CALIBRATION BEST PRACTICES: 25 YEARS EXPERIENCE FROM LANDSAT

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Abstract: Radiometric calibration of visible and infrared satellite remote sensing systems is a critically important step necessary to convert satellite imagery into data for the quantitative user. Over the past 25 years, South Dakota State University has investigated and developed a variety of radiometric calibration methods for sensors including moderate resolution sensors developed for scientific research such as the Landsat series, as well as high resolution commercial sensors such as IKONOS and Quickbird. From this experience base, it has become clear that virtually all sensors suffer degradation of responsivity while in space. If not corrected, incorrect results will be generated from applications based on this uncalibrated imagery. The purpose of this presentation is to share examples of best practices based on experiences of our research group and provide guidelines that can be used for other sensor systems.

A three step process will be presented. The first step in the process is to identify and remove artifacts from the imagery that interfere with the later calibration steps. A simple example is the scan-correlated-shift artifact in the Landsat Thematic Mapper. The second key step, relative radiometric calibration, refers to the process of equalizing the responsivity of sensors that contain multiple detectors. This is especially difficult for pushbroom sensors with thousands of detectors, and for sensors with high radiometric resolution. Examples of multiple approaches will be presented that were developed with the Advanced Land Imager (ALI) and will be applied to the Operational Land Imager (OLI) which will be launched in January, 2013. The final step, absolute radiometric calibration, allows conversion of the digital number assigned to each pixel into physical units such as radiance or reflectance. Several techniques will be presented such as on-board diffusers and vicarious approaches, as well as new methods based on pseudo invariant calibration sites (PICS).

1. INTRODUCTION

Landsat sensors have been continuously recording changes on the Earth's surface since the launch of Landsat 1 in 1972. At total of 11 instruments have been used during this time utilizing technology dating from the 1960's. The upcoming launch of Landsat 8 in early 2013 will use some of the newest technology developed for space-based imagery. Over this period of time efforts have been expended to understand the radiometric performance of these instruments and, as a result, a number of lessons have been learned that can be applied to calibration of current and future sensors. The purpose of this paper is to review these calibration lessons and provide a road map for use with other sensors. The paper will be divided into three sections. The first section will focus on lessons learned from Landsat radiometric artifacts, the second section will be describe approaches for calculating relative gain and lessons learned from these experiences, with the final section focusing on lessons learned with respect to absolute calibration. Concluding comments will finish the paper.

Table 1 illustrates the basic instrument suite, as well as launch and decommissioning dates for the Landsat sensors. The first three Landsat satellites carried the Return Beam Vidicon (RBV) and the Multi-Spectral Scanner (MSS). Early in the mission it was determined that the MSS was the more useful of the two instruments from a quantitative and scientific viewpoint. The next two satellites, Landsat 4 and 5, carried the MSS again but were also equipped with the Thematic Mapper (TM). Designed for more precise radiometry, the TM carried seven spectral bands from the visible and near infrared through the shortwave infrared with extension into the thermal regions. It also boasted an eight bit radiometric resolution as opposed to the MSS sensor's six bits with only four spectral bands in the visible and near infrared and moved into entirely incorporating solid state silicon-based detectors.

Table 1: Landsat Systems, Operational Dates and Sensors (from Markham and Helder 2012)

Satellite	Launch Date	Decommissioning Date	Sensors	
Landsat-1	July 23, 1972	January 6, 1978	MSS (4 band)	RBV (3 band)
Landsat-2	January 22, 1975	February 5, 1982	MSS (4 band)	RBV (3 band)
Landsat-3	March 5, 1978	March 31, 1983	MSS (5 band)	RBV (pan only)
Landsat-4	July 16, 1982	June 2001 (last TM data transmitter failed 1993)	TM (7 band)	MSS (4 band)
Landsat-5	March 1, 1984	Operating (MSS only)	TM (7 band)	MSS (4 band)
Landsat-6	October 5, 1993	Failed to achieve orbit	ETM (8 band)	
Landsat-7	April 15, 1999	Operating	ETM+ (8 band)	

