of this model is to provide a suitably accurate version of the bumper mode model that more closely resembles the conventional SAM mode model, in order to minimize production system impacts. This simplified model will henceforth be referred to as the SAM mode emulation model.

Physical Model

The parameters used to model the scan mirror behavior in bumper mode were selected to capture the anticipated physical changes in bumper behavior with wear. To this end, characteristic time constants were chosen as the fundamental model parameters while the scan start and stop angles, of more direct interest for line-of-sight determination, are treated as derived values.

The scan mirror assembly parameters included in the physical model are: 1) the length of time between the bumper magnetic pick-off signal and the beginning of mirror linear scanning motion, for each bumper, 2) the length of time between the end of linear scanning and the magnetic pick-off signal, for each bumper, 3) the time delay from the bumper pick-off signal to the beginning of the active scan, and 4) the angular limits of mirror linear scanning. These model parameters are summarized in table 2. Note that forward scans begin at bumper B and end at bumper A while reverse scans begin at bumper A and end at bumper B.

Parameter	Description	Characteristics
T_{dwellA}	Time between bumper A pickoff signal and beginning of reverse linear scanning motion.	Time Varying
T_{pickA}	Time between the end of forward linear scanning motion and bumper A pickoff signal.	Time Varying
$T_{offsetA}$	Time between bumper A pickoff signal and beginning of reverse major frame collection (active scan start).	Fixed by TM
α_A	The mirror field angle at which linear scanning motion begins (reverse) and ends (forward) at bumper A.	Fixed by Design
T_{dwellB}	Time between bumper B pickoff signal and beginning of forward linear scanning motion.	Time Varying
T_{pickB}	Time between the end of reverse linear scanning motion and bumper B pickoff signal.	Time Varying
$T_{offsetB}$	Time between bumper B pickoff signal and beginning of forward major frame collection (active scan start).	Fixed by TM
α_B	The mirror field angle at which linear scanning motion begins (forward) and ends (reverse) at bumper B.	Fixed by Design

Table 3: Bumper Mode Physical Model Parameters

The relationships between the model parameters listed in table 3 are depicted in figure 1. These eight physical model parameters are used in combination with the measured bumper-to-bumper scan times included in the wideband data stream and fifth-order polynomials that model the scan mirror's along- and across-scan deviations from linearity

