RADIOMETRIC CHARACTERIZATION AND PERFORMANCE ASSESSMENT OF
THE ALI USING BULK TRENDED DATA

Tim Ruggles*, Imaging Engineer
Dennis Helder*, Director
Image Processing Laboratory, Department of Electrical Engineering and Computer Science
South Dakota State University
Brookings, SD 57007
timothy.ruggles@sdstate.edu
dennis.helder@sdstate.edu

Doug Hollaren**, Software Engineering Lead
Jim Nelson**, Systems Engineer
Ron Morfitt**, Systems Engineer
Science Applications International Corporation (SAIC), Contractor to
U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center
Sioux Falls, SD 57198
hollaren@usgs.gov
jnelson@usgs.gov
rmorfitt@usgs.gov

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ABSTRACT

The Earth Observing-1 (EO-1) Advanced Land Imager (ALI), developed as part of NASA’s New Millennium
Program, utilizes advances in imaging technologies and techniques to provide high-quality image data compatible
with that produced from currently available Landsat Thematic Mapper (TM) technology. As opposed to the Landsat
7 Enhanced Thematic Mapper Plus (ETM+) focal plane design that uses 136 detector elements in eight spectral
bands, the ALI focal plane contains 15,360 detector elements in ten spectral bands, divided among four sensor chip
assemblies (SCA). To develop the ability to process the resulting volumes of data for the ALI (and any future
Landsat Data Continuity Mission (LDCM) sensors derived from an ALI-like design), a new processing system has
been implemented in a joint collaboration between the U.S. Geological Survey (USGS) Earth Resources
Observation and Science (EROS) Center and researchers at NASA Goddard Space Flight Center (GSFC) and South
Dakota State University (SDSU). One component of this processing system is designed to extract basic information
related to detector performance—bias levels, histogram statistics from image data, and response to internal
calibration sources operated at known radiance levels—from every typical ALI data collect and store the results into
a central database for later study. Analyses under development will provide the ability to thoroughly characterize the
ALI’s radiometric behavior at the individual detector level as well as the SCA level over both single-orbit and
delay intervals. For example, initial results from a lifetime bias level analysis of the trended data indicate that any
given detector can possess as many as seven distinct bias “states.”

BACKGROUND

The Earth Observing-1 (EO-1) Advanced Land Imager (ALI) utilizes advances in imaging technologies and
techniques to provide high-quality image data comparable to that of the Enhanced Thematic Mapper Plus (ETM+)
of Landsat 7. The ALI instrument demonstrates a multispectral “pushbroom” sensor that likely will be used in the
future Landsat Data Continuity Mission (LDCM). The ALI uses a single focal plane module containing 1,280
detector elements in nine multispectral bands and 3,840 detector elements for the panchromatic band, which are
divided among four sensor chip assemblies (SCA), for a total of 15,360 detectors. In comparison, the Landsat 7
focal plane contains 16 detector elements in six multispectral bands, eight detector elements in a thermal band,
32 detector elements for the panchromatic band, for a total of 136 detectors. The ALI detector samples are also quantized to 12 bits instead of the 8 bits used for each ETM+ detector. The ALI pushbroom design and large number of detectors increase the complexity of calibrating an individual detector’s response. A single ALI detector is not illuminated as often as an ETM+ detector, so gathering as much statistical information about each detector is critical to effective calibration.

Another factor affecting the calibration of ALI detector response is the availability of bias and lamp pulse reference data. The data sets from the ALI instrument have only two references for bias (pre-image and post-image) and one reference to lamp data (after imaging) per collect to use for calibration (Fig. 1). Considerably less calibration information is collected from the ALI than is collected from the Landsat Thematic Mappers (TM), which collect calibration data after every scan in all scenes. Although imaging collects for ALI are relatively small (approximately the length of one Landsat scene), those for an operational LDCM instrument could be considerably longer resulting in even less calibration information than ALI.