The last Landsat sensor to be launched, Landsat 7, carried an advanced version of the TM known as the Enhanced Thematic Mapper Plus (ETM+). This instrument carried improved calibration systems known as the Full Aperture Solar Calibration (FASC) and Partial Aperture Solar Calibrator (PASC) in addition to the calibration lamps carried by the original TM instruments. Nominal spatial resolutions for the MSS was 80 meters while the spatial resolution for the TM in the reflective bands was 30 meters. Details of these instruments can be viewed in Table 2. Both the MSS and TM were whiskbroom scanning systems. The MSS was a unidirectional (west to east) scanner, while the TM was a bi-directional scanner. Orbital motion provided the second dimension of the imagery for these systems. More complete descriptions of these instruments, and their calibration systems, can be found in (Lansing and Cline, 1975), (Markham and Barker, 1987), (Engel and Weinstein, 1983), and (Markham et al., 2004).

This paper will focus on the MSS, TM, and ETM+ instruments. In each case, a form of lamp-based onboard calibration system was employed. In addition, the ETM+ had the solar calibrators mentioned above. While, in most cases, these systems performed well based upon their design parameters and lifetime, additional calibration methodologies needed to be developed to monitor the performance of each instrument. In some cases, performance updates were made after the decommissioning of the satellites. The next section of this paper will focus on the instrument artifacts that needed to be addressed prior to measuring calibration trends.

2. INSTRUMENT ARTIFACTS

All electro-optical systems exhibit artifacts manifested within the imagery produced due to noise components generated by various parts of the system. These artifacts may be due to sudden changes in various voltages in the system, oscillator noise that may be induced into the signal path, or energy storage elements (especially capacitive elements) that were not properly considered during system design and test. Examples of each will be illustrated in this section.

2.1 Scan Correlated Shift (SCS)

SCS is a sudden change in bias level that affects both Landsat 4 and Landsat 5 TM. The change in bias occurred at the end of a scan and affected all detectors in the instrument. Thus, a random pattern is formed in the imagery on a scan-by-scan basis as shown in Figure 1. This figure shows several scans obtained from a Landsat 5 TM night image. The left side shows a random change in bias level (lighter and darker scans), while the right side shows results after SCS correction. The amplitude of SCS was only on the order of 0.5 digital counts. However, in uniform regions it was a noticeable artifact and introduced an error in instrument calibration. Fortunately, correction was easily incorporated by properly estimating the bias level at the end of each scan when detectors were covered with the shutter rather than by regressing the lamp values to find the bias.

2.2 Memory Effect

Memory Effect, or ME, was a much more significant radiometric error present in the TM instruments. It was caused by a resistor/capacitor network in the pre-amplifier which produced a delayed response that was especially significant at or near sharp transitions in image intensity. Although the magnitude of the error could be quite large (up to 8 digital counts worst case), typically errors were on the order of 2-3 digital counts and it was most apparent in uniform regions of an image near where a sharp transition in intensity occurred. An example is shown in Figure 2a where there is a sharp transition from a darker water region to a brighter land region. Correction of this artifact

Table 2: Landsat Sensor Characteristics (from Markham and Helder 2012)

Sensor /Satellite	Nominal Reflective Spectral Bands	Spatial Resolution (Instantaneous Field of View)	Normal Radiometric Quantization	Radiometric Calibration Capabilities
MSS/ Landsat 1-3	500-600 nm 600-700 nm 700-800 nm 800-1100 nm	79 meters “ “ “	6-bit (compressed) “ “ 6-bit (linear)	Shutter with calibration wedge neutral density filter Solar calibrator
MSS/ Landsat 4-5	500-600 nm 600-700 nm 700-800 nm 800-1100 nm	83 meters “ “ “	6-bit (compressed) “ “ 6-bit (linear)	Shutter with calibration wedge neutral density filter;
TM/ Landsat 4-5	450-520 nm 520-600 nm 630-690 nm 760-900 nm 1550-1750 nm 2080-2350 nm	30 meters	8-bit (linear)	Shutter with lamp transfer optics, 3 calibration lamps with sequencer, radiance feedback control
ETM+/ Landsat-7	450-515 nm 525-600 nm 630-690 nm 760-900 nm 1550-1750 nm 2080-2350 nm 500-900 nm	30 meters 15 meters	8-bit (linear)	Shutter with lamp transfer optics, 2 calibration lamps, constant voltage control, Full Aperture Solar Calibrator, Partial Aperture Solar Calibrator