during the forward and reverse active scans. These parameters are used to compute along- and across-scan mirror line-of-sight angles as functions of time. The mirror angles are computed from the time parameters assuming linear mirror motion, as modified by the mirror polynomials, between the limiting angles defined by α_A and α_B. Since, unlike SAM mode, no physical measurements of mirror angles are being taken, the bumper mode mirror model is not adjusted using the high frequency jitter data measured by the TM angular displacement sensors. The jitter data are still used as high frequency attitude data in the overall instrument pointing model.
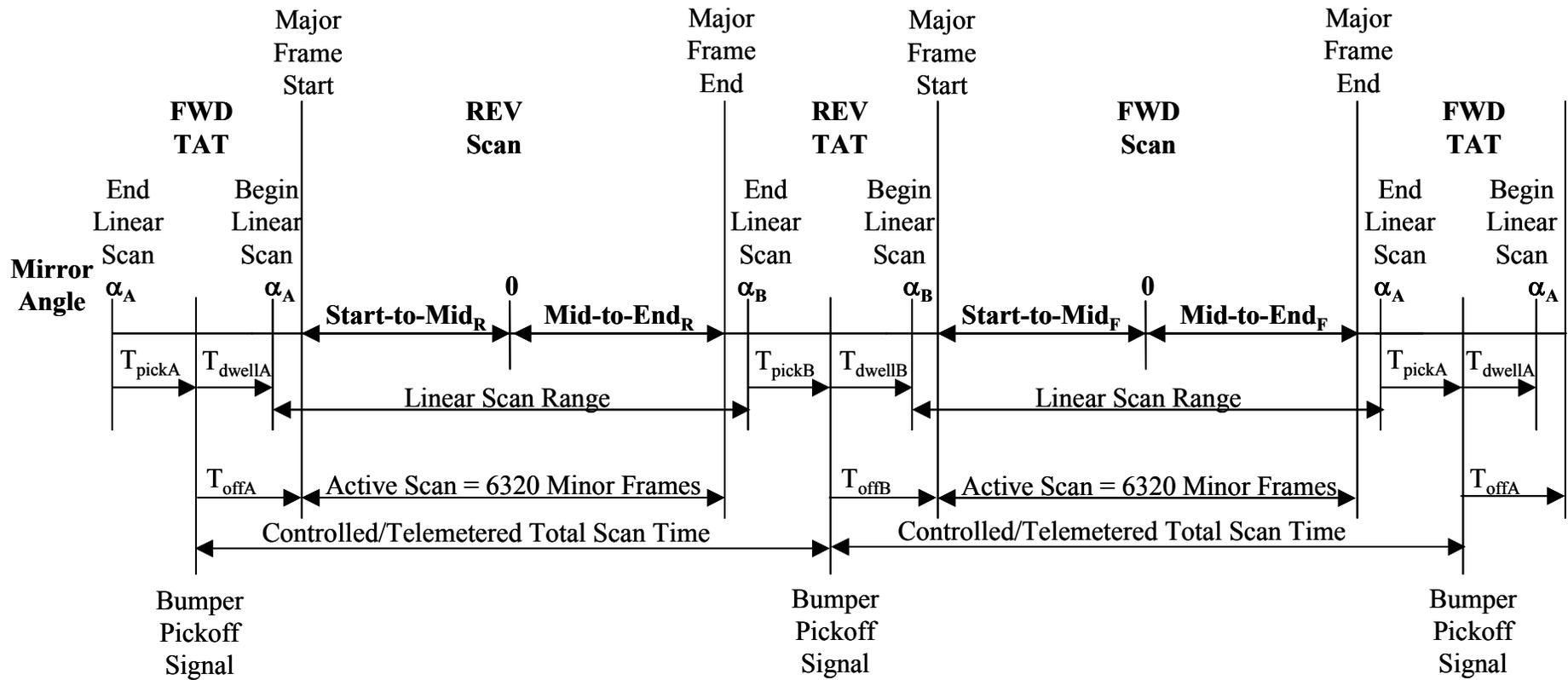
Bumper Mode Timeline

Major Frame Start   Major Frame End   Major Frame Start   Major Frame End

FWD TAT   **REV Scan**   **REV TAT**   **FWD Scan**   **FWD TAT**

End Linear Scan α_A Begin Linear Scan α_A End Linear Scan α_B Begin Linear Scan α_B End Linear Scan α_A Begin Linear Scan α_A

Mirror Angle

0 0

Start-to-Mid$_R$ **Mid-to-End$_R$**   **Start-to-Mid$_F$**   **Mid-to-End$_F$**

T_{pickA} T_{dwellA} T_{pickB} T_{dwellB} T_{pickA} T_{dwellA}

Linear Scan Range   Linear Scan Range

T_{offA} Active Scan = 6320 Minor Frames T_{offB} Active Scan = 6320 Minor Frames T_{offA}

Controlled/Telemetered Total Scan Time   Controlled/Telemetered Total Scan Time

Bumper Pickoff Signal   Bumper Pickoff Signal   Bumper Pickoff Signal

Figure 1: Bumper Mode Physical Model Parameter Relationships

The implementation of the bumper mode physical model proceeds for each scan as described below. Variables that are common to the SAM mode algorithm described above (e.g., the MSCD counts to time scaling constant) are used here without redefinition.

