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Landsat-7 ETM+ On-Orbit Reflective-Band Radiometric Stability and Absolute Calibration

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Dennis L. Helder[4], John L. Barker[1], Pat Scaramuzza[5]

The Landsat-7 spacecraft carries the Enhanced Thematic Mapper Plus (ETM+) instrument. This instrument images the Earth land surface in eight parts of the electromagnetic spectrum, termed spectral bands. These spectral images are used to monitor changes in the land surface, so a consistent relationship, i.e., calibration, between the image data and the Earth surface brightness, is required. The ETM+ has several on-board calibration devices that are used to monitor this calibration. The best on-board calibration source employs a flat white painted reference panel and has indicated changes of between 0.5% to 2% per year in the ETM+ response, depending on the spectral band. However, most of these changes are believed to be caused by changes in the reference panel, as opposed to changes in the instrument's sensitivity. This belief is based partially on on-orbit calibrations using instrumented ground sites and observations of "invariant sites", hyper-arid sites of the Sahara and Arabia. Changes determined from these data sets indicate are 0.1% - 0.6% per year. Tests and comparisons to other sensors also indicate that the uncertainty of the calibration is at the 5% level.

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Abstract -- Launched in April 1999, the Landsat-7 ETM+ instrument is in its fifth year of operation. 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, a solar diffuser based system, which has indicated changes of between 1-2% per year in the ETM+ gain for bands 1-4, and 8 and less than 0.5%/year for bands 5 and 7. However, most of 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 vicarious calibrations and observations of "invariant sites", hyper-arid sites of the Sahara and Arabia. Weighted average slopes determined from these data sets indicate changes of 0.1% - 0.4% per year for bands 1-4, and 8 and 0.6% per year for bands 5 and 7. Absolute calibration of the reflective bands of the ETM+ is consistent with vicarious observations and other sensors generally at the 5% level, though there appear to be some systematic differences.

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I. INTRODUCTION

Landsat-7 with its Enhanced Thematic Mapper Plus (ETM+) instrument has been operationally acquiring coverage of the Earth's surface since late June 1999. Salient characteristics of the ETM+ instrument are presented in Table 1. The ETM+ instrument is similar to the TM instruments on Landsats-4 and 5. The primary differences are the addition of a 15 meter panchromatic band, an improved resolution of the thermal band from 120 meters to 60 meters and the addition of two on-board radiometric calibrators. These two calibration devices, the Full Aperture Solar Calibrator (FASC) and the Partial Aperture Solar Calibrator (PASC), along with the incorporation of an Image Assessment System (IAS) within the ground data processing system, are designed to facilitate improvement in the radiometric calibration of the ETM+ data to 5% absolute uncertainty.

Prior to launch the ETM+ instrument was radiometrically calibrated and its radiometric stability verified in ambient and thermal-vacuum environments. Likewise, the on-board radiometric calibration devices were characterized prior to launch. The procedures for the pre-launch tests are presented in [1] and some of the results are presented in [2, 3]. Results from the pre-launch radiometric calibration tests that are required for processing ETM+ data are stored primarily within the Calibration Parameter File (CPF), which is generated and maintained by IAS personnel at the United States Geological Survey (USGS) EROS Data Center (EDC). When a radiometrically calibrated scene is ordered by a customer from EDC, the uncalibrated data are extracted from the archive and processed using the most recent version of the CPF applicable to the calendar year quarter in which the data were acquired. At launch, the CPF was populated with the best available calibration information available at that time. After launch each CPF may be updated with improved information. In standard radiometric processing, the detector-by-detector gains are read from the CPF and the detector-by-detector offsets are measured for each scan by viewing the back of the Internal Calibrator shutter flag. The bias is subtracted on a line-by-line basis and the net signal divided by the gain to provide the calibrated radiance value.

The Landsat-7 system including the spacecraft, instrument, ground stations and processing system is currently operated by the USGS. NASA, which developed Landsat-7, maintains a role, through the Landsat Project Science Office (LPSO) at NASA's GSFC. This role includes assisting in the radiometric calibration and characterization of the ETM+ instrument and data through revised calibration procedures and parameters. Additionally, NASA, through GSFC, has funded investigators to verify the calibration of the ETM+ by the use of ground targets, a procedure referred to as vicarious or ground-look calibration. Twice a year, the LPSO, IAS and external investigator personnel meet and discuss radiometric and geometric results for Landsat-7 ETM+. This paper presents the combined results of this group relevant to the absolute radiometric calibration and stability of the ETM+ instrument and its data products.

II. ON-BOARD CALIBRATION (OBC) SYSTEMS

The ETM+ has three on-board calibration systems: (1) the Internal Calibrator (IC), (2) the Partial Aperture Solar Calibrator (PASC) and (3) the Full Aperture Solar Calibrator (FASC). Each device provides independent information about the calibration of the ETM+ reflective bands, but each is subject to its own degradations that can complicate understanding of the ETM+ calibration itself.

A. Internal Calibrator (IC)

The IC consists of: (1) two tungsten vacuum lamps, (2) power supplies that each provide a constant voltage across a lamp in series with a resistor, (3) a calibration shutter flag that oscillates in synchronization with the scan mirror, and (4) a set of optics that pipes the light up the shutter flag to the primary focal plane. The shutter blocks the earth light from the focal plane at the end of each mirror scan and provides the detectors with a dark target followed by the light pulse from the internal lamps [1]. The dark region is used to measure the bias or offset of the detectors for each scan and the light pulse gives a measure of the gain of the detectors. Prior to launch the IC is calibrated by comparing the net integrated pulses for each detector for each lamp (pulse values minus bias values) to the detectors' responses to a calibrated external integrating sphere [1]. The locations of the shutter region to be used to measure the detectors biases are stored in the CPF along with the effective radiances of the light pulses for each of the lamps for each detector.

In pre-launch testing, the responses of the detectors to the internal calibrator lamps varied as shown in Table 2 and Figure 1. These variations appeared related to changes in the environmental conditions of atmospheric pressure (i.e., whether the tests were in ambient or vacuum) and instrument telemetry points of lamp current and temperature. Despite extensive pre-launch testing, no consistent correlations were found and no hardware or processing software correction was made.

On orbit, the IC data are analyzed from approximately 5 scenes per day processed by the Image Assessment System (IAS) and all the scenes processed by the Landsat Product Generation System (LPGS). This analysis provides bias levels and apparent gains for each of the ETM+ detectors. These values are stored in the IAS database and regularly queried to provide the current trends.

Lamp 1 has been routinely used since launch on Landsat-7. Lamp 2 was used during the initial 90 days and then not used again for about 3 years. Figures 2-5 present the results of the IC gains. The absolute gains are based on pre-launch radiances for the IC from the June 9, 1998 calibration of the IC. These pre-launch radiances and the calculated gains are subject to the additional uncertainty related to the instability of the IC during pre-launch testing as shown in Table 2 and Figure 1. Post-launch, both a warm-up phenomena and apparent temperature sensitivity have been observed for the Internal Calibrator [4]. These results are filtered to include only those acquisitions between 5 and 15 minutes after lamp turn-on in order to avoid the majority of the warm-up behavior of the lamp.

