Radiometric Calibration of Landsat

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Abstract

The radiometric calibration of the sensors on the Landsat series of satellites is a contributing factor to the success of the Landsat data set. The calibration of these sensors has relied on the preflight laboratory work as well as on inflight techniques using on-board calibrators and vicarious techniques. Descriptions of these methods and systems are presented. Results of the on-board calibrators and reflectance-based, ground reference calibrations of Landsat 5 Thematic Mapper are presented that indicate the absolute radiometric calibration of bands 1 to 4 should have an uncertainty of less than 5.0 percent. Bands 5 and 7 have slightly higher uncertainties, but should be less than 10 percent. The results also show that the on-board calibrators are of higher precision than the vicarious calibration but that the vicarious calibration results should have higher accuracy.

Introduction

The Landsat series of satellites provides the longest running continuous data set of high spatial-resolution imagery dating back to the launch of Landsat 1 in 1972. Part of the success of the Landsat program has been the ability to understand the radiometric properties of the sensors. This understanding has been due to the combination of prelaunch and post-launch efforts using laboratory, on-board, and vicarious calibration methods. The radiometric calibration of these systems helps characterize the operation of the sensors, but more importantly, the calibration allows the full Landsat data set to be used in a quantitative sense.

A brief overview of the Landsat systems is given here, but the reader is directed to Engel and Weinstein (1983), Lansing and Cline (1975), Markham and Barker (1987), and Slater (1980) for detailed descriptions. The Landsat series of satellites can be viewed in two distinct parts. The first includes Landsats 1, 2, and 3 that carried two sensor systems: the return beam vidicon (RBV) and the Multispectral Scanner (MSS) system. The RBV camera systems on Landsats 1 and 2 were multispectral with three cameras, while the system on Landsat 3 used only two cameras in a panchromatic mode. Landsats 1, 2, and 3 operated in a 919-km, sun-synchronous orbit with an 18-day repeat cycle. The second phase of Landsat includes Landsats 4 and 5. These platforms omitted the RBV cameras but still carried the MSS. These two platforms also carried the Thematic Mapper (TM), and their orbits were lowered to 705 km with a 16-day repeat cycle.

The MSS is a 6-bit, whiskbroom sensor with six detectors for each of its four bands. These bands are centered roughly at 0.55, 0.65, 0.75, and 0.85 μm (the MSS on Landsat 3 also had a fifth band between 10.4 and 12.6 μm). Bands 1 to 3 use photomultiplier tubes, while band 4 uses photodiodes. The MSS only collects data in one scan direction, and there is no compensation in the scan for the forward motion of the platform. At the end of every other scan, a rotating shutter and mirror assembly allows light from a calibration lamp to reach the detectors.

The TM is also a whiskbroom system but it scans in both the forward and backward cross-track directions, and it corrects for the forward motion of the platform. In addition, the TM has 8-bit radiometric resolution and seven bands. Bands 1 to 5 and 7 each have 16 detectors with center wavelengths of roughly 0.49, 0.56, 0.66, 0.83, 1.67, and 2.24 μm. Band 6 has four detectors and is centered around 11.5 μm. Bands 1 to 4 use silicon-based detectors, bands 5 and 7 use indium antimonide detectors, and band 6 uses mercury-cadmium-telluride detectors. Bands 5, 6, and 7 are part of the cold-focal plane that is cooled to 85°K through the use of a radiative cooler. The TM has an on-board calibration system composed of a shutter that oscillates rather than rotates and allows calibration data to be collected at the end of each scan.

A great deal of research was done during the early days of Landsat to understand these systems. This work included the extensive Landsat Image Data Quality Assessment (LIDQA) program; much of the LIDQA work was presented in a special issue of *Photogrammetric Engineering & Remote Sensing* (Markham and Barker, 1985). This work showed that the TM and MSS were not without problems. Tilton *et al.* (1985) found coherent noise in the MSS data. Metzler and Malila (1985) determined that there were within-line droop and scan-correlated level shifts. Overshoot and delay in bright-target recovery were found by Kieffer *et al.* (1985). A light leak showed up in the calibration pulse of the Landsat 5 TM, leading the data processing algorithm to ignore the lamp 000 state data and occasionally leading to an invalid calibration value for other lamp states (Singh, 1985). But the overall conclusion of this early work was that the TM and MSS data were of high quality.