1. Compute the measured total scan time (t_s) from the bumper mode MSCD by constructing the 24-bit bumper mode time field from the two 12-bit SAM mode first half/second half scan error MSCD fields:

   $$t_s = (SHSERR * 4096 + FHSERR) * T_{unit}$$

2. Compute the scan velocity:

   For a forward scan: $V_s = (\alpha_A - \alpha_B) / (t_s - T_{pickA} - T_{dwellB})$

   For a reverse scan: $V_s = (\alpha_B - \alpha_A) / (t_s - T_{pickB} - T_{dwellA})$

3. Compute the scan start angle:

   For a forward scan: $\alpha_{start} = \alpha_B + V_s * (T_{offsetB} - T_{dwellB})$

   For a reverse scan: $\alpha_{start} = \alpha_A + V_s * (T_{offsetA} - T_{dwellA})$

4. Compute the (nominally constant) active scan time using the counted line length (LL) from the MSCD and the fixed minor frame sample time (T_{sample}):

   $$t_{active} = (LL - 0.5) * T_{sample}$$

5. Compute the scan stop angle:

   $$\alpha_{stop} = \alpha_{start} + V_s * t_{active}$$

6. Compute the first half scan (zero scan angle) time:

   $$T_{fh} = -\alpha_{start} / V_s$$

7. Compute the second half scan time:

   $$T_{sh} = t_{active} - T_{fh}$$

11. Set the nominal scan start (A_{sm}) and scan end (A_{me}) angles based on scan direction:

   For a forward scan: $A_{sm} = A_{smf}$ $A_{me} = -A_{mef}$

   For a reverse scan: $A_{sm} = -A_{smr}$ $A_{me} = A_{mer}$

12. Rescale the fifth-order polynomial coefficients to account for the difference between the actual and nominal scan time:

For a forward scan: $b'_j = -b_j * (T_n / t_s)^j$ where $j = 0$ to 5
                      $Xprofile_{ij} = e_j * (T_n / t_s)^j$ where $j = 0$ to 5

For a reverse scan: $b'_j = -d_j * (T_n / t_s)^j$ where $j = 0$ to 5
                      $Xprofile_{ij} = g_j * (T_n / t_s)^j$ where $j = 0$ to 5

13. Calculate the correction (A) to the linear model needed to make the mid-scan angle equal to the observed value (zero) at time T_{fh}.

$A = -(A_{me}T_{fh} + A_{sm}T_{sh}) / t_s$

14. Using the constraints $a(0) = a(t_s) = 0.0,$ and $a(T_{fh}) = A$, the coefficients of the correction quadratic are:

$a_0 = 0.0$
$a_1 = -t_s * a_2$
$a_2 = -A / (T_{fh} * T_{sh})$

15. Compute the differences between the nominal (A_{sm} and A_{me}) and computed (α_{start} and α_{stop}) scan start/stop angles to construct scan start (θ_s), midscan (θ_m), and scan end (θ_e) corrections:

$\theta_s = A_{sm} - \alpha_{start}$
$\theta_m = 0$
$\theta_e = A_{me} - \alpha_{stop}$

16. Compute the coefficients of the scan start/stop correction quadratic:

$c_0 = \theta_s$
$c_1 = (\theta_e-\theta_s) / t_s - [(\theta_e-\theta_m) T_{fh} + (\theta_s-\theta_m) T_{sh}] / (T_{fh} T_{sh})$
$c_2 = [(\theta_e-\theta_m) T_{fh} + (\theta_s-\theta_m) T_{sh}] / (t_s T_{fh} T_{sh})$

17. Compute the net along-scan mirror profiles:

$Aprofile_{i0} = b'_0 + a_0 - c_0$
$Aprofile_{i1} = b'_1 + a_1 - c_1$
$Aprofile_{i2} = b'_2 + a_2 - c_2$
$Aprofile_{i3} = b'_3$
$Aprofile_{i4} = b'_4$
$Aprofile_{i5} = b'_5$

Scan mirror angles are generated by applying the corrected mirror polynomial for the current scan to the nominal linear profile interpolated from the nominal scan start and scan end angles (A_{sm} and A_{me}). These mirror angles must be doubled when computing the corresponding object space lines-of-sight to account for the line-of-sight's reflection off the mirror surface.