B. Full Aperture Solar Calibrator (FASC)

The FASC is a deployable diffuser panel. This aluminum panel, painted with YB71 flat white paint can be commanded to deploy in front of the ETM+ aperture. When deployed, the normal to the panel is oriented approximately 23.5° from the instrument line of sight for nadir viewing. The panel is normally deployed shortly before the spacecraft exits eclipse and is kept deployed until after the spacecraft crosses the terminator. During this period of time the solar zenith angle on the panel varies from greater than 90° to less than 70°. For the solar zenith angles from 90° to around 65°, the panel is fully illuminated by the sun, i.e., without obstruction from instrument or spacecraft structure. Prior to launch, the reflectance of the diffuser panel was measured at illumination angles of 65°, 70° and 72°, view zenith angles of 18.5, 23.5 and 28.5° and relative azimuth angles of 0°, 15°, 30°, 45° and 60°. The orientation of the panel was also measured. On-orbit, the pre-launch measured reflectance factors and orientation angles and the post launch measured responses are used to calculate the detector gains [1]. A post launch update of the panel orientation angles was performed [3] and the location of the pixels extracted for the gain calculation adjusted to reduce the impact of localized degradation of the panel observed post-launch [3]. Figures 2-5 present the FASC calibration results.

C. Partial Aperture Solar Calibrator (PASC)

The PASC is a set of auxiliary optics located in the ETM+ sunshade in front of the scan mirror that provide a direct view of the sun through a small aperture (about 4 mm). This aperture and a reflection from an uncoated silica flat reduce the signal sufficiently to bring the signal to below the saturation radiance of the ETM+ instrument. Large increases in the responses of the ETM+ detector to the sun signals through the PASC occurred during the first 6 months of ETM+ operations so the sun signals saturated for all but bands 4, 5 and 7 when operated in low gain mode. These increases have been hypothesized to be due to a build up of contamination on the uncoated silica flats [3]. Additionally, bands 5 and 7 show strong scan angle dependent responses to the PASC. PASC results currently add little to our understanding of the instruments radiometric calibration or stability, though the data have proved useful for separating instrument temperature sensitivity from the IC's temperature sensitivity (see below).

D. Temperature Sensitivity

The temperature of the primary focal plane of the ETM+ is not controlled. In normal operations it varies in temperature from about 11° C to 14° C, with temperatures largely determined by the usage level of the instrument. During periods of reduced operations, e.g., after orbital inclination maneuvers, the temperature may drop as low as 5.5° C. Special acquisitions during these periods are processed to look for temperature sensitivity and other effects. Figure 6 shows the IC and PASC results versus silicon focal plane temperature. Significant temperature sensitivity is observed using the IC results, namely an apparent increasing response with decreasing temperature. However, the PASC data show no corresponding sensitivity. This indicates that the temperature sensitivity is most likely related to a variation in output of the IC with temperature. The other primary focal plane bands show temperature sensitivities as well, but these are also likely due to IC temperature effects.

E. Gain Stability based on on-board calibration systems

Based on the combined results from the FASC and each of the two lamps in the IC, plausible statements about the ETM+ gain stability relative to the calibrator's stability are:

1) The changes in response of all bands, particularly the primary focal plane bands, during the first 6 months of on-orbit operation are due to changes in the output of the IC as opposed to changes in the gain of the detectors or transmission of the spectral filters.
    a. The lack of change in response to the FASC during this same period of time provides the primary supporting information to this statement, though the first FASC acquisition was not performed until 45 days after launch.
    b. The difference in magnitude of the changes between lamp 1 and lamp 2 also supports this statement.
2) The increase in response of the ETM+ to the IC lamp 1 in bands 4 and 8 between 6 months to 2 years after launch is due to an increase in the output of the IC system as opposed to an increase in sensitivity of the detectors or transmission of the spectral filters
    a. The lack of increase in response to the FASC during this time period in the primary supporting evidence for this statement
    b. The difficulty in providing mechanisms by which the sensitivity would increase also supports this statement

3) The change in slope of the response to IC lamp 1 at about 2 years post launch is due to a change in the degradation of the IC lamp 1 system as opposed to a change in degradation of the detectors or filters.

   a. This same change is not observed in the FASC results

   b. This change is observed in all the bands on the instrument, which makes it less likely to be a detector or filter effect as the detectors are of two different types and are spread across two focal planes.

4) The changes observed in instrument response to the IC lamp 2 (used infrequently) and the FASC are consistent with instrument response degradation.

   The FASC provides a full system calibration, whereas the IC system exercises only the focal plane and aft optics (for the cold focal plane bands), so any fore-optics degradation would cause a difference between the two trends. Thus the differences between degradations associated with lamp 2 IC, which are generally lower than those associated with the FASC, could be a representation of fore-optics degradation

5) The changes observed using the FASC should be considered an upper limit on the changes that are instrument sensitivity related.

   A non-uniform contamination or degradation of the panel is occurring (Figure 7). Although the data collection window has been adjusted to coincide with the least contaminated portion of the panel, some panel degradation is likely still present.

6) The best estimates of the ETM+ gain stability with time based on the OBC systems are shown in Table 3. These are based on a linear fit to the FASC data,

although it is realized that a linear model does not perfectly represent the changes that are occurring. The apparent gain change varies as a smooth function of wavelength, peaking in the near infrared and going through near zero change in band 5.

III. VICARIOUS OR GROUND LOOK CALIBRATION

Teams fielded by two organizations have been performing ground look or vicarious calibration of the Landsat-7 ETM+ reflective bands since launch in April 1999. The University of Arizona, Optical Sciences Center, Remote Sensing Group has conducted the larger effort. This group works primarily at two dry lakebed sites: Railroad Valley (RRV), Nevada and Ivanpah Playa, California. The second effort is conducted by South Dakota State University at a grass site in Brookings, SD. The basic procedures for these ground look calibration efforts are to characterize the surface reflectance properties of a ground site simultaneous with the satellite overpass, characterize the atmospheric optical properties, predict the radiance at the sensor aperture based on these measurements and an atmospheric model and compare the predicted radiance to the sensor's output to determine a sensor gain. The details of the procedures vary between the two groups and are detailed in Thome et al. [5] for the University of Arizona and Vogelman et al. [6] for South Dakota State University.

A. Gain Stability based on ground look calibration results

As of this writing the UAz group has performed 34 successful ground look calibrations of the ETM+ reflective bands over 4 years using their RRV and Ivanpah sites. The SDSU group has performed 7 successful ground look calibrations. Sample results for bands 1 and 5 are presented in Figures 8 and 9. The slopes of linear regressions of the gains versus time, shown in table 4, generally are not significant at the alpha = 0.05 level, i.e., the 95% confidence interval for the slope includes "0", indicating stability at the level that these measurements are able to detect. The lower bounds of the 95% confidence intervals for these slopes indicates that none of these bands have been changing at greater than 1%/year, which is less than the indicated changes using the best on-board calibration device.

B. Consistency of applied calibration with ground look calibration measurements as measure of absolute calibration uncertainty.

In Table 5 are presented the differences between the ground-look based calibrations and the currently operationally applied calibrations. The current calibration is the pre-launch calibration.

IV "INVARIANT SCENES"

"Invariant scenes" are considered as those relatively time invariant regions of the Earth surface. Various researchers have studied sensor stabilities using largely vegetation free desert regions, including portions of the Sahara and Arabian deserts. Sensors studied have included AVHRR [7], METEOSAT [8], and SPOT HRV [9]. Previously Cosnefroy et al [10] evaluated a number of Saharan and Arabian Desert sites for monitoring optical satellite sensors. The sites they selected were a starting point for this study.

Four of the Cosnefroy sites were selected based of the number of cloud free acquisitions of the site available at the time of the initial analysis (late 2001) and the uniformity of the entire Landsat scene. The site uniformity was calculated as the standard deviation of the full scene divided by the mean value of the full scene. This value was averaged across all 30-meter bands and all acquisitions available and is shown in table 6 for the scenes selected.