Much of this LIDQA work concerned itself with the radiometric calibration of the MSS and TM. This calibration work was both absolute and relative. Here, the term absolute calibration refers to methods that allow the digital data to be converted to radiance. Relative methods, e.g., histogram equalization, are used to determine multiplicative (gain) and additive (bias) factors to normalize the detector's response to an average or reference response. Absolute calibration also accounts for differences in calibration between bands and detectors to be removed, but in relative calibration it is only how the detectors compare to each other that matters, and not how they compare to an absolute standard. It is also difficult to use absolute calibration to remove all detector-to-detector effects and, thus, there is typically striping in image data that have not been relatively calibrated. Early work in

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Canada showed that these effects could be removed from TM data to better than 0.8 percent (or 2 digital numbers) for most scenes, although the method still had trouble handling the bright target recovery problem (Murphy *et al.*, 1985).

While relative calibration is of great importance to the usability of Landsat data, especially for removing within-scene detector-to-detector effects, it is not discussed in detail here. Rather, emphasis is placed on the absolute calibration methods used for Landsat. These methods included the prelaunch calibration using spherical integrating sources, the on-board systems used after launch, and ground-reference vicarious techniques. Each of these techniques is discussed as applied to the MSS and TM sensors. Results are also presented from Landsat 5 TM to show how its calibration has varied with time. Landsat 5 TM is used because of the system's more than 12-year data record.

Prelaunch Calibration

The prelaunch calibration of the Landsat sensors is that work done in the laboratory prior to the launch of the system. Several reasons exist for doing prelaunch calibrations. It allows the system to be tested to ensure it operates properly before being integrated into the launch vehicle. Laboratory calibrations can also be easier to control and perform than methods used after launch. For example, the spectral characterization of sensors is much easier on the ground, preflight, rather than inflight. In the case of the MSS and TM, the absolute radiometric preflight calibrations relied on a source-based approach. That is, a well-characterized (and calibrated), spatially uniform source fully illuminates the entrance pupil of the satellite sensor. The sensor output is compared to the "known," source output to give the sensor's calibration coefficient (or gain).

In the case of the MSS, the source used for the preflight calibration was a 76-cm diameter, spherical integrating source with 12 "equal" intensity lamps that operated independently. The output of this source was calibrated to standards set forth by the National Institute of Standards and Technology (NIST) (then called the National Bureau of Standards). These calibrations also used a neutral density filter for the calibration of band 4; otherwise, only three radiance levels could have been used due to saturation. No specific estimates were made of the accuracy of the calibration of the 76-cm source. For several of the MSSs, a significant lag in time took place between a calibration of the 76-cm sphere source to NIST standards and the use of the sphere for the calibration of the Landsat sensors. For instance, the Landsat 4 MSS was calibrated in April 1982 and the calibration of the sphere was done in May 1980. These time lags must be considered when trying to determine the accuracy of the calibration (for instance, the 122-cm TM sphere showed a 4.0 percent change over a period of two years). Markham and Barker (1987) estimate that the calibration of the MSS is better than 10 percent when the sphere calibration uncertainty and spectral response uncertainty are considered.

The calibration of Landsats 4 and 5 TM relied on a 122-cm spherical integrating source with 12 lamps that could be operated independently. As with the MSS source, the TM source was calibrated to NIST standards. This was done using a monochromator that alternately viewed the 122-cm sphere and a pressed polytetrafluoroethylene (PTFE) sample using a rotating, folding mirror. A NIST-traceable standard of spectral irradiance illuminated the PTFE sample from a distance of 50 cm. Measurements with the monochromator were made at 0.05-μm intervals over the spectral range from 0.4 to 2.5 μm. Similar values for the absolute accuracies of the preflight calibration of the TM were estimated as for the calibration of the MSS.

The preflight calibrations of the thermal bands (band 6 on TMs 4 and 5) and the internal calibrator were conducted by reference to external blackbodies at the focus of the Thematic Mapper Calibrator (TMC). The TMC collimates the radiation from the blackbodies and provides a full aperture signal to the TM. The calibration was performed in a thermal vacuum chamber under a variety of operating conditions. The results of this calibration are factors to convert the internal gain of the TM band 6, derived from viewing the internal blackbody that operates at about 308°K, and the internal shutter, which floats with instrument temperature, to an external gain appropriate for calibrating Earth viewing scenes.

Postlaunch, On-Board Calibration

On-board calibration of the MSS and TM uses solar- and lamp-based approaches for the solar reflective bands. On-board blackbodies are used to calibrate the thermal bands. These systems give inflight, radiometric calibrations of the sensors. Reference to the preflight, absolute radiometric calibration of each sensor allows the on-board systems to provide an absolute calibration.

