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Brian L. Markham

NASA Goddard Space Flight Center

John L. Barker

NASA Goddard Space Flight Center

Julia A. Barsi

NASA Goddard Space Flight Center

Ed Kaita

NASA Goddard Space Flight Center

Kurtis J. Thome

University of Arizona

See next page for additional authors

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Authors

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Landsat-7 ETM+ Radiometric Stability and Absolute Calibration

Brian L. Markham^{*a}, John L. Barker^{*a}, Julia A. Barsi^{*a,b}, Ed Kaita^{*a,b},
Kurtis J. Thome^{†c}, Dennis L. Helder^{♦d}, Frank D. Palluconi^{☉e},
John R. Schott^{✱f}, Pat Scaramuzza^{†g}

^aLandsat Project Science Office/Goddard Space Flight Center/NASA; ^bScience Systems and Applications, Inc; ^cRemote Sensing Group/Optical Sciences Center/University of Arizona; ^dDept. of Electrical Engineering/South Dakota State University; ^eJet Propulsion Laboratory/NASA; Center for Imaging Science/Rochester Institute of Technology; ^gLandsat-7 Image Assessment System/EROS Data Center, USGS

ABSTRACT

Launched in April 1999, the Landsat-7 ETM+ instrument is in its fourth year of operation. The quality of the acquired calibrated imagery continues to be high, especially with respect to its three most important radiometric performance parameters: reflective band instrument stability to better than $\pm 1\%$, reflective band absolute calibration to better than $\pm 5\%$, and thermal band absolute calibration to better than ± 0.6 K. The ETM+ instrument has been the most stable of any of the Landsat instruments, in both the reflective and thermal channels. To date, the best on-board calibration source for the reflective bands has been the Full Aperture Solar Calibrator, which has indicated changes of at most -1.8% to -2.0% (95% C.I.) change per year in the ETM+ gain (band 4). However, this change is believed to be caused by changes in the solar diffuser panel, as opposed to a change in the instrument's gain. This belief is based partially on ground observations, which bound the changes in gain in band 4 at -0.7% to $+1.5\%$. Also, ETM+ stability is indicated by the monitoring of desert targets. These image-based results for four Saharan and Arabian sites, for a collection of 35 scenes over the three years since launch, bound the gain change at -0.7% to $+0.5\%$ in band 4. Thermal calibration from ground observations revealed an offset error of $+0.31$ W/m² sr μ m soon after launch. This offset was corrected within the U. S. ground processing system at EROS Data Center on 21-Dec-00, and since then, the band 6 on-board calibration has indicated changes of at most $+0.02\%$ to $+0.04\%$ (95% C.I.) per year. The latest ground observations have detected no remaining offset error with an RMS error of ± 0.6 K. The stability and absolute calibration of the Landsat-7 ETM+ sensor make it an ideal candidate to be used as a reference source for radiometric cross-calibrating to other land remote sensing satellite systems.

Keywords: Landsat, ETM+, absolute calibration, vicarious calibration

1. INTRODUCTION

Landsat-7 is continuing the 30-year record of moderate resolution global imagery with the latest Landsat instrument, the Enhanced Thematic Mapper Plus (ETM+). The ETM+ design closely follows the Thematic Mapper (TM) instrument of Landsats -4 and -5. Hardware improvements include a higher resolution panchromatic band, higher resolution thermal data and the addition of two calibration devices to improve the radiometric calibration. Selected ETM+ characteristics are provided in Table 1. The incorporation of the Image Assessment System (IAS) to the ground processing system has allowed a more thorough monitoring of the instrument performance and calibration. The IAS processes approximately four scenes per day and hundreds of instrument and image parameters are recorded to a database. These data are trended over time and are used to detect changes in any of the systems. If detected changes are significant, this system is used to provide input into the Calibration Parameter File (CPF), a file that is issued with each scene, contains most of the