All acquisitions available for each of the sites were examined. Those with no apparent cloud cover were ordered in raw format from the EROS data center. Scenes with visible cloud cover when examined at full resolution or with significant saturation (>1% of pixels) were rejected from further analysis. The scene data were radiometrically calibrated by subtracting the line-by-line biases and applying the detector-by-detector gains from the CPF. The CPF gains are the pre-launch gains with the exception of a few detectors that have been updated for small (<1%) changes since launch. The calibrated data were then converted to exoatmospheric reflectances (ρ^*) by band per:

$$\rho^* = \frac{\pi \times L_\lambda \times d^2}{ESUN_\lambda \times \cos(\theta_s)} \quad (1)$$

Where:

L_λ= Spectral radiance at sensor aperture for given band (W/m^2 sr μm)

d = Earth-Sun distance (AU)

$ESUN_\lambda$ = Solar Exoatmospheric Irradiances for given band (W/m^2 μm)

θ_s= Solar zenith angle (degrees)

The resulting scene-mean reflectances were normalized to the operational gains for each band to place them on the same scale as the other gain measures. Figures 10 and 11 provide samples of the invariant scene results over time for selected bands. Table 7 provides the weighted average linear slopes for all four sites and uncertainties on these slopes. All bands show a 0.3% to 0.6%/year change in gain; all but band 4 are statistically significant at $\alpha = 0.05$.

V. DISCUSSION

A. Radiometric stability

Figure 12 shows the slopes with 95% confidence intervals for all bands using the on-board FASC calibration system, the ground look calibrations and the "invariant scene" results. The FASC results are clearly the highest precision and statistically different from both the ground look and invariant site results. These results support the hypothesis that the FASC diffuser panel is itself experiencing some change with time at the 0.5 to 1.5%/year level, depending on band. Given that the ground look and "invariant scene" results are not statistically different, they can be combined, weighting by their uncertainties (Table 8) Table 8 can be considered as giving our current best estimates of the gain changes of the ETM+ instrument since launch, i.e., on the order of 1/4%/year for bands 1-4 and marginally significant at alpha = 0.05 and about 1/2% year for bands 5 and 7 and significant. Currently these changes are not incorporated into the U.S. operational processing system at the USGS's EDC. Users choosing to adjust previously processed data for these changes would calculate the year since launch for the scene in question, calculate the percentage degradation (time since launch times % of pre-launch gain/year) and divide the data by the resulting factor. All adjustments to date will be less than 3%.

B. Absolute calibration

The determination of absolute accuracy is difficult, given that there are no inherent absolute radiometric targets available for viewing by the ETM+ on orbit. Information can be gained on the absolute accuracy based on the consistency of the ETM+ calibrations performed by independent measures and by comparisons to other sensors independently calibrated.

Comparing the operational calibration of the ETM+ with the calibration provided by the FASC diffuser immediately after launch, i.e., with minimum panel contamination, provides a measure of the absolute calibration accuracy of the ETM+(Table 9). The accuracy of the diffuser based calibration is dependent on the accuracy of the pre-launch diffuser panel reflectance characterization, the knowledge of the diffuser panel orientation, the solar irradiance data, any stray light/shadowing of the panel, etc.. All bands agree within 5% between the initial FASC calibrations and the operational calibration. The VNIR bands are in better agreement than the SWIR bands. The panel reflectance measurements, the solar irradiance and the pre-launch radiometric calibration are subject to greater uncertainties in the SWIR[3]. Also, some change in the reflectance of the panel in the SWIR is known to occur with outgassing of water from the paint [11].

Comparison to the ground look calibration results provides another measure of calibration accuracy. The results of the ground look calibrations have been presented in Table 5. The calibrations generally agree to within 5%, but the ground look gain estimates generally have a negative bias relative to the operational calibration and they vary between sites.

Intercalibrations of ETM+ and the MODIS, MISR and SEAWIFS sensors have been presented in the literature. Comparisons of the VNIR, i.e., bands 1-4 of the ETM+ to MODIS and SEAWIFS have shown consistency at the 5% level or uncertainty [12]. SWIR [bands 5 and 7] comparison to MODIS showed consistency at the 5% level in band 5 and about the 7% level in band 7[12]. Comparisons to MISR [13], that has its current radiometric scale tied to vicarious calibrations, showed ETM+ derived radiances 4-5% low relative to MISR on one site (Lunar Lake) and 6-12% low relative to MISR on a second site (RRV) in June 2000. These same comparisons also included MODIS. MODIS agreed with ETM+ to within 2% on the Lunar Lake site and was 4-10% different on the RRV site.

Overall, based on on-board calibration, vicarious and cross calibration, the Landsat-7 ETM+ reflective bands appear to be radiometrically calibrated to ±5% uncertainty. Some apparent biases relative to other instruments remain. The operational calibration of ETM+ produces radiances that are lower, on average, than the vicarious based calibrations. This bias is largest at about 5% in bands 1 and 2 relative to the University of Arizona measurements. Comparisons to MISR radiances, which are tied to a vicarious calibration scale, show differences of 5-10% in all bands in some comparisons.

VI. SUMMARY AND CONCLUSIONS

Landsat-7 ETM+ has been shown to be the most stable of the Landsat instruments, changing by no more than 0.5%/year in its radiometric calibration. In general, the on-board calibration devices, although very precise, are themselves changing more rapidly than the instrument, requiring the less precise measurements based on vicarious calibrations or "invariant" sites to discern trends. Absolute calibration is generally consistent with other instruments and methods to 5%, though biases are present. Solar irradiance uncertainties are also a significant contributor to the consistency between instruments, particularly in the SWIR region.

ACKNOWLEDGEMENTS

The USGS Landsat Program Office and the NASA/Goddard Space Flight Center, Landsat Project Science Office jointly conduct the radiometric calibration of Landsat-7 ETM+. We acknowledge the support and encouragement of Tracy Zeiler, USGS Landsat Project Chief, Kristi Kline, USGS Deputy Landsat Project Chief, Darrel Williams NASA

Landsat Project Scientist and James Irons, Deputy Landsat Project Scientist. Specific acknowledgement is given to the Image Assessment System, under Ron Hayes, the Landsat Project Science Office, particularly Jen Sun and Jeff Miller, the SDSU calibration team including Steve Schiller and Dave Aaron, Kurt Thome's calibration team and Jon Smid, Funding for the NASA work is through the Office of Earth Science, Code YS.

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Figure Captions

Figure 1: Band 4 band average responses to the internal calibrator during pre-launch testing.

Figure 2. Band 1 radiometric gains over time calculated using the on-board calibration devices

Figure 3. Band 4 radiometric gains over time calculated using the on-board calibration devices

Figure 4. Band 5 radiometric gains over time calculated using the on-board calibration devices

Figure 5. Band 7 radiometric gains over time calculated using the on-board calibration devices

Figure 6. Band 4 responses to on-board calibration devices as a function of instrument primary focal plane (PFPA) temperature

Figure 7. Band 4 response to the FASC diffuser panel as a function of scan angle (shown as pixel number) and time. Responses have been extracted for the same solar zenith angle and corrected for Earth-Sun distance induced solar irradiance variation.