For Landsats 1 to 3, the MSS included a partial aperture, partial-path solar calibrator. The design of the system used a four-facet optical element that reflected sunlight into the optical path of the MSS during the platform's orbit over the North Pole. Data from the solar calibrator on Landsat 1 was problematic because of degradation of the optics (Horan, 1974). Problems with the attitude control of Landsat 2 made the data difficult to interpret, but the solar calibrators on both Landsats 2 and 3 appeared to operate normally (Lansing, 1986). The data from these systems has not been used for absolute radiometric calibration of the MSS sensors because the on-board lamp systems described below worked well (Lansing, 1986).

The on-board lamp calibrator (also referred to as the internal calibrator or IC) for the MSS uses a shutter wheel and a pair of redundant, tungsten-filament lamps. Within the shutter wheel is a mirror and neutral density filter. The mirror reflects light from the lamps through the neutral density filter and onto the focal plane. The neutral density filter has a wedge-shaped design such that the attenuation varies as it rotates with the shutter wheel. The shutter wheel also serves the purpose of preventing light from the entrance aperture of the MSS reaching the focal plane. The output from the MSS, while illuminated by the calibration system, rises rapidly to a peak that saturates the MSS detectors, and then falls off slowly as the neutral density filter is rotated. This calibration process occurs during the scan-line retrace of every other scan. The point should also be made that the internal calibrator does not test the full optical path of the sensor.

The IC used for the TM is somewhat different and is illustrated in Figure 1. A lamp-based approach is still used, but with three lamps. The image of each lamp filament falls on a different attenuating filter, as shown at the bottom of Figure 1c. With this arrangement, eight different irradiance levels can be incident on the end of a fiber-optics bundle by varying the choice of lamps that are turned on. The fiber bundle is attached to an oscillating arm that is referred to as a flag, and directs six circular spots of light, corresponding to the six solar-reflectance bands, onto the TM image plane at the start and end of each scan (Figure 1a). Preflight, the irradiance levels from the fibers are matched to the sensitivity of each TM band by changing the separation of a gap in the fibers, shown in the lefthand enlargement in Figure 1a. An integrating rod, added to the end of the fibers, makes the circular spots of light uniform. A lens and prism system is used to direct and focus these spots of light onto the filters and detectors, as shown in the righthand enlargement of Figure 1a. The thermal infrared band also uses the flag arrangement. The output from a temperature-controlled blackbody

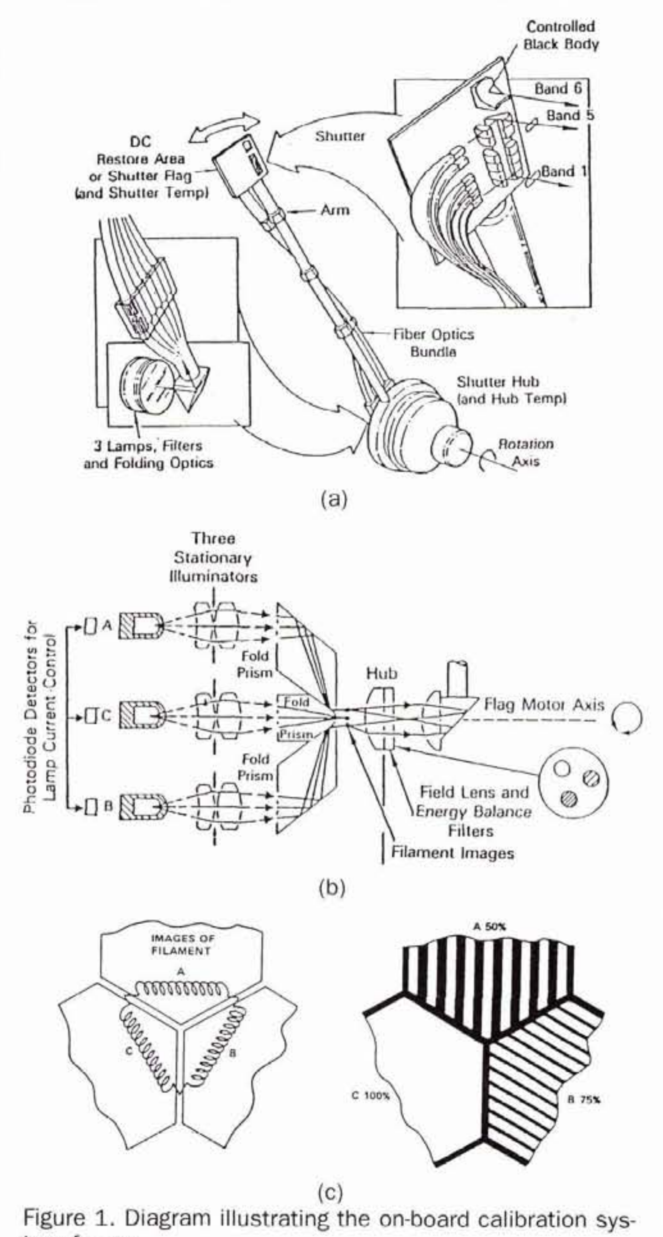

Figure 1. Diagram illustrating the on-board calibration system for TM.