*Brian.L.Markham@gsfc.nasa.gov, John.L.Barker@gsfc.nasa.gov, Julia.Barsi@gsfc.nasa.gov, Edward.Kaita.1@gsfc.nasa.gov; NASA/GSFC, Code 923, Greenbelt MD 20771; †kurt.thome@opt-sci.arizona.edu; Remote Sensing Group/University of Arizona, 1630 East University Boulevard, Tucson AZ 85721; ♦Dennis_Helder@sdstate.edu, Department of Electrical Engineering/South Dakota State University, Brookings SD 57007; ☉frank.d.palluconi@jpl.nasa.gov; NASA/JPL, M/S 183-501, 4800 Oak Grove Drive, Pasadena CA 91109; ✱schott@cis.rit.edu; Rochester Institute of Technology Center for Imaging Science, 74 Lomb Memorial Dr, Rochester NY 14623; †pscar@usgs.gov, EROS Data Center, 47914 252nd St, Sioux Falls SD 57198

processing parameters and is specific to the quarter in which the scene is acquired. When a scene is processed, it is processed with the most recent CPF for that quarter, so each scene is processed with the most up-to-date calibration information.

The IAS is located at the USGS EROS Data Center (EDC) in Sioux Falls, SD. The NASA/GSFC Landsat Project Science Office (LPSO) works with the IAS in analyzing the calibration information and updating the algorithms used within the IAS. Additional funding from NASA supports vicarious radiometric calibration efforts at NASA/JPL, Rochester Institute of Technology (RIT), South Dakota State University (SDSU) and the University of Arizona (UAz).

Table 1: ETM+ SPECTRAL BAND CHARACTERISTICS

Band (#)	Bandpass (μm)	Spatial Resolution (meters)	NE $\Delta\rho$ (%) [*]	NE ΔT (K @ 300K)
1	0.452 – 0.514	30	0.19	
2	0.519 – 0.601	30	0.15	
3	0.631 - 0.692	30	0.19	
4	0.772 - 0.898	30	0.14	
5	1.547 - 1.748	30	0.18	
6	10.31 – 12.36	60		0.22
7	2.065– 2.346	30	0.28	
8 (pan)	0.515 – 0.896	15	0.39	

^{*}High Gain Mode at ~6% exoatmospheric reflectance @ 30° solar zenith angle

Approximately every six months, the scientists and analysts involved in characterizing ETM+ radiometric calibration meet and present their results. The results form the basis for updating the radiometric gain calibration parameters in the CPF. This paper presents the results of the most recent comparisons.

2. ON-ORBIT CALIBRATION METHODS

There are three on-board calibration devices on the Landsat-7 ETM+: 1) a Full Aperture Solar Calibrator (FASC), a white painted diffuser panel; 2) a Partial Aperture Solar Calibrator (PASC), a set of optics that allow the ETM+ to image the sun through small holes; and 3) an Internal Calibrator (IC), an assembly which consists of two lamps, a black body, a shutter and optics to transfer the energy from the sources to the focal plane.

2.1 Full Aperture Solar Calibrator (FASC)

The FASC is a deployable, white-painted diffuser mounted on the outside of the instrument. When deployed in front of the ETM+ aperture in the vicinity of the terminator, the Sun illuminates the panel and light is diffusely reflected into the ETM+ aperture, through the entire optical system. The FASC has been deployed over 30 times to date, roughly once per month after the initial verification period. A typical acquisition has the FASC panel deployed for about six minutes covering a range of solar zenith angles on the panel of about 20° (from ~85° to ~66°) and encompassing up to 38 standard sized scenes. The along track signal response increases approximately linearly with increasing solar illumination after sunrise on the panel until the signal level reaches saturation (Fig. 1). One scene from each of the acquisitions has been processed to provide absolute gain factors for each detector in each reflective band. Each scene was selected to be near the terminator and to have nearly the same solar zenith angle on the diffuser panel. The panel has shown degradation that appears to have a uniform component across the panel, presumably due to solar exposure, and a localized component, presumably due to contamination (Fig. 2).

Fig. 1: Mid-scan average response of ETM+ Band 2, Detector 15, during FASC panel calibration on January 3, 2001. The panel is deployed during satellite eclipse. As the spacecraft exits eclipse, the sun hits the instrument, causing stray light reflecting off the instrument faceplate to hit the panel. Once the sun "rises" on the panel, the signal increases approximately linearly until the instrument begins to stow the panel. The absolute calibration data are taken near the terminator when the solar rays are nearly parallel to the instrument faceplate and stray light is at a minimum.

Fig. 2: FASC along-scan response. Over time, degradation has caused changes on the panel. A localized contamination has apparently affected the "east" side of the panel, pixels 3000 and higher. (a) A single scan line of Band 2, Detector 15 for multiple FASC acquisitions, all at the same sun angle. (b) since the discovery of the local contamination, a 500 pixel window of the panel on the "west" side is used for calibration.