To address these calibration challenges, the Advanced Land Imager Assessment System (ALIAS) was developed to process and analyze all of the ALI data collected since the launch of EO-1 in November 2000. The processing for calibration and analysis purposes focuses on gathering, from every data collect, basic statistical information (e.g., minimum, maximum, mean, and standard deviation of the detector response and the number of pixels used to calculate the statistics) for every detector from the calibration sources and the imaging interval. Through such a process, coined “bulk trending,” significant amounts of data are generated and stored in a database, which can then be used to trend individual detector responses over time, monitor the instrument’s overall performance, and calibrate the image data. Along with the bulk trended information, ALIAS collects data from a small subset of scenes for more detailed trending and calibration analysis. In comparison, the Landsat 7 Image Assessment System (IAS) uses approximately ten scenes acquired each day (out of 250 total) for calibration and instrument assessment purposes. Having these data for all imaging times and detailed trending information from special calibration scenes provides an improved view for the calibration analysts to monitor the overall operating performance of all radiometrically important components of the sensor (Christopherson, 2004).

In addition to gathering detector statistics, select housekeeping fields, such as focal plane temperatures and ephemeris, are collected from every housekeeping data set and stored in a database for trending, analysis, and calibration purposes. The EO-1/ALI housekeeping data are collected at regular intervals, independent of data collection events, and stored in individual files containing one day’s worth of telemetry. With this information, researchers can analyze sensor and/or spacecraft behavior outside of a data collection event.

An added benefit of processing all of the data to derive trending information is to allow the detection and flagging of anomalies in the data. In an operational LDCM environment, the best time and place to execute bulk trending is after the raw data are converted to a Level-0 format, prior to its transfer to the Level-0 archive (Fig. 2). During Level-0 processing, all data is accessed, and it is the earliest time that anomalies in the imagery and housekeeping data can be detected. Since the bulk trending concept was developed four years after the launch of EO-1, the majority of scenes input to bulk trending come from the historical ALI archive (Christopherson, 2004).
BULK TRENDING SIZE AND PERFORMANCE

The concept of processing every scene acquired and storing statistics to a trending database requires significant performance and sizing considerations. For example, to properly detect errors in imagery prior to its inclusion in the archive, bulk trending must be completed in a timely manner. Also, the sheer volume of information created by storing detector-level statistics on every acquired scene is staggering, creating demands for sufficient storage capacity as well as efficient data retrieval. Therefore, the algorithms for bulk trending are kept simple yet useful.

The EO-1 satellite was a prototype mission to demonstrate new satellite and instrument technology. As such, only one-fifth of the ALI focal plane was populated. Assuming the LDCM instrument will follow the same or similar instrument design, the bulk trending database will contain five times as much data from a fully populated focal plane. As currently implemented in ALIAS, bulk trending processes one data collect in approximately 45 seconds and inserts 16,361 records into the trending database. There are approximately 325 million “records” (or rows) for the approximately 20,000 data collects processed to date.

EO-1/ALI housekeeping files are received once a day and are of a fixed size. Assuming that LDCM will follow a similar scheme, the bulk trending database will contain the same amount of housekeeping information as the ALIAS bulk trending database. Bulk trending processes one day of housekeeping data in about ten minutes and inserts about 700,000 records into the trending database. For the 1,500 days of telemetry information currently available, this translates into approximately 1 billion housekeeping records stored in the trending database.

The entire ALIAS trending database consists of the bulk trending data along with “detailed” trending performed on special calibration scenes. Table 1 lists the total estimated size for the required trending.