Figure 8. Band 1 vicarious calibration results

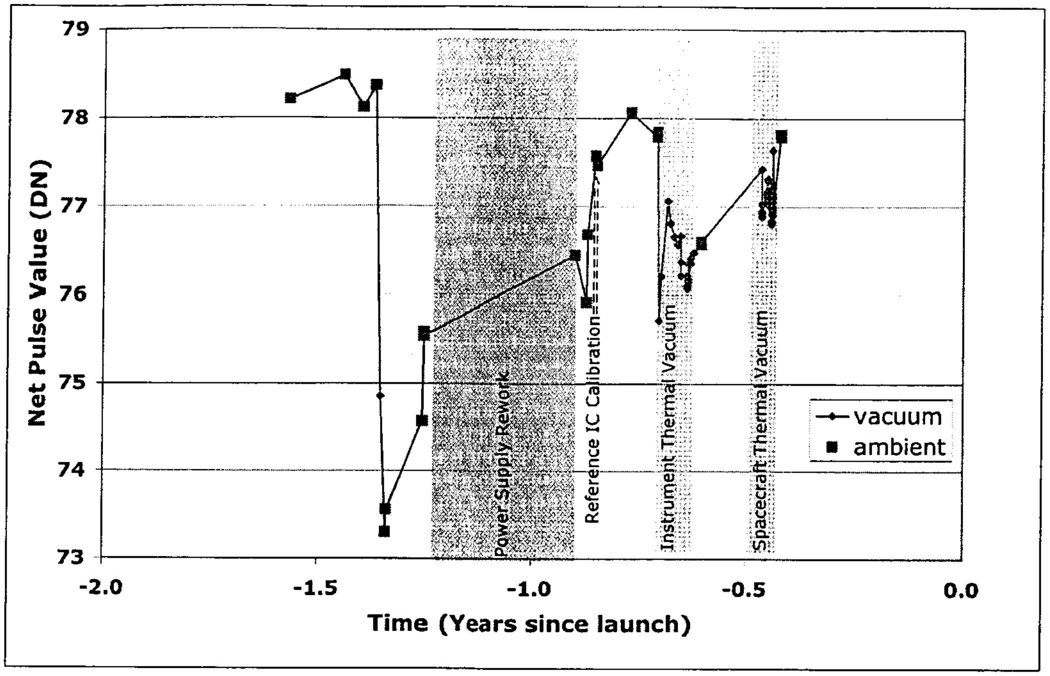
Figure 9. Band 5 vicarious calibration results.

Figure 10. Band 1 response to "invariant sites." Results have been adjusted so that the average value for each site equals the operational gain

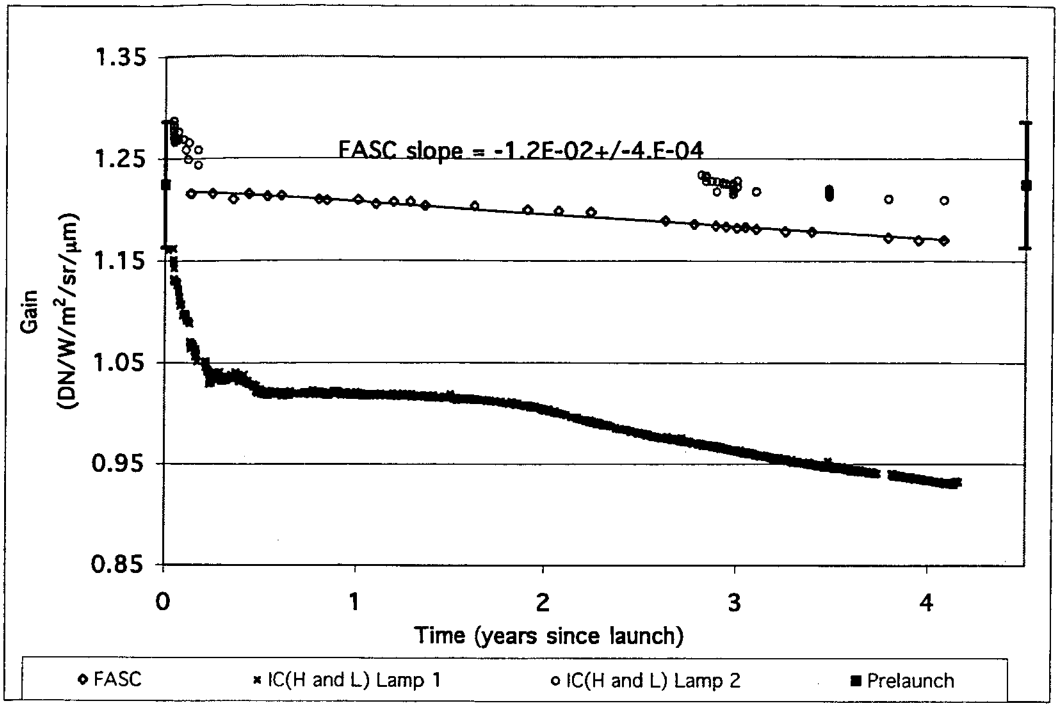
Figure 11. Band 5 responses to "invariant sites." Results have been adjusted so that the average value for each site equals the operational gain.

Figure 12. Slopes with 95% confidence intervals for the ETM+ bands based on the on-board FASC calibration system, the vicarious calibrations and the "invariant sites."

Figure 1

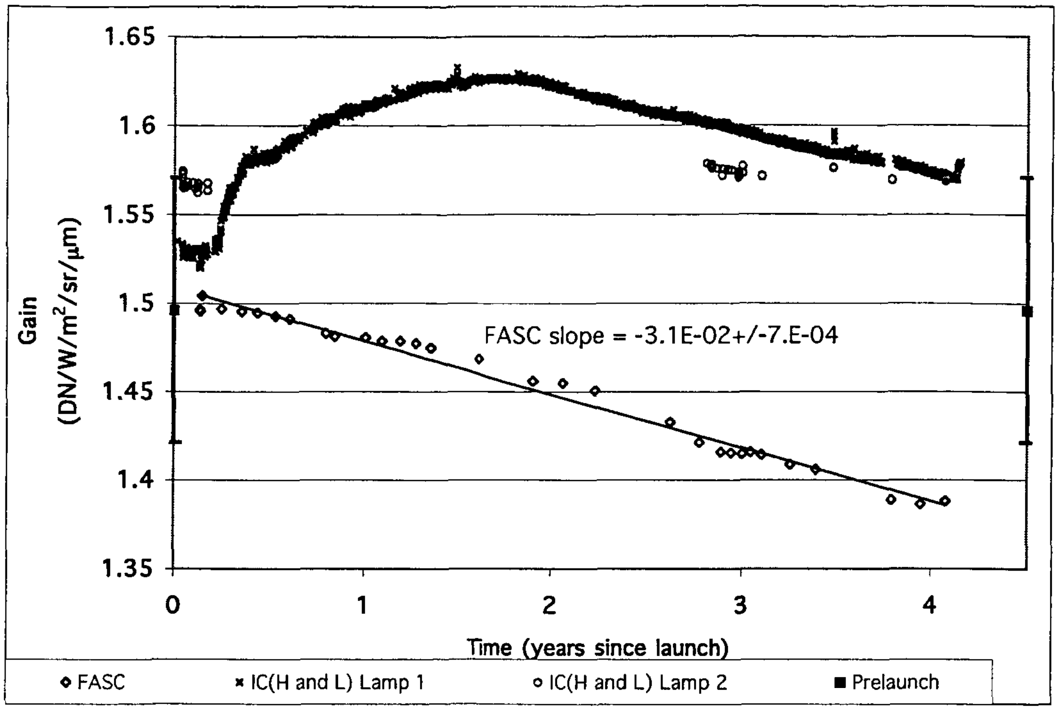


79
78
77
76
75
74
73
Net Pulse Value (DN)
-2.0
-1.5
-1.0
-0.5
0.0
Time (Years since launch)
Power Supply Rework
Reference IC Calibration
Instrument Thermal Vacuum
Spacecraft Thermal Vacuum
vacuum
ambient



1.35
1.25
1.15
1.05
0.95
0.85
FASC slope = -1.2E-02+/-4.E-04
Gain
(DN/W/m2/sr/µm)
0
1
2
3
4
Time (years since launch)
FASC
IC(H and L) Lamp 1
IC(H and L) Lamp 2
Prelaunch