SAM Mode Emulation Model
The simplified SAM mode emulation model for bumper mode data reformulates the physical model described above, to cast the physical model parameters in the form of the familiar SAM mode calibration parameters and mirror scan correction data. Specifically, instead of working directly with the bumper timing parameters, they are converted to equivalent scan angles based on the nominal (controlled) total scan time. From the resulting forward and reverse scan start and stop angles it is possible to compute the midscan time by assuming linear scan motion. Comparing this midscan time to the SAM mode midscan target time and to the (fixed) total scan time makes it possible to compute effective first half and second half scan errors for each scan direction. These fixed first half/second half scan errors would be used in place of the corresponding mirror scan correction data provided in SAM mode. When combined with the fifth-order mirror nonlinearity polynomials these mirror angles and first half/second half scan errors can be inserted directly into the SAM mode mirror model to compute mirror line-of-sight angles as a function of time. Since all of these parameters depend on the time varying bumper timing parameters they are all (slowly) varying with time and must be maintained through periodic calibration updates.

The SAM emulation approach has two fundamental differences from the physical model. First, the scan-by-scan measurements of the total scan time contained in the bumper mode MSCD are not used in the SAM emulation method. Instead, a typical value for total scan time is used to compute the fixed first half/second half scan error parameters. Since the total scan times are actively controlled in bumper mode, the values typically do not vary significantly, so this simplification should have little effect. Second, since the normal SAM mode processing logic is applied to the emulated parameters derived for the bumper mode data, the effects of along-scan jitter, suppressed in the physical model, are included in the simplified model. Tests using both the physical and SAM emulation models have demonstrated that these model differences do not result in significant performance degradation in the simplified model. In fact, the SAM emulation model has been seen to yield slightly better image-to-image registration performance when compared to Landsat 7 ETM+ data, than the physical model. This improved performance, though marginal, coupled with the relative ease of implementation make the SAM emulation model the preferred approach to bumper mode data processing.

Table 4 lists the modeling parameters used by the SAM mode emulation algorithm along with notes on the source and usage of each. All of the parameters listed in table 4 are estimated and maintained as part of the bumper mode scan mirror calibration process. Parameter values with associated effective dates would be provided to image product generation systems in a time sequence of calibration parameter files. New files would be generated over time as required by changes in the values of the model parameters.

Parameter(s)	Description	Source	Usage
$FHSERR_F$	Forward scan first half scan error	Ground calibration	Replaces corresponding MSCD fields
$SHSERR_F$	Forward scan second half scan error	Ground calibration	Replaces corresponding MSCD fields
$FHSERR_R$	Reverse scan first half scan error	Ground calibration	Replaces corresponding MSCD fields
$SHSERR_R$	Reverse scan second half scan error	Ground calibration	Replaces corresponding MSCD fields
A_{smF}	Forward scan start to midscan angle	Ground calibration	Same as corresponding SAM mode parameter
A_{meF}	Forward midscan to scan end angle	Ground calibration	Same as corresponding SAM mode parameter
A_{smR}	Reverse scan start to midscan angle	Ground calibration	Same as corresponding SAM mode parameter
A_{meR}	Reverse midscan to scan end angle	Ground calibration	Same as corresponding SAM mode parameter
b_0,b_1,b_2,b_3,b_4,b_5	Forward along-scan mirror deviation polynomial coefficients	Ground calibration	Same as corresponding SAM mode parameters
d_0,d_1,d_2,d_3,d_4,d_5	Reverse along-scan mirror deviation polynomial coefficients	Ground calibration	Same as corresponding SAM mode parameters
e_0,e_1,e_2,e_3,e_4,e_5	Forward across-scan mirror deviation polynomial coefficients	Ground calibration	Same as corresponding SAM mode parameters
g_0,g_1,g_2,g_3,g_4,g_5	Reverse across-scan mirror deviation polynomial coefficients	Ground calibration	Same as corresponding SAM mode parameters