source, which can be set at three different temperatures, is directed to the focal plane by means of a toroidal mirror (righthand enlargement in Figure 1a). The shutter, shown in the center of Figure 1a, is blackened to provide a dark signal. The eight lamp irradiance levels are recorded as calibration pulses beyond the edge of the image, and they are removed from the image after they have been used for calibration purposes. Twenty-one calibration pulses, with one lamp combination on continuously, are recorded sequentially down each side of the image for each irradiance level. This number is recorded to avoid any transient lamp variations in output associated with lamp turn on.

The primary advantage to the on-board lamp calibrators is that a calibration is performed with high temporal frequency. For the MSS, this is after every other scan while, for the TM, it is at the end of each scan. The stability of the lamps is also such that variability over several scan lines is quite small. This makes the on-board lamps ideal for looking at within-scene variability of the detectors. Experience with the lamps on the Landsat systems indicates that large, abrupt changes in the lamp output do not occur. Thus, the lamps are also excellent calibration sources over the period of weeks to months. However, it is possible that degradation of the calibration system can occur over long periods of time. Also, the accuracy to which the lamps can provide an absolute calibration is limited by the accuracy of the preflight calibration. That is, the accuracy of the inflight, absolute calibration must be worse than the preflight calibration, because the preflight calibration source is used to calibrate the onboard lamps using the MSS or TM as a transfer radiometer.

Post-Launch, Ground-Reference Calibration

Many methods have been proposed and used for the inflight radiometric calibration of satellite sensors without using onboard calibration sources. Of these, the ground-reference approach has been applied to Landsats 4 and 5 TM (Slater *et al.*, 1987; Slater *et al.*, 1996). The basic approach of ground-reference methods is to predict the radiances at the top of the Earth-atmosphere system over a selected test site based on radiative transfer code calculations. In the reflectance-based approach, these calculations are constrained by the measured surface reflectance of, and atmospheric characteristics over, the test site at the time of satellite overpass (Slater *et al.*, 1987). In the radiance-based approach, measurements of the upwelling radiance from the test site are made from an aircraft using a well-calibrated radiometer. These radiances are then used to further constrain the radiative transfer code calculations to predict the radiances at the sensor (Slater *et al.*, 1987; Slater *et al.*, 1996). A further modification to the reflectance-based approach is to use measurements of the diffuse and global downwelling irradiances to better characterize the radiative properties of the atmosphere (Biggar, 1990).

The test sites used for these vicarious calibrations are primarily located in the desert southwest of the United States. This region is used because the low probability of clouds improves the chances of the satellite sensor seeing the test site at the time of overpass. In addition, low aerosol loading, typical of this region, decreases the uncertainties due to the atmospheric characterization. The site should also have high surface reflectance to both decrease the uncertainty of the calibration and to calibrate the sensor at a high response value. For Landsats 4 and 5, the primary site has been an area of White Sands Missile Range known by the military as Chuck Site (Slater *et al.*, 1987; Thome *et al.*, 1997).

Sensitivity analyses of these approaches show that the reflectance-based method should have an absolute uncertainty less than 5.0 percent for bands 1 to 4 of the TM (Biggar *et al.*, 1994). Similar studies show the irradiance-based approach to have uncertainties less than 3.5 percent and the radiance-based approach better than 3.0 percent (Biggar *et al.*, 1994). The precision of these methods also appears to be about the same level as the accuracy. The biggest advantage of these vicarious calibrations is that they are full-path, full-aperture. In addition, the calibration is done with the system operating in the mode in which the system collects its remote sensing data, and thus is less susceptible to size-of-source effects.

The problem with these vicarious approaches is that they can be labor intensive. This typically limits the number of calibrations that can be performed. Another factor limiting ground-reference approaches is that the calibrations can only be done when the system collects data over the site. For the TM, this means that the maximum number of calibrations in a given year, for a given site, is 22. This number will certainly be smaller because on some of the days clouds will obscure the test site.