Figure 2



1.65
1.6
1.55
1.5
1.45
1.4
1.35
Gain (DN/W/m2/sr/μm)
FASC slope = -3.1E-02+/-7.E-04
0
1
2
3
4
Time (years since launch)
FASC
IC(H and L) Lamp 1
IC(H and L) Lamp 2
Prelaunch

Figure 3

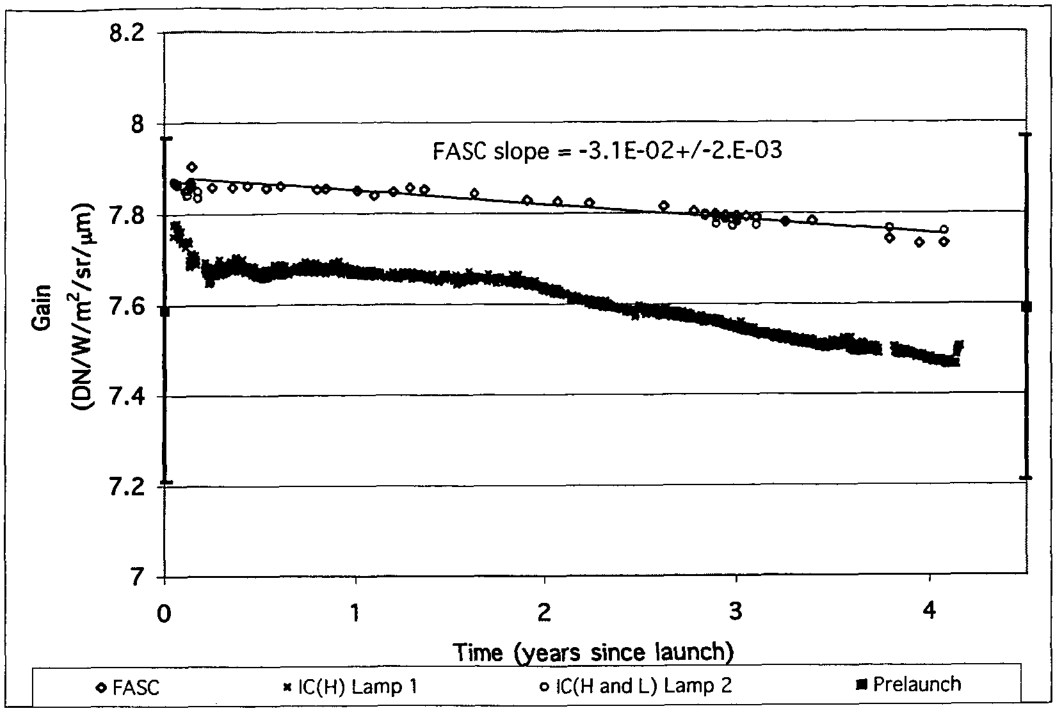
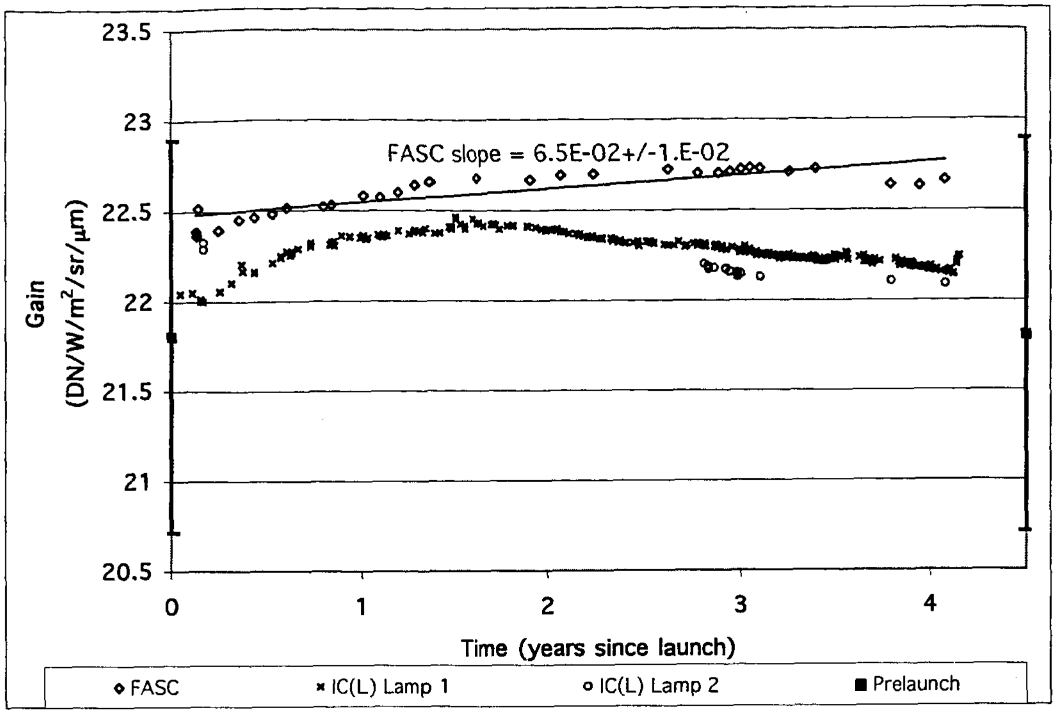

8.2
8
7.8
7.6
7.4
7.2
7
Gain
(DN/W/m2/sr/μm)
FASC slope = -3.1E-02+/-2.E-03
0
1
2
3
4
Time (years since launch)
FASC
IC(H) Lamp 1
IC(H and L) Lamp 2
Prelaunch

Figure 4



23.5
23
22.5
22
21.5
21
20.5
Gain
(DN/W/m²/sr/µm)
FASC slope = 6.5E-02+/-1.E-02
0
1
2
3
4
Time (years since launch)
FASC
IC(L) Lamp 1
IC(L) Lamp 2
Prelaunch