Table 4: Bumper Mode SAM Emulation Model Parameters

It should be noted that although the scan mirror calibration parameters for the SAM emulation bumper mode are the same as for the normal SAM mode, the values these parameters take on in the bumper mode could be expected to be quite different. This applies to both the scan angles and the fifth-order polynomial coefficients. The large differences between the SAM mode and bumper mode start-to-mid and mid-to-end scan angles can be seen visually in the unprocessed (level 0) digital image data. These scan angles effectively define the instrument cross-track field of view for forward and reverse scans. When operating in SAM mode this field of view is defined by the scan angle monitor wing mirror angles. Since the SAM behavior is symmetric for forward and reverse scans, the instrument field of view is essentially the same for both scan directions. The same is not true in bumper mode where the variability in bumper behavior leads to significantly different angular fields of view for forward and reverse scans. This is demonstrated in figure 2 where the coverage offsets between bumper mode forward and reverse scans can be compared to the better aligned coverage in the (ETM+) SAM mode image. The diagonal "wedges" apparent in the ETM+ SAM mode data are calibration shutter incursions into the Earth-view portion of the reverse scans. This phenomenon is caused by bumper wear and the ensuing growth in SAM mode total scan time.
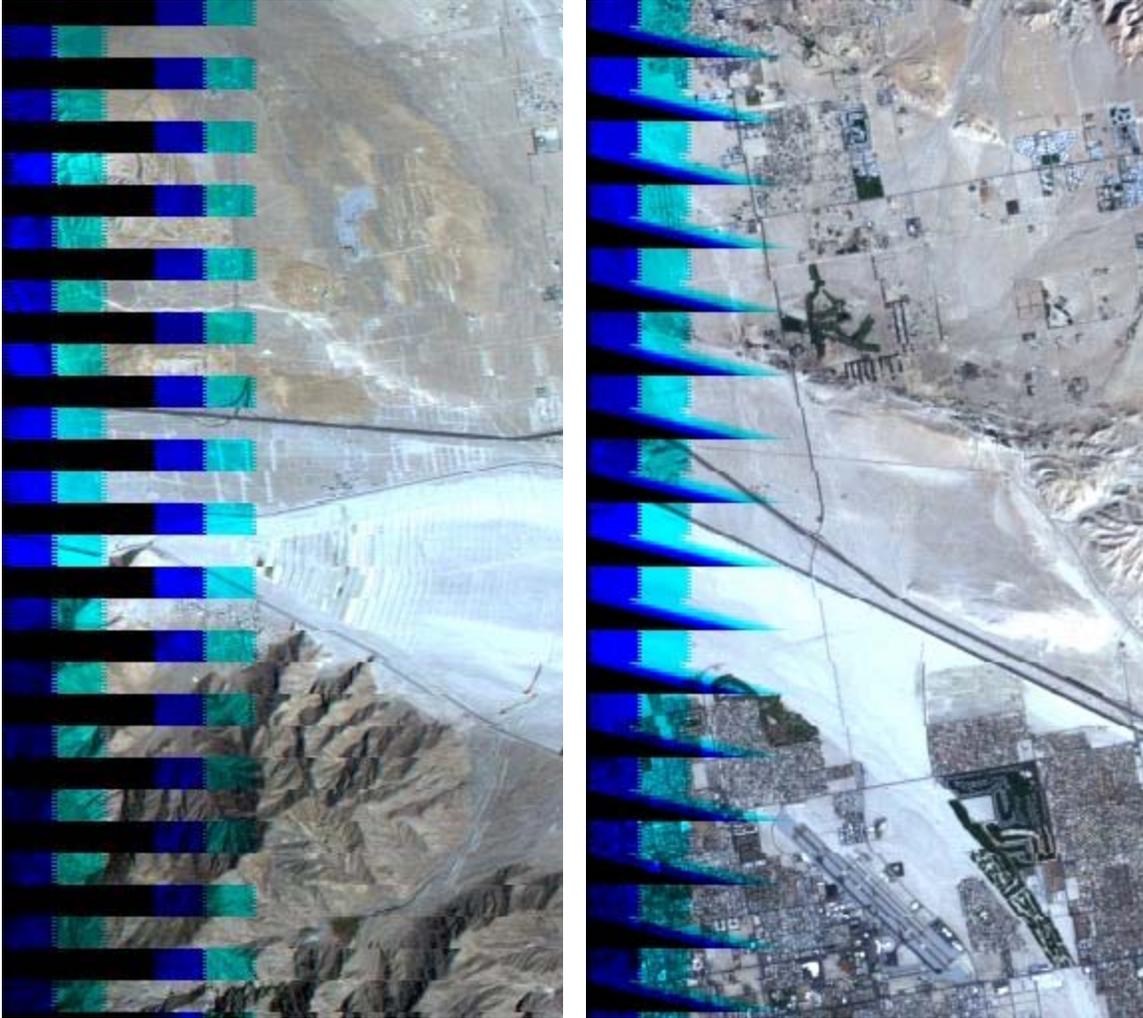
Figure 2: TM Bumper Mode (left) and ETM+ SAM Mode (right) Level 0 Image Data
Showing Forward/Reverse Scan Coverage Asymmetry in Bumper Mode