was very difficult due to complications in characterizing it. However, a method of characterization was developed using the detector response to the calibration lamps which occurs during the shutter region of the calibration at the end of each scan. A first order exponential model was developed that is applied to both imagery and calibration intervals on each image. Results of this correction are shown in Figure 2b. Residual striping is due primarily to slight differences in detector responsivity. Note the additional detail now observable in the water region.

2.3 Coherent Noise

Coherent Noise (CN) is present at some level in all instruments due to the presence of electrical or mechanical oscillators (both intended and unintended). The magnitude of CN is a function of the degree of isolation that exists between these oscillators and the signal path of the system. All Landsat instruments have exhibited CN but, fortunately, of the three artifacts mentioned it is the one that has the smallest affect on the system. CN magnitudes are typically much less than one digital count and are normally masked by all but the most uniform regions of an image (water, for example). Often CN can be characterized and corrected by using Fast Fourier Transform techniques. In the case of Landsat TM, the frequency of the CN is not perfectly stable. So, while it has been well characterized, and correction algorithms have been developed, they have not been implemented operationally. Many sensors developed recently have substantially improved isolation between oscillators and the signal path and this radiometric artifact is of such a small magnitude that it is often very difficult to observe

2.4 Lessons learned

Lessons learned from these examples include the need to deal with artifacts prior to establishing the radiometric calibration of the imaging system. Artifacts have the potential to cause errors of several percent and, if not dealt with ahead of time, will manifest themselves as calibration errors. Secondly, it is important to design systems so that it is possible to identify and eventually correct artifacts. For example, the ability to image at night for reflective sensors is very useful for isolating system characteristics in the absence of external signal. Being able to apply a controlled, or characterizable, radiant input to the system is also important to diagnose and correct artifacts that are signal dependent (such as ME). This can be done a variety of ways such as lamps, lunar looks, etc.

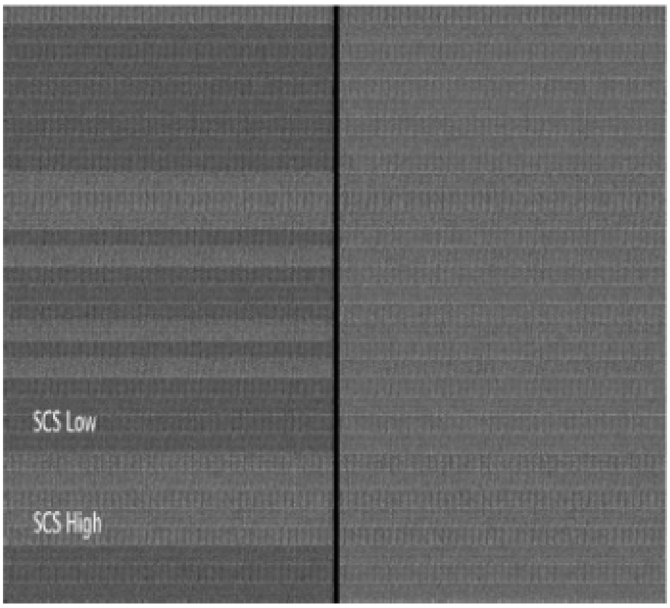

Figure 1. Example of SCS from Landsat 5 night image. Left side shows SCS before correction, right side shows results after correction. (from Helder and Ruggles 2004)

3. RELATIVE CALIBRATION

A second major area of calibration is often termed ‘relative calibration’ and refers to equalizing the response of detectors in those systems that utilize more than one detector per spectral channel. For example, Landsat MSS used 6 detectors per band and TM used 16 detectors in each reflective band. This section describes radiometric lessons learned in relative gain calibration.