The panel makes an excellent source for evaluating the noise performance of the ETM+. Not only is it a uniform source of illumination, its brightness varies as a function of time due to the decrease in the solar zenith angle. As such, the noise level can be evaluated as a function of a continuous varying signal level.

2.2 Internal Calibrator (IC)

The Internal Calibrator (IC) includes an oscillating flat shutter mounted between the telescope and the aft-optics. The shutter is synchronized with the scan mirror, and swings in front of the focal plane while the mirror is changing direction at the end of a scan line. The IC also includes 1) lamp sources for reflective band bright target, 2) an internal blackbody for thermal band bright target, and 3) a black surface which provides both dark target for reflective and thermal bands.

There are two lamps in the internal calibrator; the power supply for each lamp is designed to provide a constant voltage across the series combination of the lamp filament and a resistor. The lamps are placed near the pivot point of the

shutter and optics feed the light into light pipes that transmit the light up the shutter flag. Only Lamp 1, the primary lamp, is used routinely. Lamp 1 has shown various instabilities including a slow warm up time, a decrease in the first six months of operation in bands 1-3, an increase in response in the first two years of operation in bands 4 and 8, and no change in response in bands 5 and 7. Lamp 2, which is only occasionally used, has shown smaller changes, indicating that changes in response may be related to lamp use.

The internal blackbody is located near the shutter and is inserted into the optical path by a toroidal mirror on the shutter. The blackbody is routinely operated at 45C. This temperature set point causes some detectors to saturate regularly in high gain mode, but the gain ratio between high and low gains is well known and stable so the high gain can be derived based on the low gain data.

2.3 Partial Aperture Solar Calibrator (PASC)

The Partial Aperture Solar Calibrator (PASC) is a set of auxiliary optics sitting in the ETM+ sunshade that reflect direct sunlight through a small aperture into the ETM+ instrument. There are four nearly identical set of optics each viewing a different portion of space. Each set consists of an uncoated silica facet, a mirror set at a 45° angle and an approximately 4mm circular aperture. The PASC reflects sunlight into the ETM+ aperture shortly after the spacecraft exits eclipse, but before the northern hemisphere terminator is crossed. The result is an image of the Sun superimposed on the dark earth background. The sun image is stretched in the along-track direction. Performance of the PASC has been anomalous¹ and results will not be included here.

2.4 Ground Look Calibration (GLC) Methods

There are four investigations evaluating the ETM+ radiometric calibration using Ground Look Calibration (GLC) or vicarious methods. Each of these investigations predicts the radiance at the sensor aperture using a combination of ground- and/or aircraft-based reflectance, radiance or temperature measurements, coupled with measured and/or modeled atmospheric parameters. Two investigations look primarily at the reflective band calibrations: those of UAz and SDSU. The investigations of NASA/JPL and RIT concentrate on the thermal band.

The reflective band GLC investigators characterize the surface reflectance of large, uniform land targets using field spectrometers referenced to characterized diffuser panels. The UAz efforts concentrate on desert regions such as Railroad Valley in Nevada and Ivanpah Playa in California, among others², while SDSU makes use of a large grass field outside Brookings, South Dakota. The sunphotometer measurements of atmospheric aerosols and water vapor are used as input to model the top-of-atmosphere (TOA) radiance. The precision of these techniques has been shown to be ± 2 -3%.

The thermal band GLC efforts make use of the well-known properties of water. Both teams use large water bodies as their primary targets. NASA/JPL has permanent data-collecting buoys on Lake Tahoe on the Nevada/California border³ and places temporary buoys on the Salton Sea in southern California. RIT takes measurements on Lakes Erie and Ontario, and within the smaller bays and ponds in the area⁴. The atmospheric measurements are either obtained from various National Weather Service products or collected on-site through their regular weather stations or the local teams collect radiosonde data themselves. The precision of these techniques has been shown to be ± 0.6 K.