The bumper mode $FHSERR_{F/R}$ and $SHSERR_{F/R}$ parameters take the place of the scan-by-scan first half/second half scan error data, provided in the mirror scan correction data (MSCD) when operating in SAM mode. The bumper mode MSCD are used only to determine the scan direction and to verify the (fixed) counted number of minor frames per scan. The most straightforward implementation of the bumper mode SAM emulation algorithm is to simply populate the SAM model data fields with their bumper mode counterparts and then process the data using the conventional SAM mode model, as follows:

1. Using the acquisition date of the data being processed, select the applicable bumper mode calibration parameter set.
2. Load the applicable bumper mode calibration parameter values.
3. Populate the SAM mode scan field angles with the bumper mode A_{smF}, A_{meF}, A_{smR}, and A_{meR} values.
4. Populate the SAM mode scan mirror profile polynomial coefficients with the bumper mode b_{0-5}, d_{0-5}, e_{0-5}, and g_{0-5} values.

5. For each scan in the image data set, replace the MSCD first half scan time value with the value of the bumper mode FHSERR$_F$ parameter for forward scans, and the FHSERR$_R$ parameter for reverse scans.
6. For each scan in the image data set, replace the MSCD second half scan time value with the value of the bumper mode SHSERR$_F$ parameter for forward scans, and the SHSERR$_R$ parameter for reverse scans.
7. Continue with the SAM mode algorithm described above.

The bumper mode SAM emulation algorithm thus involves simply substituting new calibration values into the existing SAM mode algorithm rather than requiring an entirely new model.

Bumper Mode Scan Mirror Calibration
A key challenge in effectively utilizing Thematic Mapper data acquired in bumper mode will be the estimation and maintenance of the scan mirror geometric parameters required by the bumper mode mirror models. The absence of the external geometric reference provided by the scan angle monitor, and the resulting decoupling of the major frame (active scan) collection logic from scan mirror position allows the critical active scan start and stop angles to vary significantly with bumper wear and, hence, time. This time-varying behavior makes the bumper mode scan mirror calibration process more challenging than the corresponding SAM mode activity.

The TM bumper mode scan mirror calibration process uses a variant of the technique used to perform on-orbit scan mirror calibration for ETM+ SAM mode data [4]. This technique uses cloud free images acquired over geometric calibration test sites where precisely registered reference images are available. A terrain corrected band 5 image of the calibration scene is generated at 15-meter pixel spacing, using supporting ground control and digital elevation data. Special constraints are applied to the cross-track and radial orbital position and velocity adjustments in the precision correction process so that errors in the initial scan mirror calibration angles are not modeled as ephemeris corrections but, instead, appear in the terrain corrected image as uncompensated scale errors.

Test points along the Thematic Mapper scan centerlines are extracted from the terrain corrected image and correlated with a reference image derived from digital orthophotoquad (DOQ) data. The observed deviations between the TM image and the DOQ reference are organized by scan direction and used to provide measurements of the along- and across-scan mirror errors as functions of time in scan. After filtering for outliers, these measurements are fit to fifth-order Legendre polynomials characterizing the along- and across-scan errors for forward and reverse scans. The resulting Legendre polynomial coefficients are used to derive corrections to the initial scan mirror calibration parameter values. When calibrating SAM mode data this includes computing updates to the scan mirror start-to-mid and mid-to-end angles as well as corrections to the fifth-order nonlinearity profile polynomial coefficients. For bumper mode data the Legendre correction polynomial coefficients are used to compute updates to the physical model's

bumper timing parameters in addition to the nonlinearity profile corrections. The updated physical model parameters are then used to derive corresponding updates to the SAM emulation model parameters.