Figure 5

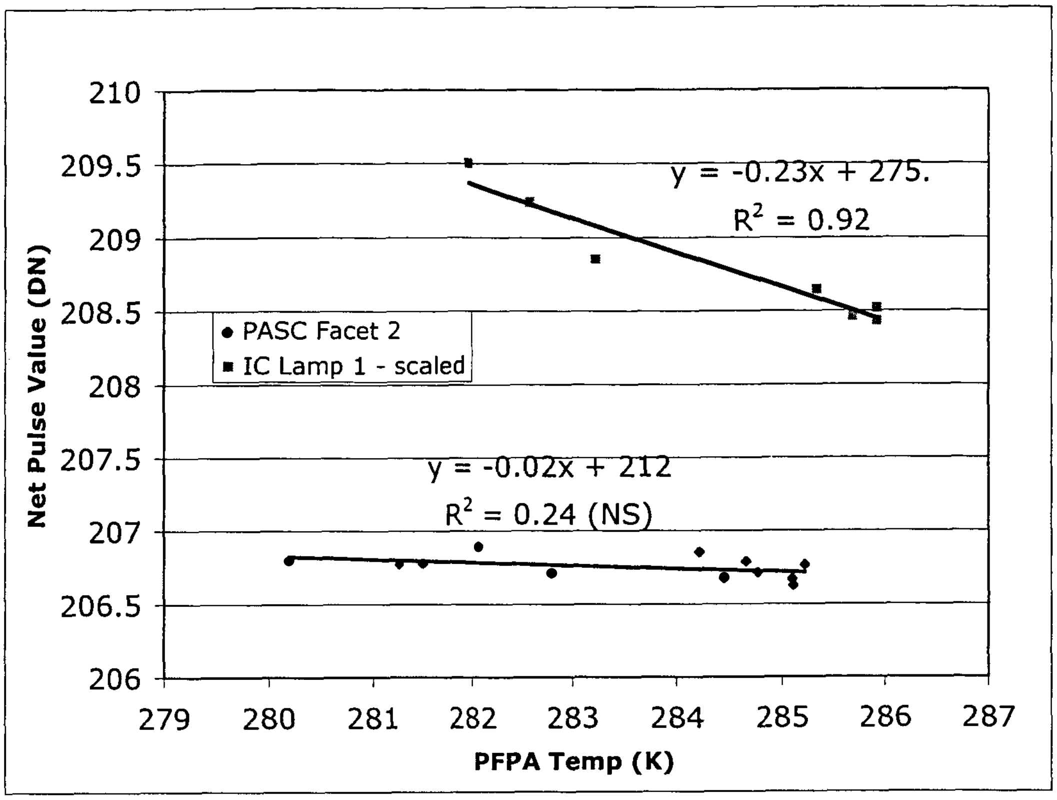

210
209.5
209
208.5
208
207.5
207
206.5
206
Net Pulse Value (DN)
279
280
281
282
283
284
285
286
287
PFPA Temp (K)
PASC Facet 2
IC Lamp 1 - scaled
y = -0.23x + 275.
R2 = 0.92
y = -0.02x + 212
R2 = 0.24 (NS)

Figure 6

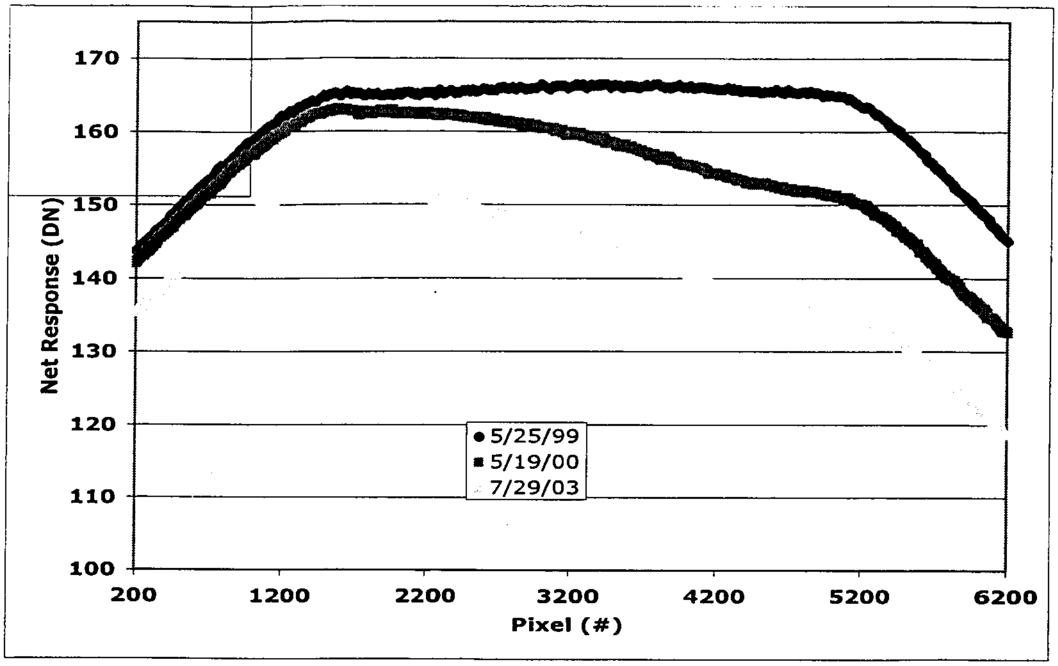

Net Response (DN)
170
160
150
140
130
120
110
100
200
1200
2200
3200
4200
5200
6200
Pixel (#)
5/25/99
5/19/00
7/29/03

Figure 7

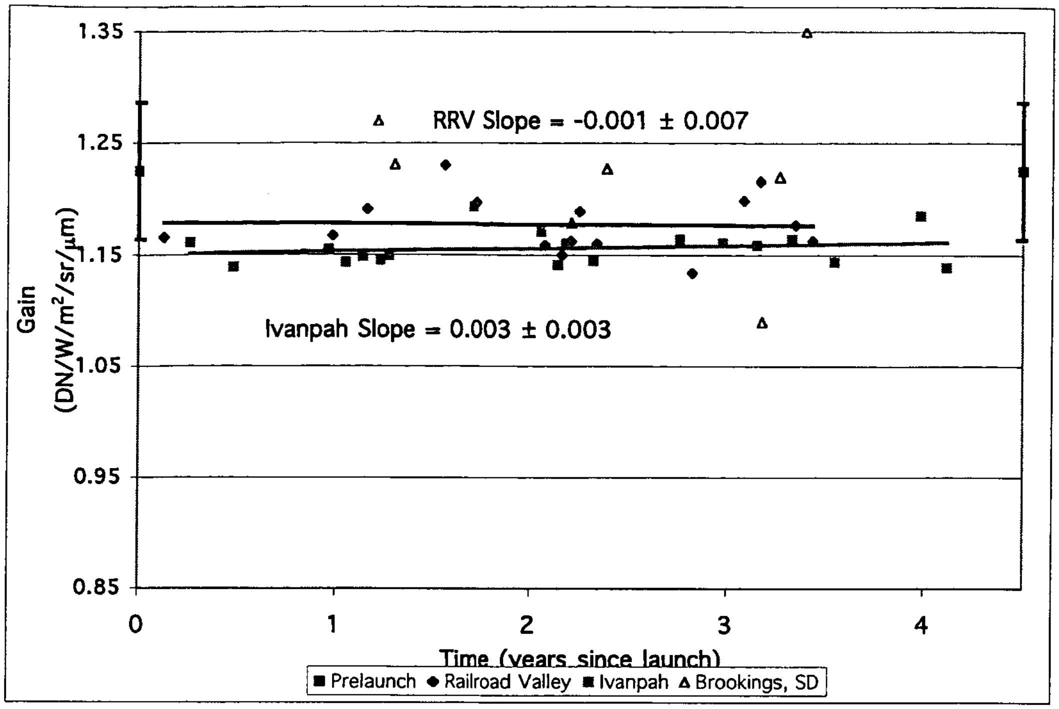

1.35
1.25
1.15
1.05
0.95
0.85
Gain
(DN/W/m²/sr/µm)
RRV Slope = -0.001 ± 0.007
Ivanpah Slope = 0.003 ± 0.003
0
1
2
3
4
Time (years since launch)
Prelaunch
Railroad Valley
Ivanpah
Brookings, SD