An additional stability study for reflective bands was begun last fall using a scene based method. Four sites with highly uniform content throughout the Saharan and Arabian deserts were identified based on Cosnefroy, 1996⁵ and Hilbert (K. Hilbert, personal communication, January, 9, 2002). Selected details about each site are in Table 2. Each site has been acquired approximately once per quarter since launch and processed through the IAS. To date, the analysis contains 35 scenes. IAS routines are used to determine the mean scene reflectance. The results are corrected for solar zenith angle and the reflectance is trended throughout the lifetime of the mission. Though this method cannot verify the absolute calibration of the instrument, it can validate the assumption that most of the changes to-date are caused by changes in the calibrators, rather than the ETM+ instrument.

The figure of merit (FOM) for uniformity is based on the RMS coefficient of variation across the bands of the entire scene.

Table 2: Uniformity figure of merit (FOM) for the four sites used in the scene based stability monitoring. A more typical scene which includes large regions of urban and vegetation has a FOM of ~0.35.

Location	Site (Path/Row)	number of scenes	average FOM for all scenes
Egypt/Sudan	177/45	10	0.033
Mauritania	201/46	7	0.053
Saudi Arabia	165/47	10	0.057
Libya	181/40	8	0.061

3. CALIBRATION RESULTS AND DISCUSSION

The combined calibration results for bands 1-5, 7, and 8 are presented in Figs. 3-9 respectively. In each case, the pre-launch calibration currently in the CPF is presented along with error bars representing $\pm 5\%$. The FASC results presented are based on the "west" portion of the FASC panel, that portion least affected by degradation, and have been adjusted based on an apparent 1° difference in the orientation of the panel from pre-launch measurements¹. The IC results for both lamps have been included, recognizing that part of the variability present is related to the IC itself. The uniform scene results have been rescaled to match the pre-launch calibration values; they provide no absolute calibration on their own. Linear regression lines, with their slopes and uncertainties, are shown for the FASC, UAz GLC, and uniformity data. The confidence intervals for the slopes are provided in Table 3. In Table 4, the FASC slopes are provided in terms of percentage change per year (all significant) and are compared to the maximum "allowed" slope based on either the GLC or uniformity sites' confidence intervals. In Table 5, the average UAz GLC calibrations are compared to the pre-launch calibration currently in use.

In general, the current operational pre-launch calibration, the FASC results and the GLC calibration results all agree to within the $\pm 5\%$ bounds, though the trends are different. All the FASC slopes are significantly different from zero, due to the high precision of the measurements, though few of the GLC or uniform site slope measurements are. Some of the FASC slopes fall outside the bounds permitted (with 95% confidence) based on the GLC or uniform site results, suggesting the FASC results contain a component that is diffuser degradation related as opposed to instrument related. The largest slope, i.e., Band 4, in particular, appears to be at least half due to diffuser degradation. The Lamp 2 IC results show smaller changes than Lamp 1 again indicating that the Lamp 1 results are usage related as opposed to instrument related. Band 5 results are most suggestive of a true instrument change in response. The FASC, UAz GLC (not significant) and uniformity sites (barely significant) give similar slopes and the IC also shows a downward trend, though not linear. The trend ($<0.5\%/year$) in Band 5, though small, will be considered a candidate for updating in the next calibration meeting.

Table 3: Comparison of FASC, GLC and Uniformity gain trends.

band	FASC slope	FASC lower 95% CI	FASC upper 95% CI	UAz slope	UAz lower 95% CI	UAz upper 95% CI	Scaled Uniform. slope	Scaled Uniform. lower 95% CI	Scaled Uniform. upper 95% CI
1	-3.2×10^{-5}	-3.6×10^{-5}	-2.8×10^{-5}	3×10^{-5}	-2×10^{-5}	8×10^{-5}	-2×10^{-5}	-4×10^{-5}	0×10^{-5}
2	-3.3×10^{-5}	-3.7×10^{-5}	-2.9×10^{-5}	4×10^{-5}	-2×10^{-5}	9×10^{-5}	-6×10^{-6}	-1.7×10^{-5}	8×10^{-6}
3	-5.3×10^{-5}	-5.8×10^{-5}	-4.7×10^{-5}	1×10^{-5}	-7×10^{-5}	9×10^{-5}	-3×10^{-6}	-1.8×10^{-5}	1.2×10^{-5}
4	-7.8×10^{-5}	-8.4×10^{-5}	-7.2×10^{-5}	2×10^{-5}	-3×10^{-5}	6×10^{-5}	-1×10^{-5}	-3×10^{-5}	2×10^{-5}
5	-9.5×10^{-5}	-1.15×10^{-4}	-7.5×10^{-5}	-1×10^{-4}	-3×10^{-4}	1×10^{-4}	-9×10^{-5}	-1.7×10^{-4}	-1×10^{-5}
7	2.2×10^{-4}	1.4×10^{-4}	3.0×10^{-4}	1×10^{-4}	-6×10^{-4}	8×10^{-4}	-1×10^{-4}	-5×10^{-4}	3×10^{-4}

Table 4: Apparent FASC response change per year as compared to the maximum allowable slope based on either the UAz GLC slopes or the uniformity sites slopes, whichever is smaller.