Physical Model Calibration Parameter Estimation

The scan mirror calibration procedure generates a set of four fifth-order Legendre polynomial coefficients: along- and across-scan polynomials for each scan direction. The across-scan coefficients are converted directly to time-based polynomial coefficients and are then added to the initial across-scan coefficients as is the case for SAM mode calibration data [4]. The coefficients (a_0, a_1, a_2, a_3, a_4, a_5) of the two along-scan polynomials are used to compute corrections to the bumper timing parameters (T_{pickA}, T_{dwellA}, T_{pickB}, T_{dwellB}) and scan start/stop angles (A_{smF}, A_{meF}, A_{smR}, A_{meR}) as follows:

1. For both scan directions, constrain the Legendre correction polynomial to be zero at the end points by computing constrained linear coefficients:

$$a'_0 \ = \ -a_2 - a_4$$
$$a'_1 \ = \ -a_3 - a_5$$

2. For both scan directions, compute the residual linear error terms:

$$c_0 \ = \ a_0 - a'_0$$
$$c_1 \ = \ a_1 - a'_1$$

3. For both scan directions, compute corrections to the scan start/stop angles:

$$\Delta A_{sm} \ = \ c_0 - c_1$$
$$\Delta A_{me} \ = c_0 + c_1$$

4. Apply the scan start/stop angle corrections:

For forward scans: $A'_{smF} \ = \ A_{smF} - \Delta A_{sm}$
                       $A'_{meF} \ = \ A_{meF} + \Delta A_{me}$

For reverse scans: $A'_{smR} \ = \ A_{smR} + \Delta A_{sm}$
                       $A'_{meR} \ = \ A_{meR} - \Delta A_{me}$

5. Compute the average measured total scan time (t_s) for each scan direction:

$$t_{sF} \ = \ \Sigma_{i=FWD} \ [(SHSERRi * 4096 + FHSERRi) * T_{unit}] \ / \ n$$
$$t_{sR} \ = \ \Sigma_{i=REV} \ [(SHSERRi * 4096 + FHSERRi) * T_{unit}] \ / \ n$$

6. Compute the active scan time (t_{active}) noting that it is the same for both scan directions:

$$t_{active} \ = \ (LL - 0.5) * T_{sample}$$

7. Compute the scan velocity:

For forward scans: $V_F = (\alpha_A - \alpha_B) / (t_{sF} - T_{pickA} - T_{dwellB})$

For reverse scans: $V_R = (\alpha_B - \alpha_A) / (t_{sR} - T_{pickB} - T_{dwellA})$

8. Compute the correction to the bumper dwell time:

For forward scans:
$$\Delta T_{dwellB} = -c_0 / V_F + c_1 (t_{active} + 2 T_{offsetB} - 2 T_{dwellB}) / (V_F t_{active})$$

For reverse scans:
$$\Delta T_{dwellA} = -c_0 / V_R + c_1 (t_{active} + 2 T_{offsetA} - 2 T_{dwellA}) / (V_R t_{active})$$

9. Compute corrections to the bumper pickoff times:

For forward scans:
$$\Delta T_{pickA} = c_0 / V_F + c_1 (2 t_{sF} - t_{active} - 2 T_{pickA} - 2 T_{offsetB}) / (V_F t_{active})$$

For reverse scans:
$$\Delta T_{pickB} = c_0 / V_R + c_1 (2 t_{sR} - t_{active} - 2 T_{pickB} - 2 T_{offsetA}) / (V_R t_{active})$$

10. Apply the time corrections:

$T_{dwellA} = T_{dwellA} - \Delta T_{dwellA}$
$T_{dwellB} = T_{dwellB} - \Delta T_{dwellB}$
$T_{pickA} = T_{pickA} - \Delta T_{pickA}$
$T_{pickB} = T_{pickB} - \Delta T_{pickB}$

The constrained along-scan Legendre coefficients (a'_0, a'_1, a_2, a_3, a_4, a_5) for each scan direction are converted to time-based polynomial coefficients (Δb_0, Δb_1, Δb_2, Δb_3, Δb_4, Δb_5) and are then added to the initial along-scan coefficients to compute the updated mirror profiles (b'_0, b'_1, b'_2, b'_3, b'_4, b'_5).