3.1 Whiskbroom Scanners

Both Landsat MSS and TM employ a whiskbroom scanning mechanism with a small number of detectors per band. The MSS utilized photomultiplier tubes for several bands while the TM employed solid state photodiode detectors in the reflective bands. In both cases, some instability in the detectors was present such that the gain of one detector relative to another would tend to drift over time. As a result it was necessary to regularly estimate the relative gain of each detector with respect to a reference detector or a band average of all detectors. Fortunately, with whiskbroom scanners this is fairly easily done on a scene-by-scene basis as each detector, in a statistical sense, sees the same overall radiance field. Methods for relative gain estimation and correction based on mean detector response or standard deviation of the detector response within an image are well known.

However, relative gain estimates are often noisy and are much improved by looking at trends in relative gain over time. With the Landsat sensors this has been possible through use of the Landsat Image Assessment System (IAS) which collects calibration information and stores it in a database each time an image is processed (http://landsathandbook.gsfc.nasa.gov). As a result, a very accurate estimate of relative gains is possible. An example of this information is shown in Figure 3 where relative gain is plotted as over 26 years for one detector of Landsat 5 TM. Note that the relative gain estimates are noisy indicating the need for trending and smoothing, but abrupt changes do occur that must be incorporated into the calibration of image products.

3.2 Pushbroom Scanners

Pushbroom scanners normally employ large number of detectors oriented into a linear array orthogonal to the velocity vector of the satellite and an image is scanned by using the motion of the satellite. This complicates the relative gain estimation problem in two ways: first, there are many more detectors to calibrate; and, second, the assumption that each detector sees the same radiance field in a statistical sense is no longer valid. Thus, the simple single image based approach in the previous section cannot be used. Fortunately, other methods have been developed and, since Landsat instruments are whiskbroom scanners, will be illustrated using the Advanced Land Imager (ALI) that was part of the Earth Observing – 1 (EO-1) mission. Detailed characteristics of the ALI, a multispectral pushbroom scanner, can be found elsewhere (Digenis 1998).

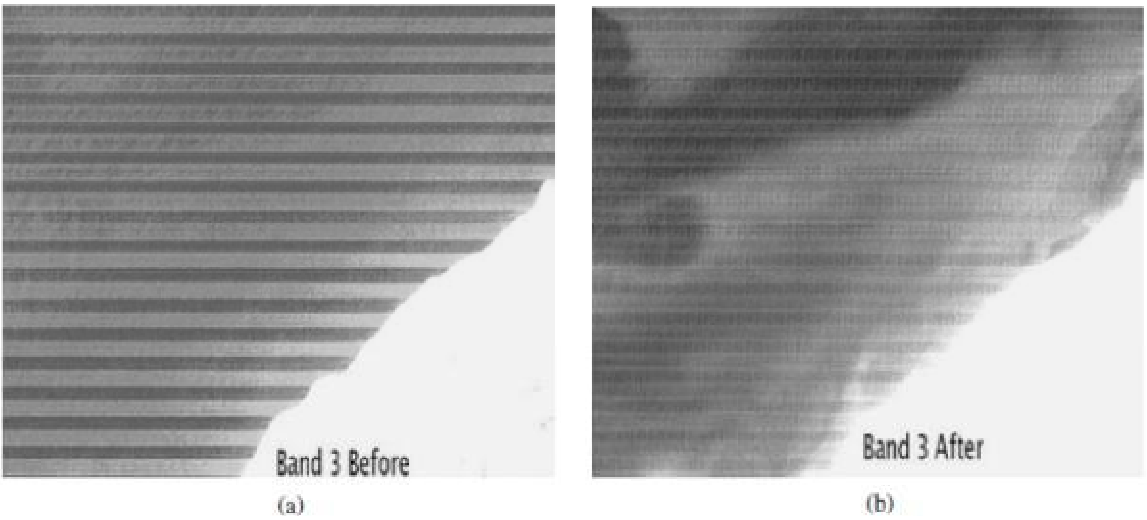

Figure 2. Memory Effect in band 3 of the Landsat 5 TM. Figure on left shows ME at a land/water boundary. Figure on right shows results after correction. Note detailed structure in water that was not previously observable. (from Helder and Ruggles 2004)

Since, in a given scene, each detector no longer sees the same radiance field statistically in a pushbroom scanner, one has to extend the concept to include multiple images. If an imager collects data from a large enough number of scenes, one can again assume each detector has observed the same radiance field on average and calculate relative gains based on multiple scenes. Initial work using the ALI suggests that only 100 scenes may be required (Shrestha 2010). These data can be collected using an image assessment system as described earlier. An example of using this approach is shown in Figure 4. This is from the ALI shortwave infrared band using relative gains from several hundred scenes. The image on the left shows the striping that occurs without any radiometric equalization. The result after correction (in the center) shows nearly a complete absence of striping especially as indicated with the small zoom window (on the right).