Table 1. DNs per Unit Radiances ($Wm^{-2}sr^{-1}\mu m^{-1}$) for the Dates Shown and for the Six Solar Reflective Bands of Landsat-5 TM Based on Level-0 Data (or Equivalent)

Date	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Preflight	1.555	0.786	1.020	1.082	7.875	14.77
08 Jul 1984		0.734	0.955	1.055		
28 Oct 1984	1.389	0.732	0.927	1.087	7.024	14.99
24 May 1985		0.749	0.942	1.045		
28 Aug 1985		0.715	0.914	1.121	7.227	15.24
16 Nov 1985	1.367	0.716	0.922	1.094	7.506	16.11
27 Mar 1987	1.307	0.702	0.891	1.048	7.441	16.18
10 Feb 1988	1.304	0.721	0.918	1.059	7.351	16.29
15 Aug 1992		0.651	0.883	1.048	7.416	15.45
21 Oct 1993	1.281	0.683	0.924	1.094	7.477	15.24
08 Oct 1994	1.222	0.653	0.887	1.054	6.811	13.166

In the thermal infrared, the approaches to inflight calibration that do not rely on the on-board calibration are similar in philosophy to those in the solar reflective. Measurements of the atmospheric conditions over a test site and of the upwelling radiance from the site are used to constrain the output of a radiative transfer code that predicts the radiance at the sensor (Schott and Volchok, 1985; Palmer, 1993). While the sites used for the solar reflective part of the spectrum are typically bright land areas, those for the thermal infrared are primarily water. This is because the emissivity of water is well known and the temperature should be slowly varying because of water's high heat capacity. Vicarious calibrations in this part of the spectrum have the same advantages and disadvantages as those in the solar reflective. Schott (1988) used vicarious techniques to show that the thermal band on Landsat 5 could be calibrated to give uncertainties less than 0.9°K.

Results of Landsat 5 TM Calibration

The results shown in this section focus on comparisons between the vicarious and the on-board lamp calibrations for Landsat 5 TM. The reason for this is the long history of the Landsat 5 results. Table 1 gives the calibration coefficients derived from the vicarous results using data from White Sands Missile Range. The values shown were derived from data that have been corrected for relative differences between detectors, and as such there is only one value per band rather than one value per detector. Details of how these results were obtained can be found in Slater *et al.* (1987) and Thome *et al.* (1997). Missing values in the table for band 1 are due to saturation of the detectors over the test site. The missing values for bands 5 and 7 correspond to data collections for which there were no surface reflectance data collected in the shortwave infrared. In addition, the table also includes values based on the preflight calibration.

Figure 2 shows these results graphically in a relative sense for bands 1, 2, 4, and 5 as a function of days since launch. The bands shown here have been selected because they clearly show that the degradation of the system is much larger for the shorter wavelength bands than for the longer wavelength bands. In fact, if the last data point is omitted, the change in calibration from the preflight values of bands 4 and 7 is small enough that it is within the uncertainties of the reflectance-based approach. It is unclear why band 5 data show a different trend, but this could be due to an inadequate correction for water vapor effects in the vicarious results.

Figure 3 shows results of the on-board calibrators for the same bands for the same period; the lamp state illustrated "010" has only one of the three lamps on. This lamp state was chosen as it showed an apparently smooth continuous behavior over time. Lamp states "100" and "001" showed at least one discontinuity each. All of the primary focal plane bands 1 to 4 show an initial exponential decay in responsivity. This decay is believed to be a real instrument effect caused by outgassing of the spectral bandpass filters. The scatter about the exponential function is correlated with instrument operating temperature in bands 1 to 4; a variation in the alignment between the IC and detectors with temperature is suspected. After the initial decay in responsivity, an apparent linear increase in responsivity of the system is observed in bands 2 to 4. In bands 5 and 7, the responsivity is dominated by scatter superimposed on a linearly increasing trend. The scatter is apparently related to an interference pattern generated by a thin film of frost that builds up on the window to the cold focal plane. As the frost thickness increases through the 1/4-wave optical thicknesses, the window transmittance alternates through a maxima and minima.

Based on the two figures, it is clear that the precision of the on-board calibrators is superior to the vicarious approach. This is especially true for those bands that are not part of the cold focal plane. The agreement for bands 1 and 2 is quite good, with both methods showing approximately the same degradation with time, though the reflectance-based results show a greater decrease. Also, there is no apparent upward trend in band 2 of the reflectance-based results. The greater decrease in sensitivity seen by the reflectance-based results could be due to the fact that the on-board calibrators are not able to monitor changes in the scan mirror. The on-board calibrator data for band 4 shows about a 5.0 percent degradation early in the sensor's lifetime. This degradation is not apparent in the reflectance-based data, but this level of change is at the limits of the uncertainties of the reflectance-based approach, particularly in the early years.