Table 1. Estimated Trending Database Sizes

<table>
<thead>
<tr>
<th></th>
<th>Yearly ALIAS (GB)</th>
<th>5-Year ALIAS (GB)</th>
<th>5-Year LDCM (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housekeeping</td>
<td>44</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>Image Statistics</td>
<td>93</td>
<td>465</td>
<td>2,325</td>
</tr>
<tr>
<td>Totals</td>
<td>137</td>
<td>685</td>
<td>2,545</td>
</tr>
</tbody>
</table>

Through table designs, partitioning/sub-partitioning, and indexing, the database is optimized for the writing and retrieval of the large amounts of data required for the processing, evaluation, calibration, and analysis of the bulk
trending information. For example, a query to extract the lifetime pre-image and post-image bias statistics for an individual detector from the bulk trending database completes in approximately one minute.

BULK TRENDING EVALUATION

Data from the bulk trending database are used by the following ALIAS evaluation tools to help identify anomalies and artifacts affecting the ALI’s image and calibration data, trending of radiometric performance on a detector-by-detector basis, and calibration information. Brief descriptions of these algorithms are presented next; additional details can be found in the ALIAS Radiometric Algorithm Description Document (Kaita et al, 2005).

Check Detector Operability

The detector operability algorithm compares the bulk trended along-track bias and lamp data statistics for each detector to a reference value to determine an overall operability status. Analysis of the dark data statistics identifies detectors that are “stuck at” a constant DN value, excessively noisy, or exhibiting an excessive dark current value. Analysis of the current contamination-free internal calibrator (IC) statistics from lamp state [111], all three IC lamps on, identifies detectors exhibiting “moderate” to “extreme” changes in dynamic range. In both cases, current operability states and changes to/from an initially operative state for each detector are trended to an evaluation database through integer flags. Based on this operability status information, obtained at regular intervals, an ALIAS analyst adds or removes the affected detector(s) to/from the list of current nonfunctioning/malfunctioning detectors in a Calibration Parameter File (CPF) that contains the relevant information necessary to perform an accurate calibration of a specific ALI image.

Calculate Relative Gains

This algorithm calculates relative detector gain, either as a ratio of means or a ratio of standard deviations, for a given band, SCA, and date range from estimates of scene histogram statistics recorded in the bulk trending database. The set of relative gain estimates is recorded in the evaluation database for further off-line evaluation by the ALIAS analyst to determine whether to change the set currently listed in the CPF. In addition to providing the source data for deriving correction factors to perform relative radiometric calibration, the set of relative gains is a required input for generation of absolute detector gains used to create Level-1R (radiometrically corrected) imagery.

Characterize Contamination

This algorithm characterizes variations in observed detector response in the ALI due to focal plane contamination effects. Given two consecutive focal plane bakeout end dates (the dates when the focal plane is heated to remove contaminants), a linear regression is fit to the bias-corrected lamp state [111] detector responses recorded in the bulk trending database. The resulting slope and intercept information for each bakeout interval are recorded in the CPF and used to generate date-specific contamination correction factors of the form

$$CF = \frac{b}{a(t - t_{bakeout}) + b} \tag{1}$$

where $a$ and $b$ are the estimated regression slope and intercept, respectively, for the current bakeout interval, and $t_{bakeout}$ is the start of the current bakeout interval. The bakeout dates and correction factors are also stored in the evaluation database, with the bulk trending information, allowing further detailed analysis and characterization of the contamination phenomenon. The contamination correction factors from the CPF are also used in generating the absolute gains that are used to create a Level-1R image.

INITIAL RESULTS

As mentioned earlier, approximately 20,000 ALI scenes have been processed to date with the bulk trending approach. The wealth of statistical data extracted from these scenes is currently influencing the development of
analysis techniques and tools that efficiently utilize this information, with the ultimate goal of providing a comprehensive assessment and radiometric characterization of every detector in the instrument. This section presents representative examples of results obtained from initial analyses of the bulk trended data, covering issues of radiometric interest such as bias stability, IC lamp stability, and relative gain characterization. These examples demonstrate the value of the bulk trending approach applied to radiometric characterization of the ALI and, indirectly, its potential for application to the radiometric characterization of the future LDCM sensor.