Figure 8

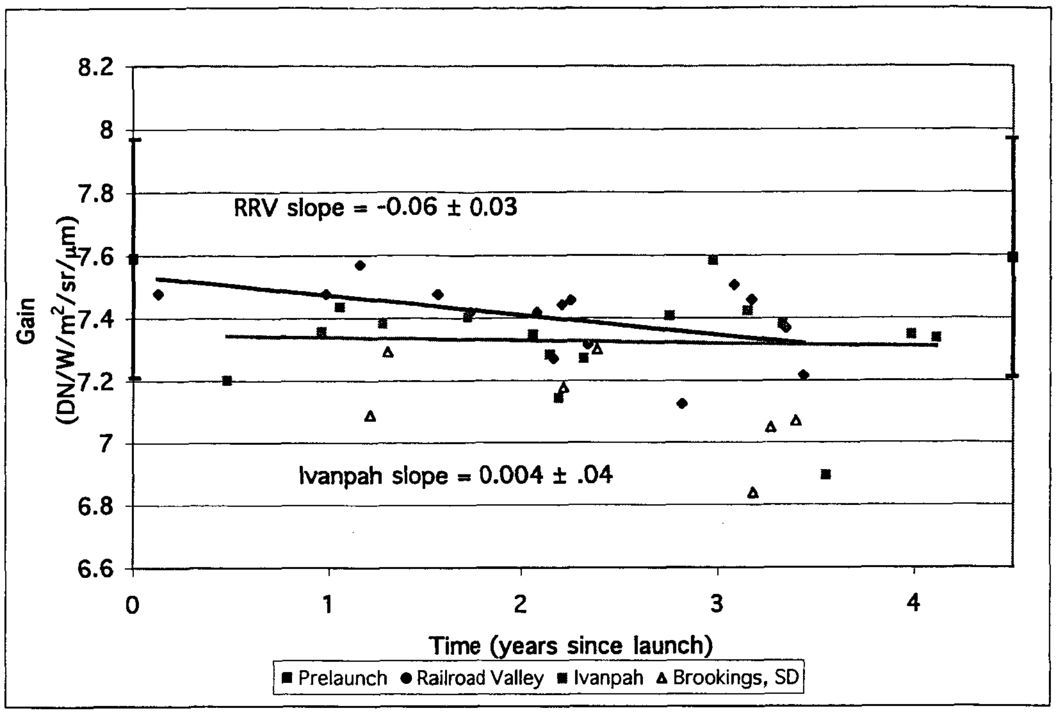

8.2
8
7.8
7.6
7.4
7.2
7
6.8
6.6
Gain
(DN/W/m2/sr/μm)
RRV slope = -0.06 ± 0.03
Ivanpah slope = 0.004 ± .04
0
1
2
3
4
Time (years since launch)
Prelaunch
Railroad Valley
Ivanpah
Brookings, SD

Figure 9

Figure 10

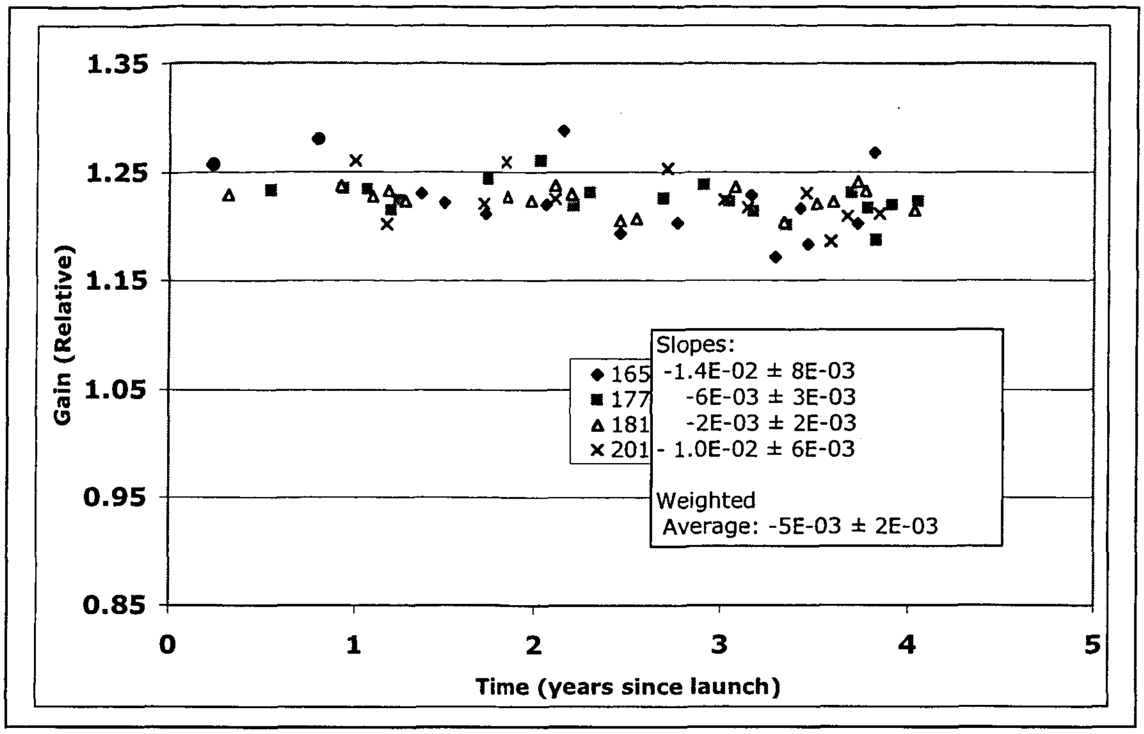
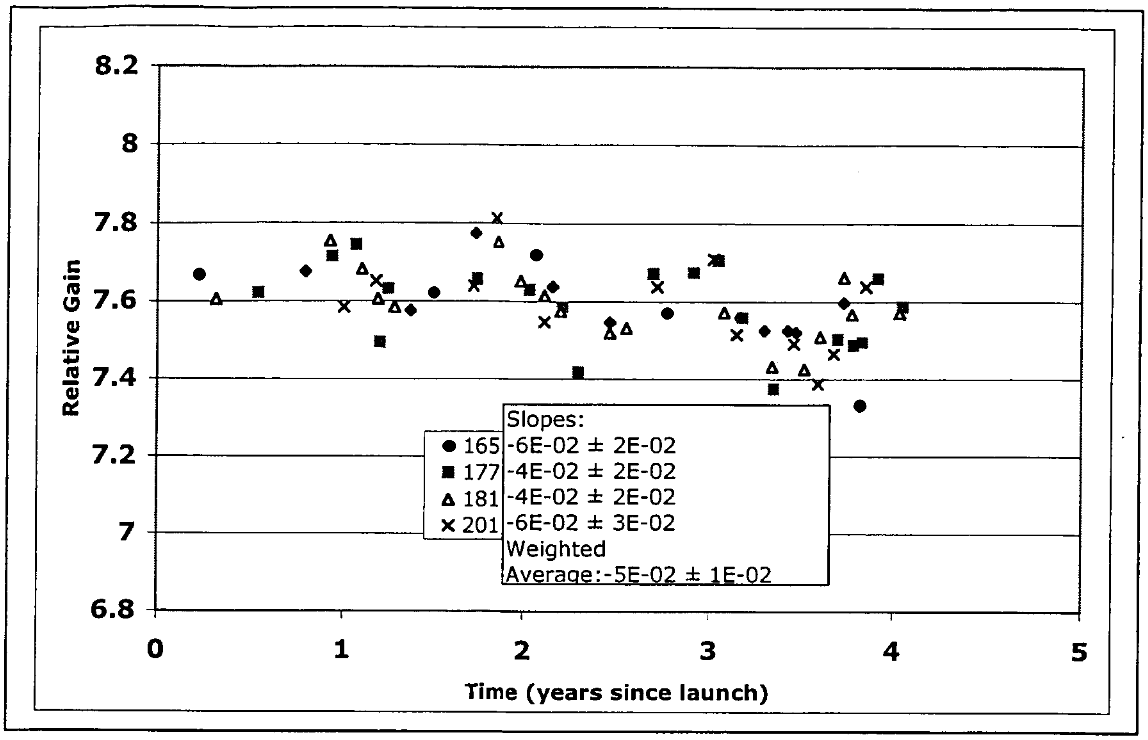
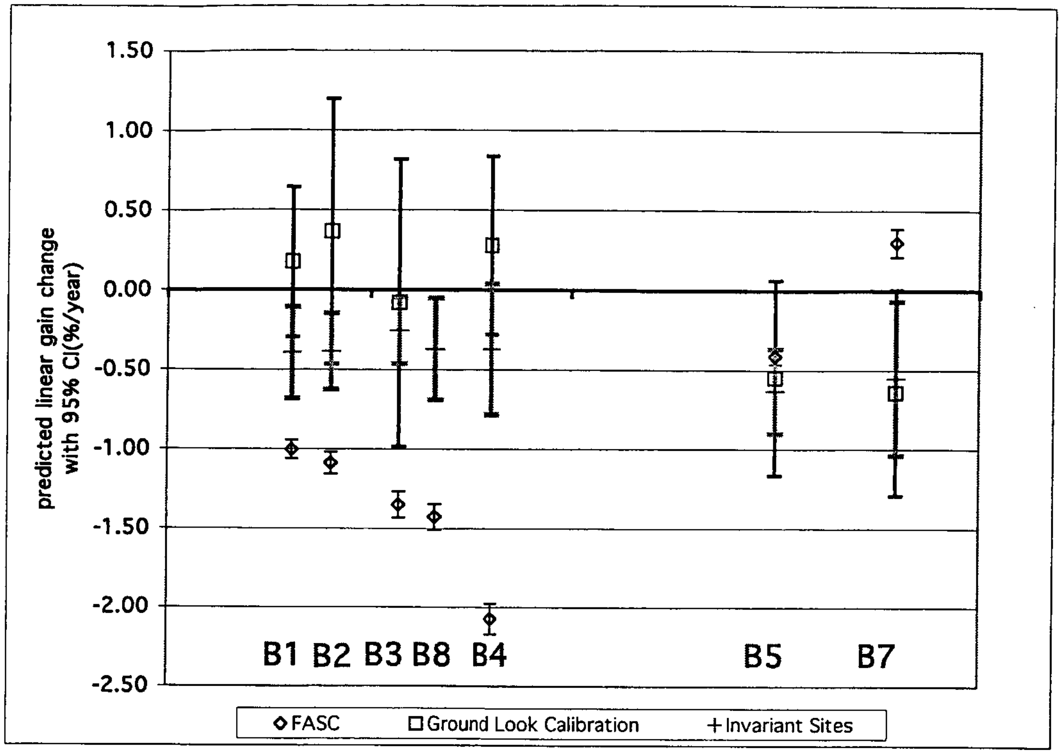