A second on-orbit method for relative gain estimation involves yawing the satellite 90 degrees so that the linear array is essentially oriented parallel to the orbital velocity vector. In this configuration, each detector views the same location on the Earth. By calculating the ratio of individual detectors to the reference at each of these locations a very accurate estimate of relative gains can be obtained (Krause 2004). In fact, the scene statistics and yaw method can be combined in an optimal manner that overcomes shortcomings of each method (Anderson, 2012). A third method involves use of an onboard solar diffuser and can be very effective. As radiometric resolution for recently developed sensors becomes increasingly precise, accurate relative gain estimation becomes much harder to obtain.

3.3 Lessons Learned

Relative gain estimation precision needs to increase as the radiometric resolution (bits/pixel) increases and is driven as much by asthetic dislike of striping as anything else. Single image estimates of relative gain are often poor estimates, so the use of databases to derive detector response data significantly improves the estimates. This approach can be used without regard to sensor design. Periodically performing a yaw maneuver substantially increases the accuracy relative gains estimates and should be incorporated whenever feasible.

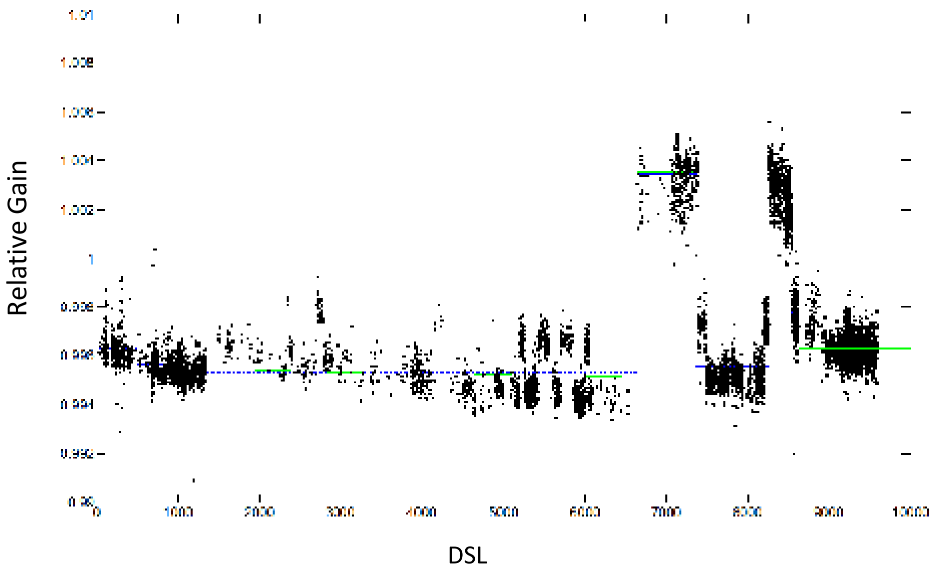

Figure 3. Relative Gain for Landsat 5 Band 4, Detector 15, as a function of Days Since Launch (DSL). (from Helder and Dewald, 2010)

4. ABSOLUTE CALIBRATION

Absolute radiometric calibration represents, in many ways, the most difficult part of the calibration process. Ultimately, it should tie the sensor to a calibration standard traceable to a national standards laboratory and should incorporate a rigorous error analysis to ascertain the total uncertainty associated with the calibration. This is often not the case. Historical experiences with Landsat sensors outline a path of development with absolute calibration that includes traditional onboard systems as well as vicarious methods that may prove to be just as accurate.