Before presenting any results, a brief explanation of the detector numbering convention used in this paper is provided. Within ALIAS, detector numbering is considered relative to an individual SCA. Within the SCA’s image data, the western-most pixels are imaged by Detector 1, and detector numbers increase from west to east across the image. This numbering scheme also applies to the bias and lamp data sets.

**Bias Response**

As shown in Figure 1, the typical ALI bias data set consists of the pre-image measurement, acquired at the beginning of the data collect after a short period following instrument turn-on, and the “post-image” measurement, acquired a short period after completion of the image acquisition and closure of the telescope aperture cover. Long-duration bias-level data acquisitions are also obtained. However, these data sets are not processed by bulk trending and consequently are not considered further in this paper.

Examination of the bulk trended data demonstrates that, in general, the bias response of the ALI’s detectors is quite stable, from time intervals as short as a single day to those across significant portions of the instrument’s lifetime. This is especially evident after 500 days since launch (DSL) (early 2002), as can be seen in Figures 3a and 3b for Detector 100 in Band 1 of SCA 4. Hypothesis testing at the 0.01 significance level of this detector’s mean pre-image and post-image responses over 650 DSL (Table 2) provides additional evidence of this stability. The low P-value obtained for the lifetime comparison, while suggesting rejection of the equal means hypothesis is warranted, is most likely due to the large number of samples, making the test especially sensitive to very small differences. As can be seen from the table, the mean pre-image and post-image bias levels within both the 650 DSL and lifetime intervals differ by less than 0.25 DN.

![Lifetime PREDX Bias From ALIAS Bulk Trending, SCA4, MS-1, Det. 100](image)

**Figure 3a.** Lifetime pre-image bias, SCA 4, Band MS-1, Detector 100. The slight “bump” around 400 DSL (late 2001–early 2002) corresponds to a period when data collects were acquired at a cooler focal plane temperature than is typically used.
Interestingly, analysis of the bulk trended bias data also indicates that a significant number of detectors are exhibiting multiple bias levels or “states” (Hijazi, 2003). The greatest number of states observed to date from the available bulk trended data is seven; this is the case with Detector 259 in SCA 1 in the panchromatic band for the post-image acquisition shown in Figure 4. The existence of these multiple states is somewhat analogous to the scan-correlated shift (SCS) phenomenon observed in the detectors of the Landsat 4/5 Thematic Mappers, in that it appears to be a random shift in the bias level (Helder/Ruggles, 2004). It differs from SCS, however, in that the bias level does not randomly change in a single data collection event. The initial bias level appears to be fixed when the instrument is turned on prior to a data collect. Based on these observations using the ALIAS bulk trended data, algorithms to allow prediction of bias levels for any detector in the absence of direct measurements are currently under investigation. Such algorithms would be particularly applicable to the LDCM sensor, which may have bias data associated with only a few images.

Figure 4. Seven states of post-image bias, SCA 1, PAN Band, Detector 259.
Table 2: Pre-Image/Post-Image Bias Stability, SCA 4, MS-1, Detector 100

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>650 DSL</td>
<td>14</td>
<td>283.934 ± 0.267</td>
<td>283.954 ± 0.286</td>
<td>“T”</td>
<td>-0.191</td>
<td>0.850</td>
</tr>
<tr>
<td>Lifetime*</td>
<td>16,847</td>
<td>283.568 ± 6.522</td>
<td>283.441 ± 0.769</td>
<td>“Z”</td>
<td>2.491</td>
<td>0.013</td>
</tr>
</tbody>
</table>

* Excludes first 500 days

**Internal Calibration Response**

As shown in the example data set in Figure 1, measurements of detector response to the three IC lamps are acquired, for a limited number of data collection events, after the post-image bias acquisition. After an 8-second period to allow the outputs to stabilize (Mendenhall, 2000), lamps are sequentially turned off in 2-second intervals; the resulting 8-second acquisition measures three distinct radiance levels, as well as a bias level estimate obtained with all lamps turned off. Due to the mounting of the SCAs onto the focal plane, several detectors at the edge of each band in each SCA are not fully exposed to the lamp outputs (Fig. 5).