The bumper mode calibration process was initialized by setting the scan mirror profile coefficients to zero, estimating starting values for the eight bumper mode parameters listed in table 3, and then computing the corresponding initial scan start/stop angles from:

$A_{smF} = \alpha_B + V_F * (T_{offsetB} - T_{dwellB})$
$A_{meF} = -A_{smF} - V_F * t_{active}$
$A_{smR} = -\alpha_A - V_R * (T_{offsetA} - T_{dwellA})$
$A_{meR} = -A_{smR} + V_R * t_{active}$

Where V_F, V_R, and t_{active} are computed as indicated above.

Derivation of SAM-Mode Emulation Model Parameters
The scan mirror start/stop angles and nonlinearity profile coefficients computed for the physical model calibration are used as-is in the SAM emulation model. All that remains to complete the SAM emulation model calibration is to compute new values for the forward and reverse scan first half and second half scan error parameters. This is done for both scan directions as follows:

1. Compute the zero scan angle time assuming linear mirror motion:

    For forward scans: $T_{fh} = T_{zero} = -A_{smF} / V_F$

    For reverse scans: $T_{fh} = T_{zero} = A_{smR} / V_R$

2. Compute the active scan time from the nominal first half/second half times:

    For forward scans: $T_s = T_{fhf} + T_{shf}$

    For reverse scans: $T_s = T_{fhr} + T_{shr}$

3. Evaluate the along-scan mirror nonlinearity polynomial at the first half scan time:

    $Q = b_0 + (b_1 * T_{fh}) + (b_2 * T_{fh}^2) + (b_3 * T_{fh}^3) + (b_4 * T_{fh}^4) + (b_5 * T_{fh}^5)$

4. Compute the corrected first half scan time including the effects of mirror nonlinearity:

    For forward scans: $T_{fh} = T_{zero} + Q * T_s / (A_{smF} + A_{meF})$

    For reverse scans: $T_{fh} = T_{zero} + Q * T_s / (A_{smR} + A_{meR})$

5. Iterate steps 3 and 4 until T_{fh} stops changing. One iteration is typically sufficient.

6. Compute the second half scan time:

    $T_{sh} = T_s - T_{fh}$

7. Compute the first half and second half scan error values from the first half and second half scan times:

    For forward scans: $FHSERR_F = (T_{fhf} - T_{fh}) / T_{unit}$
    $SHSERR_F = (T_{shf} - T_{sh}) / T_{unit}$

    For reverse scans: $FHSERR_R = (T_{fhr} - T_{fh}) / T_{unit}$
    $SHSERR_R = (T_{shr} - T_{sh}) / T_{unit}$

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Summary and Recommendations

Algorithms for performing geometric corrections for Landsat 5 Thematic Mapper data collected in bumper mode have been successfully developed and tested. These algorithms modify the conventional SAM mode scan mirror modeling algorithm to account for the differences in bumper mode operating characteristics. Two algorithms have been developed: one based on a physical model of the scan mirror's behavior in bumper mode and one that creates synthetic SAM mode-like data to emulate the SAM mode. Both provide adequate geometric correction for bumper mode imagery but they achieve this through different degrees of alteration to the existing SAM mode algorithm. The SAM mode emulation algorithm requires a relatively minor adjustment to the data preprocessing logic used by the SAM mode scan mirror algorithm and achieves geometric correction accuracies as good or better than the physical model, based on initial test results. The SAM mode emulation algorithm described above is therefore the preferred approach to performing geometric correction processing for bumper mode data.

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