4.1 Onboard Systems

Landsat onboard calibration has used tungsten lamps in each instrument that has flown from Landsat 1 through Landsat 7. The MSS series of instruments relied solely on lamps throughout their entire lifetime, as did the Landsat 4 TM. Landsat 5 carried lamps too, but was also used with additional calibration methods including vicarious ground-based methods and pseudo invariant calibration sites (PICS). In each case, pre-launch lamp calibration was performed by allowing the instrument to view a calibrated source (integrating sphere) and the instrument itself was used to transfer the calibration of the sphere to the lamps. This method performed reasonably well with the Landsat system during the design life of the instruments (typically 3 years), and was especially useful for discovering trends in the responsivity. However, absolute calibration was always at issue due to additional uncertainties that occur during the launch process and the space environment. An example of instrument response to lamps is shown in Figure 5 for Landsat 7 ETM+. In this figure, Lamp 1 degraded rapidly over time due to its use with every scene collect. However, Lamp 2, which was used very sparingly (once per month or less, instead of daily), showed good stability.

The second onboard system used for Landsat (ETM+) is imaging an onboard painted panel used as a solar diffuser. This calibration source is also shown in Figure 5 and results showed a steady decay in responsivity that could be attributed to the diffuser and not the instrument. This was due to the type of paint used to manufacture the diffuser (Markham and Helder, 2012). Other instruments have used Spectralon™ panels with much better stability (Xiong, 2006).

4.2 Vicarious Methods

In addition to onboard systems, vicarious calibration methods have been used extensively with Landsat sensors. The first method employed involves fielding teams to measure surface and atmospheric parameters at well-known test sites. One of the best known sites is Railroad Valley and has been highly developed by the University of Arizona's Remote Sensing Group (Thome, 2003). Bright desert sites such as Railroad Valley have produced the smallest uncertainties, but vegetative sites have also been used such as the Brookings site by South Dakota State University to validate calibration at radiance levels most often of interest to researchers. Estimates of ETM+ calibration from both of these groups is also highlighted in Figure 5. From the figure it is clear to see that this vicarious method on average has provided a consistent estimate of ETM+ gain. However, the variability is relatively large and the method is limited in sampling due to the expense required to field teams.

A second vicarious approach that has been developed is to use locations on the earth that have been shown to be essentially invariant over time with respect to surface reflectance and have very stable atmospheres. Often termed Pseudo Invariant Calibration Sites, or PICS, this approach has the advantage of dense sampling and less variability than other vicarious methods. As seen in Figure 5, PICS have provided an indication of stability over the lifetime of ETM+ in band 3 which was unattainable using the onboard calibrators and with more precision than the vicarious field campaign method. Recently it was demonstrated that the PICS approach could estimate changes in Landsat responsivity as small as 0.2 ± 0.02 %/year (Note this is a k=2 or 2σ uncertainty) (Barsi et al., 2012).

PICS methodology has been used for long term trending of satellites for some time now. In addition to using PICS for relative calibration trending, absolute calibration models for PICS are also being developed (Govaerts 2012, Helder 2012a). These models suggest that absolute calibration can be estimated at 3-5% uncertainty in the reflective bands using only minimal ancillary information such as date, time, viewing and illumination geometry.

Lastly, PICS have been used to calibrate the entire Landsat series across all sensors from 1972 through the present (Helder et al., 2012b). In this method, near coincident imagery of PICS locations in North America and Africa were used to tie the calibration of the MSS series of sensors to one another and then to the Landsat 5 TM. A key factor in this cross calibration was to consider the differences in the spectral passbands of the sensors. In all cases a spectral band adjustment factor was calculated to compensate appropriately for this effect. Prior to this calibration the MSS sensors produced results which varied by up to 16% when viewing a PICS location. After calibration this variability was reduced to 1-2% in the shorter wavelengths and 3-5% in the red and near infrared bands.