It is unclear at this time what causes the different results for band 5. It is known that the reflectance-based results are less accurate in this band due to lower surface reflectance of the test site at White Sands. This low reflectance also means that the calibration coefficient is being determined by a point that is lower on the responsivity curve for the TM, and this increases the uncertainty of the retrieved calibration coefficient, as well. Another effect is that the surface reflectance is not as spectrally flat in this part of the spectrum, so shifts in the spectral response of TM would have a larger effect in the vicarious data than for the on-board calibrator because lamp output is relatively smooth spectrally. Work is currently underway to better understand these differences.

While the precision of the on-board calibrators is quite good, their accuracy is lower in an absolute sense because

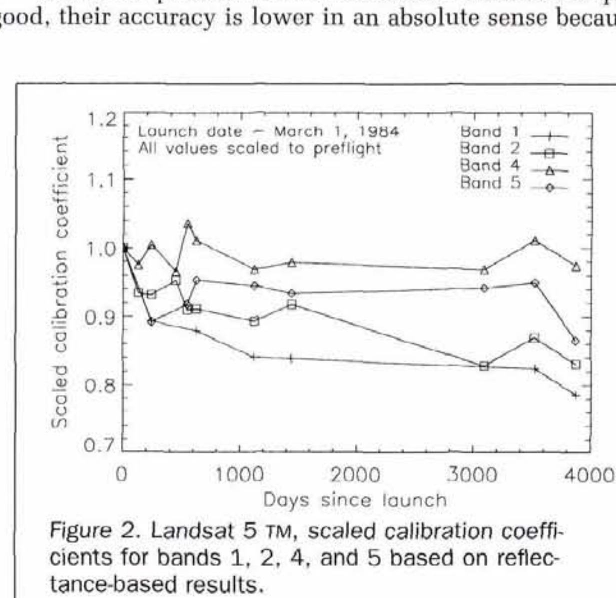

Figure 2. Landsat 5 TM, scaled calibration coefficients for bands 1, 2, 4, and 5 based on reflectance-based results.

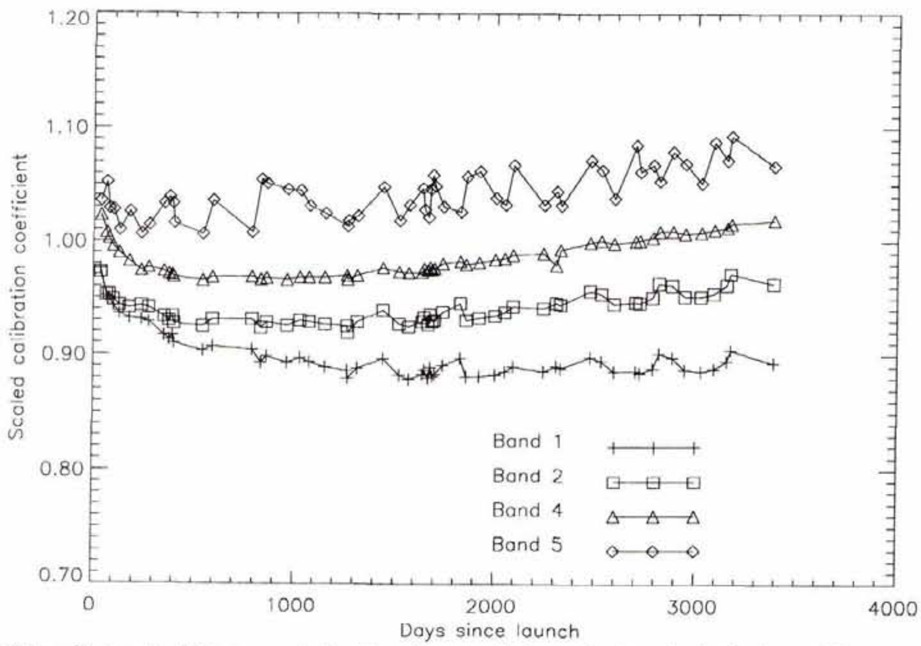

Figure 3. Landsat 5 TM, scaled calibration coefficients for bands 1, 2, 4, and 5 based on on-board calibrator data with the lamps in the 010 state.

the absolute scale is obtained by cross-calibrating against the preflight calibration source using the TM as a transfer radiometer. In addition, for the accuracy of the on-board lamps to be valid, it must be assumed that no changes in the lamp system occurred during the launch of the sensor, that it did not change during the life of the mission, and that no changes occured in the optics ahead of the internal calibration system. Thus, from an absolute calibration standpoint, the vicarious results should be superior.