![Figure 5. Bias-corrected LS [111] response across detector array, SCA 3, MS-4p.](image)

![Figure 6. Bias-corrected lifetime LS [111] trend with estimated model, SCA 3, MS-4p, Detector 60.](image)
For the majority of detectors that are illuminated with the full-lamp output, the bulk trended response provides useful information relating to the health of the IC system. The results from such a trending analysis for lamp state [111], measured by Detector 60 in Band 4p of SCA 3, are shown in Figure 6. Linear model coefficients and the results of hypothesis tests performed on those coefficients at the 0.01 significance level are presented in Table 3. The decreased response around 400 DSL corresponds to the temporary change in operating focal plane temperature discussed earlier. As is visually apparent from Figure 6, the trend takes on a linear character especially after 500 DSL, indicating a response decrease of approximately 22 DN/year (on the order of 1%). Although obscured by uncorrected contamination effects, the response prior to 500 DSL does not appear to be adequately characterized by a linear model. The low P-values shown in Table 3 provide further evidence of a non-zero slope to the trend model.

Table 3: Lifetime IC Stability, SCA 3, Band 4p, Detector 100

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Std. Error</th>
<th>Stat. Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>–0.059 DN/day</td>
<td>0.0013</td>
<td>–44.103</td>
<td>&lt; 10⁻⁸</td>
</tr>
<tr>
<td>B</td>
<td>1999.32 DN</td>
<td>0.92</td>
<td>2180.22</td>
<td>&lt; 10⁻⁸</td>
</tr>
</tbody>
</table>

Relative Gain

Due to the geometry of the ALI’s pushbroom design, it cannot be assumed that a detector at one end of an array measures the same incident radiance levels, in a statistical sense, as a detector at the opposite end. Consequently, there is not enough information within an individual ALI image to reliably calculate the statistics necessary for estimating relative gain. However, techniques have recently been developed and implemented in ALIAS to calculate relative gain for the detectors within an individual SCA or band using the bulk trended summary histogram statistics obtained from many images. For both cases, relative gain estimates can be based on a ratio of means or standard deviations, as mentioned earlier.

Figure 7. Relative gain, SCA 1, Band 1p, estimated from ALIAS bulk trending.

Corrections for relative gain differences between detectors using this technique are generally equal or superior to corrections based on pre-launch methods. Figure 7 shows the relative gain estimates for Band 1p of SCA 1 based on the bulk trended histogram statistics obtained from 1,694 images acquired during 2001; slight differences in relative gain between odd and even detectors are noticeable across most of the array. Correction factors derived from this set of relative gains were applied to the Level 0, SCA 1, Band 1p image of the area near Phoenix, Arizona, acquired on July 25, 2001. Comparison of a full-resolution, 400 x 400 pixel region from the image before and after correction (Figs. 8a and 8b) demonstrates significant reduction in the observed striping. Further examination of a 50...
x 50 pixel area within this region (Figs. 8c and 8d) indicates that slight residual striping is still present. The reduced efficacy of the striping correction is likely due, in part, to contamination effects in both the bulk trended histogram statistics and in the image data itself, as discussed in the next section. This technique shows great promise for tracking and correcting on-orbit changes to relative gain.

**Figure 8a.** Original Level 0R image data.  
**Figure 8b.** Destriped Level 0R image data.

**Figure 8c.** Original Level 0R image data, 50 x 50 pixel area roughly represented by the red square in Fig. 8a.  
**Figure 8d.** Destriped Level 0R image data, 50 x 50 pixel area.

**Contamination Characterization**

Previous analyses of the ALI contamination phenomenon (Mendenhall, 2000) indicate that contaminant deposition on the focal plane is generally non-uniform across the detector array, particularly in the longer wavelength Visible and Near Infrared (VNIR) and Short Wavelength Infrared (SWIR) bands. Consequently, to achieve adequate characterization of this phenomenon, detector-level analysis is required. The amount of data generated from bulk trending makes this kind of analysis feasible.