1.35
1.25
1.15
1.05
0.95
0.85
Gain (Relative)
0
1
2
3
4
5
Time (years since launch)
165
177
181
201
Slopes:
-1.4E-02 ± 8E-03
-6E-03 ± 3E-03
-2E-03 ± 2E-03
- 1.0E-02 ± 6E-03
Weighted
Average: -5E-03 ± 2E-03

Figure 11



8.2
8
7.8
7.6
7.4
7.2
7
6.8
Relative Gain
0
1
2
3
4
5
Time (years since launch)
Slopes:
165 -6E-02 ± 2E-02
177 -4E-02 ± 2E-02
181 -4E-02 ± 2E-02
201 -6E-02 ± 3E-02
Weighted
Average:-5E-02 ± 1E-02



1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
predicted linear gain change with 95% CI(%/year)
B1 B2 B3 B8 B4
B5
B7
FASC
Ground Look Calibration
Invariant Sites

Figure 12

Tables

Table 1

Band (#)	Bandpass (μm)	Spatial Resolution (meters)	NEΔρ (%)*	NEΔT (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

Table 2

Band	Pre-launch variation in response to IC Lamp 1
1	±9%
2	±7%
3	±4%
4	±3%
5	±1%
7	±1%
8	±4%

Table 3.

Band	Center Wavelength (μm)	Band Average Apparent Gain Change (% of pre-launch/year)	Band Average Apparent Gain Change Uncertainty (% of pre-launch/year)
1	0.48	-1.01	0.03
2	0.56	-1.09	0.03
3	0.66	-1.34	0.04
4	0.84	-2.06	0.05
5	1.65	-0.41	0.03
7	2.20	+0.30	0.05
8	0.71	-1.41	0.04

Table 4

	95% CI on Slopes (Percentage of pre-launch/year)	
Band	RRV	Ivanpah
1	-1.3 to 1.2	-0.3 to 0.7
2	-1.2 to 2.2	-0.6 to 1.2
3	-1.7 to 0.9	-1.0 to 1.5
4	-1.4 to 1.1	-0.2 to 1.0
5	-1.6 to -0.0	-1.1 to 0.9
7	-1.7 to -0.1	-1.2 to 1.1

Table 5

	Band Average Gains [standard deviations] (DN/(W/m^2 sr μm))				Difference from Pre-launch & Operational		
Band	Pre-launch	Railroad Valley	Ivanpah	Brookings	Railroad Valley	Ivanpah	Brookings
1	1.225	1.18 [0.03]	1.16 [0.02]	1.22 [0.08]	-3.9%	-5.6%	-0.1%
2	1.191	1.14 [0.04]	1.11[0.03]	1.19 [0.10]	-4.2%	-6.9%	0.3%
3	1.538	1.50 [0.04]	1.47 [0.04]	1.51 [0.13]	-2.8%	-4.4%	-1.6%
4	1.496	1.50 [0.03]	1.47 [0.02]	1.51 [0.02]	0.0%	-1.7%	1.2%
5	7.590	7.40 [0.12]*	7.33 [0.15]	7.12 [0.16]	-2.5%	-3.5%	-6.3%
7	21.80	21.4 [0.3]*	21.1 [0.6]	20.3 [0.9]	-1.9%	-3.4%	-6.7%
N		15	19**	7			

* Significant slope at alpha= 0.05 **Some bands have as few as 15 due to saturation

Table 6

Location	WRS (Path/Row)	Corresponding Cosnefroy [10] designation	Center Latitude	Center Longitude	average FOM for all scenes
Egypt/Sudan	177/45	Sudan 1	21.7N	28.2 E	0.033
Mauritania	201/46	Mauritania 1/2	20.2N	9.2W	0.053
Saudi Arabia	165/47	Arabia 1	18.8N	46.1E	0.057
Libya	181/40	Libya 4	28.9N	23.8E	0.061

Table 7

Band	Weighted Average Slope Gain/yr		Weighted Average Slope Uncertainty Gain/yr		Statistical Significance
	Absolute	Percentage of Pre-launch Gain	Absolute	Percentage of Pre-launch Gain	t-Value
1	-5E-03	-0.4	2E-03	-0.1	2.8
2	-5E-03	-0.4	1E-03	-0.1	3.2
3	-4E-03	-0.3	2E-03	-0.1	2.4
4	-6E-03	-0.4	3E-03	-0.2	1.8
5	-5E-02	-0.6	1E-02	-0.1	4.7
7	-1.2E-01	-0.5	5E-02	-0.2	2.3
8	-4E-03	-0.4	2E-03	-0.2	2.3

Table 8

Band	Weighted Average Slope Gain/yr		Weighted Average Slope Uncertainty Gain/yr		Statistical Significance
	Absolute	Percentage of Pre-launch Gain	Absolute	Percentage of Pre-launch Gain	t-Value
1	-3E-03	-0.2	2E-03	-0.1	2.0
2	-4E-03	-0.3	1E-03	-0.1	2.8
3	-4E-03	-0.2	2E-03	-0.1	2.4
4	-2E-03	-0.1	2E-03	-0.2	0.9
5	-5E-02	-0.6	9E-03	-0.1	5.1
7	-1.3E-01	-0.6	4E-02	-0.2	3.0
8	-4E-03	-0.4	2E-03	-0.2	2.3

Table 9

Band	(Initial FASC Calibrations −Operational Calibration) /Operational Calibration
1	-0.7%
2	-1.4%
3	-2.0%
4	+0.2%
5	+3.8%
7	+2.8%
8	-1.2%