One difficulty with the vicarious calibration approach, that has been pointed out earlier and is apparent in the figures, is that the number of calibrations is far fewer than can be supplied by the on-board lamps. The results shown here are a total of ten calibrations. When one considers that the on-board lamps supply data at the end of each scan, it is obvious that the on-board data are better at showing temporal variability of the sensor's calibration.

Because of the design of the TM, and to a similar extent the MSS, it should be clear that both the vicarious and on-board systems are necessary for an accurate picture of the status of the Landsat sensors. The vicarious results give full-aperture, full-path calibrations with relatively high accuracy. The on-board systems provide a high precision view of the sensor's behavior as a function of time over periods of hours to months. Beyond this time period, it becomes necessary to verify the status of the lamps through independent means. The vicarious methods provide these independent data, and give calibration information over periods of months to years.

Conclusions

The Landsat program has provided the longest continuous data set of high spatial resolution image data. These data have been useful for many applications in part because of the high-radiometric stability of the TM and MSS and their adequate calibration. Investigations of data from the Landsat 5 TM show that the uncertainties in the radiometric calibration should be on the order of 5.0 percent for bands 1 to 4. Uncertainties for the other bands is most likely higher, but further work is needed to verify this. This level of accuracy has been obtained through combined use of the on-board calibration systems and vicarious methods, and is encouraging because it should allow for the development of an image data set that spans over two decades and can be used for surface change analysis. Critical to creating such a data set is relating the calibration of the multiple Landsat systems to allow for the intercomparison of data sets from each system. Successful comparisons between separate platforms have been done using nearly coincident scenes (Price, 1989; Metzler and Malila, 1985), so it should be feasible to create such a long-term, calibrated data set.

Further evidence of the radiometric quality of the Landsat sensors has been the use of Landsat 5 TM data in the cross-calibration of AVHRR (Teillet *et al.*, 1990) and SPOT-HRV (Gustafson *et al.*, 1996). In the AVHRR case, the absolute calibration of AVHRR using the TM had uncertainties of <10 percent, with much of this uncertainty due to registering the two data sets. The TM-HRV calibration work showed that a relative calibration of better than 1.0 percent could be achieved with proper selection of ground targets and by accounting for spectral differences between the sensors. This result is especially encouraging considering the fact that the overpasses of the two systems ocurred one day apart and with slightly different view-sun geometry.

Probably the greatest impact that Landsats 1 through 5 have had on radiometric calibration are the designs of future sensors. The Enhanced Thematic Mapper Plus (ETM+) on Landsat 7 will use similar calibration approaches as the first five Landsats (Markham *et al.*, 1994) (recall Landsat 6 failed to achieve orbit). A similar lamp-based, on-board calibrator will be used. Improvements have been made to the solar view calibration, so it is hoped that this method will have greater use. In addition, ETM+ will make use of a full-aperture, full-path, solar diffuser. This diffuser should provide an additional calibration pathway that can be used to better determine the radiometric accuracy of the data. In addition to affecting the design of ETM+, the Landsat systems have affected the design of an additional sensor, the Advanced Land Imager. This system, on-board the New Millenium Program's

Earth Observer 1 platform, is being used to evaluate possible technology for a follow-on Landsat type system to Landsat 7 (Ungar, 1997; see pages 901-905 in this issue). This sensor makes use of a partial-path, full-aperture solar diffuser as well as on-board lamps for radiometric calibration. In addition, there are plans to rotate the platform to view the moon as recommended by Kieffer and Wildey (1985; 1996). If these systems, and their follow-on systems, operate as planned, a well-calibrated historical data set spanning over three decades should be available.

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References

Biggar, S.F., R.P. Santer, and P.N. Slater, 1990. Irradiance-based calibration of imaging sensors, *International Geoscience and Remote Sensing Symposium*, College Park, Maryland, 1:507–510.

Biggar, S.F., P.N. Slater, and D.I. Gellman, 1994. Uncertainties in the in-flight calibration of sensors with reference to measured ground sites in the 0.4 to 1.1 μm range, *Rem. Sens. Env.*, 48: 242–252.

Engel, J., and O. Weinstein, 1983. The Thematic Mapper - an overview, *IEEE Trans. on Geoscience and Rem. Sens.*, GE-21:258–265.

Gustafson-Bold, C.L., and K.J. Thome, 1996. Cross-calibration of two small footprint sensors, *International Geoscience and Remote Sensing Symposium*, Lincoln, Nebraska, pp. 1283–1285.

Horan, J.J., D.S. Schwartz, and J.D. Love, 1974. Partial performance degradation of a remote sensor in a space environment and some possible causes, *Appl. Opt.*, 13:1230–1237.