As mentioned earlier, an algorithm was developed and implemented for ALIAS to characterize contamination effects at the detector level. It makes use of bias-corrected lamp state [111] data obtained from bulk trending along with knowledge of the dates that bakeout procedures were finished. For a given bakeout interval, a linear model fit to the observed data generates the necessary parameters for calculating date-specific contamination correction factors, as defined in Equation (1). Figure 9 shows an example of the characterization (and subsequent correction) of lamp state [111] IC data for Detector 160 in Band 4p of SCA 1, across a time period covering five bakeout intervals between 450 and 500 DSL. Further analysis of this data throughout the lifetime suggests that the rate of contaminant buildup is approaching a constant value. Slight variation from interval-to-interval is due to incomplete removal of contaminants or sensor noise.
Figure 9. Contamination-corrected IC response, SCA 1, Band 4p, Detector 159, 450–500 DSL. The green vertical lines represent the dates when the bakeout procedure was ended. The black “+” signs represent the bias-corrected, contaminated IC data. The red lines represent the linear model applied to the data within the given bakeout interval. The magenta squares represent the contamination-corrected data. Finally, the red triangles and blue horizontal lines represent the DN value, measured at the start of the bakeout interval under consideration, when the normalized response is equal to 1 (indicating no contamination has occurred). Variations in response between bakeout intervals are due to the overall IC trend.

Figure 10. Post-image bias, SCA 1, Band 5p, Detector 100, 600–1,000 DSL. As in Fig. 9, the green vertical lines represent the estimated bakeout end dates.
Interestingly, variation in bias response in the SWIR bands is observed to be consistent with changes in contaminant buildup (Hijazi, 2003). This is readily seen in the post-image bias response for Detector 100 in Band 5p of SCA 1, as shown in Figure 10. The “saw tooth” pattern, especially prominent between 600 and 1,000 DSL, strongly suggests that contamination effects are the cause of this variation. VNIR bands do not show such contamination effects in bias data.

![Graph showing comparison of contamination-free vs. contaminated bias-corrected detector response, SCA 1, Band 1p.](image)

**Figure 11.** Comparison of contamination-free vs. contaminated bias-corrected detector response, SCA 1, Band 1p. The overall response due to contamination effects is about 5% less than the corresponding contamination-free response, resulting in an approximate 1% to 3% change in relative gain.

Finally, contamination effects have recently been observed to affect estimates of relative gain. A comparison of the average detector response generated from contaminated and uncontaminated histogram statistics is shown in Figure 11 for all detectors in Band 1p of SCA 1. Initial studies suggest an effect on the order of 1% to 3%, depending on the band. If contamination correction of the image data prior to bulk trending is not feasible, it is recommended that relative gain estimates should be obtained from the histogram statistics of scenes acquired only within 1–2 days after the end of any bakeout procedure.

**CONCLUSION**

The pushbroom design of the ALI and future LDCM sensors pose significant challenges to radiometric analysis, characterization, and calibration. The bulk trending approach, which collects detector statistics from all calibration and imaging sources over the instrument’s lifetime, provides a wealth of data to enable a comprehensive assessment of radiometric response of each detector on the instrument. The results from new analysis techniques and tools developed to utilize this statistical data demonstrate the value of the bulk trending approach applied to radiometric characterization of the ALI and future LDCM sensors.

The database design and approach developed for ALIAS demonstrates the feasibility of writing, managing, and retrieving large amounts of data in support of these analysis and evaluation techniques. Further investigations are necessary to better understand the scalability and management of the trending database for LDCM. Continued analysis and development of techniques to further utilize bulk trending information provides the ability to thoroughly characterize the radiometric behavior at the individual detector, SCA, and band levels over both single-orbit and lifetime intervals.
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