Band	FASC Slope % change/year	Maximum slope magnitude based on GLC and uniform sites
1	-0.96	-0.7
2	-1.03	-0.6
3	-1.28	-0.4
4	-1.90	-0.6
5	-0.44	-0.8
7	0.35	0.5
8	-1.41	

Table 5. Systematic differences between current (pre-launch) calibration and GLC results.
((GLC-current)/current)

band	gain difference (% difference)
1	-4.6
2	-5.6
3	-3.3
4	-0.8
5	-2.9
7	-2.5

Fig. 3: ETM+ Band 1 band average high gain calibration results from on-board and ground-look sources compared to pre-launch values. The uniformity results measure only relative stability and are normalized to pre-launch gains.

Fig. 4: ETM+ Band 2 band average high gain calibration results from on-board and ground-look sources compared to pre-launch values. The uniformity results measure only relative stability and are normalized to pre-launch gains.

Fig. 5: ETM+ Band 3 band average high gain calibration results from on-board and ground-look sources compared to pre-launch values. The uniformity results measure only relative stability and are normalized to pre-launch gains.

Fig. 6: ETM+ Band 4 band average high gain calibration results from on-board and ground-look sources compared to pre-launch values. The uniformity results measure only relative stability and are normalized to pre-launch gains.

Fig. 7: ETM+ Band 5 band average high gain calibration results from on-board and ground-look sources compared to pre-launch values. The uniformity results measure only relative stability and are normalized to pre-launch gains.

Fig. 8: ETM+ Band 7 band average high gain calibration results from on-board and ground-look sources compared to pre-launch values. The uniformity results measure only relative stability and are normalized to pre-launch gains.

Fig. 9: ETM+ Band 8 band average low gain calibration results from on-board and ground-look sources compared to pre-launch values. The ground look teams do not produce results for Band 8 and the uniformity analysis was not run on Band 8.

In Band 6, the IC is the only on-board calibration device. The response to the IC over the life of the mission is shown in Fig. 10a. The slope of the responsivity, though significant, shows a change of less than 0.03%/year. This system is remarkably stable, particularly relative to the Landsat-4 and -5 TM thermal bands which regularly varied by up to 30% due to the accumulation of ice on the dewar window. The ETM+ instrument also appears stable relative to the vicarious measurements. Though a significant bias of $0.31 \text{ W/m}^2 \text{ sr } \mu\text{m}$ was detected soon after launch, a correction was applied to the CPF on October 1, 2000 and to the processing system on December 20, 2000⁶, though it is unknown how or when international processing systems dealt with the correction. Vicarious calibration results since the correction was implemented continue to validate the correction (Fig. 10b). The calibrated product radiance has a scatter of about 1% around the vicarious results or $\pm 0.6\text{K}$ at 300K.

Fig 10: Band 6 on-board gain and validation results from the GLC efforts. In (a), at about Day 630, the processing system was updated to correct for a noisy telemetry sensor, which decreased the noise in the gain. For the time period since this correction, the gain is stable to 0.03%/year. The collected vicarious calibration results are shown in (b). Data collected before the bias was discovered and corrected have been reprocessed and included with the data collected after the correction. The remaining RMS error is $\pm 0.6\text{K}$ at 300K.

4. SUMMARY

On-orbit results indicate that the Landsat-7 ETM+ absolute radiometric calibration is stable to better than 2.0%/year in the reflective bands and 0.1%/year in the thermal band. The uncertainty in the calibration is estimated at <5% in the reflective and ~1% in the thermal regions.

For the most current information, calibration updates can be found at the USGS IAS Calibration Notices web page (http://edcwww.cr.usgs.gov/17dhf/ias_folder/cal_notes/) or in the Landsat Science Data User's Handbook (http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html).

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