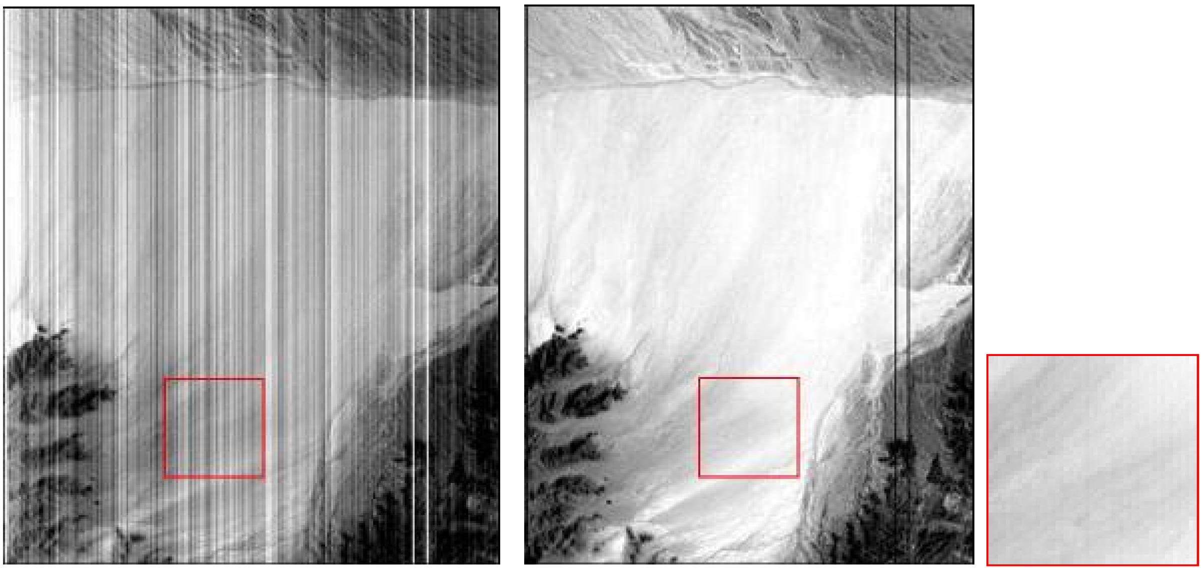

Figure 4. Left image shows striping in ALI Band 5p prior to relative gain estimation. Center image shows substantial improvement in striping using relative gain correction based on detector response from numerous scenes. Right hand image is zoom of region in red box.