Kieffer, H.H., D.A. Cook, E.M. Eliason, and P.T. Eliason, 1985. Intraband radiometric performance of the Landsat Thematic Mapper, *Photogrammetric Engineering & Remote Sensing*, 51:1331–1350.

Kieffer, H.H., and R.L. Wildey, 1985. Absolute calibration of Landsat instruments using the moon, *Photogrammetric Engineering & Remote Sensing*, 51:1391–1394.

———, 1996. Establishing the moon as a spectral radiance standard, *J. Atmos. and Oceanic Tech.*, 13:360–375.

Lansing, J.C., 1986. Solar calibration performance in Landsat multispectral scanners, *Appl. Opt.*, 25:333–334.

Lansing, J.C., and R.W. Cline, 1975. The four- and five-band multispectral scanners for Landsat, *Opt. Eng.*, 14:312–322.

Markham, B.L., and J.L. Barker (editors), 1985. Special Issue: LIDQA Final Symposium, *Photogrammetric Engineering & Remote Sensing*, 51:1245–1493.

Markham, B.L., and J.L. Barker, 1987. Radiometric properties of U.S. processed Landsat MSS data, *Rem. Sens. of Env.*, 22:39–71.

Markham, B.L., J.L. Barker, W.C. Boncyk, E. Kaita, and D.L. Helder, 1996. Landsat-7 Enhanced Thematic Mapper Plus in-flight radiometric calibration, *International Geoscience and Remote Sensing Symposium*, Lincoln, Nebraska, pp. 1270–1272.

Metzler, M.D., and W.A. Malila, 1985. Characterization and comparison of Landsat-4 and Landsat-5 Thematic Mapper data, *Photogrammetric Engineering & Remote Sensing*, 51:11315–1330.

Murphy, J.M., F.J. Ahern, P.F. Duff, and A.J. Fitzgerald, 1985. Assessment of radiometric accuracy of Landsat-4 and Landsat-5 Thematic Mapper data products from Canadian production systems, *Photogrammetric Engineering & Remote Sensing*, 51:1359–1370.

Palmer, J.M., 1993. Calibration of Thematic Mapper band 6 in the thermal infrared, *Proceedings of SPIE #1938*, Orlando, pp. 109–117.

Price, J.C., 1989. Calibration comparison for the Landsat 4 and 5 multispectral scanners and tehmatic mappers, *Appl. Opt.*, 28: 465–471.

Schott, J.R., 1988. Thematic Mapper, band 6, radiometric calibration assessment, *Proceedings of SPIE #924*, Orlando, pp. 72–88.

Schott, J.R., and W.J. Volchok, 1985. Thematic Mapper thermal infrared calibration, *Photogrammetric Engineering & Remote Sensing*, 51:1351–1357.

Singh, A., 1985. Thematic Mapper radiometric correction research and development results and performance, *Photogrammetric Engineering & Remote Sensing*, 51:1379–1384.

Slater, P.N., 1980. *Remote Sensing: Optics and Optical Systems*, Addsion-Wesley Publishing Company, Reading, Massachusetts, pp. 465–509.

Slater, P.N., S.F. Biggar, K.J. Thome, D.I. Gellman, and P.R. Spyak, 1996. Vicarious radiometric calibrations of EOS sensors, *J. of Atmospheric and Oceanic Technology*, 13:349–359.

Slater, P.N., S.F. Biggar, R.G. Holm, R.D. Jackson, Y. Mao, M.S. Moran, J.M. Palmer, and B. Yuan, 1987. Reflectance- and radiance-based methods for the in-flight absolute calibration of multispectral sensors, *Rem. Sens. Env.*, 22:11–37.

Teillet, P.M., P.N. Slater, Y. Ding, R.P. Santer, R.D. Jackson, and M.S. Moran, 1990. Three methods for the absolute calibration of the NOAA AVHRR sensors in-flight, *Rem. Sens. Env.*, 31:105–120.

Thome, K.J., S.F. Biggar, D.I. Gellman, P.R. Spyak, P.N. Slater, and M.S. Moran, 1997. In-flight radiometric calibration of Landsat-5 Thematic Mapper from 1984 to 1994, submitted to *Rem. Sens. of Env.*

Tilton, J.C., B.L. Markham, and W.L. Alford, 1985. Landsat-4 and Landsat-5 MSS coherent noise: characterization and removal, *Photogrammetric Engineering & Remote Sensing*, 51:1263–1280.

Ungar, S.G., 1997. Technologies for future Landsat missions, *Photogrammetric Engineering & Remote Sensing*, 63(7):901–905.