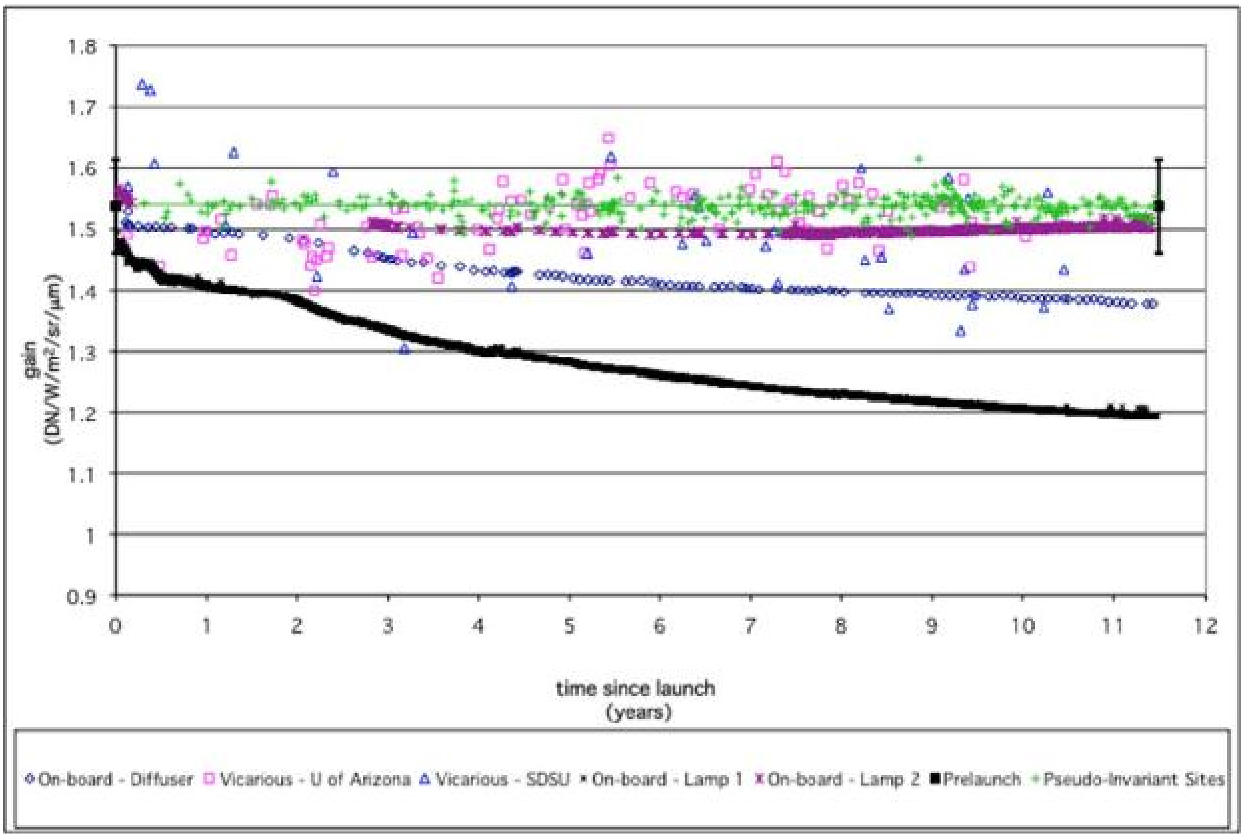

Figure 5. Absolute calibration of Landsat 7 ETM+ Band 3 (red). Lamp 1 response degraded most rapidly, followed by the onboard diffuser. Vicarious calibration is limited to isolated points in time with large variability. PICS provided an independent indication of system stability. (from Markham and Helder, 2012).

4.3 Lessons Learned

Several lessons become apparent from this discussion on absolute calibration. First, the use of lamps is valuable because of the quick turnaround and the temporally densely sampled calibration data that can be obtained from them. However, , in order to mitigate concerns with lamp degradation, it is recommended that several lamps be employed so that some can be used very often (daily to multiple times per day) and others can be used sparingly (weeks to months). This provides a means to separate lamp degradation from sensor degradation. Secondly, diffuser panels need to be carefully characterized and designed to withstand the rigors of space and cannot be assumed to degrade negligibly. Designs that use diffusers sparingly, or even use multiple diffusers should be considered.

Vicarious calibration methods can be very effective and provide a high degree of precision. Methods employing PICS are very inexpensive and can yield not only trending information but also absolute calibration. PICS are always limited by stability of the site. Consequently, it is important that multiple sites be trended. Combining PICS with other calibration methodologies is also recommended.

5. CONCLUSIONS

After more than 40 years of monitoring the Earth's surface the Landsat series of sensors provides not only a vast collection of imagery for scientists, but also a number of lessons for those who must maintain the calibration of imaging satellites. Key lessons which were incorporated to make this a 'well calibrated vast collection' can be summarized as follows:

- Characterize and remove radiometry artifacts prior to estimating radiometric gains and biases.
- Design systems so that well known inputs can be provided to the imager so that artifacts can be more easily characterized.
- Relative gain estimates, especially for pushbroom systems, are enhanced through analyses of multiple images suggesting that appropriate ground processing systems be developed to accomplish this.
- Yaw maneuvering can be especially effective for relative gain estimates for pushbroom systems, and can be used in conjunction with the multiple scene approach.

- Multiple lamp systems are recommended with lamp usage scaled temporally to monitor lamp degradation.
- Diffuser panel designs should include multiple panels or a stability monitor to ensure understanding of panel degradation in the space environment.
- Use of PICS can provide very precise temporal trending, absolute calibration, and cross-calibration between sensors, even those sensors with minimal temporal overlap.

All Landsat data are now available to the public without charge and can be ordered from USGS EROS at http://glovis.usgs.gov/. The overview of Landsat calibration presented in this paper allows users of these data to have confidence in their consistent calibration down to the 3% level for the TM and ETM+ data. Efforts to reduce these uncertainties are ongoing with goals in the 1-2% range based on refinement of current technologies as well as development of new space-based and vicarious methods.

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