CONTINUOUS CALIBRATION IMPROVEMENT: LANDSAT 5 THROUGH LANDSAT 8

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Abstract: Launched in February 2013, the Operational Land Imager (OLI) on-board Landsat 8 continues to perform exceedingly well and provides high science quality data globally. Several design enhancements have been made in the OLI instrument relative to prior Landsat instruments: pushbroom imaging which provides substantially improved Signal-to-Noise Ratio (SNR), spectral bandpasses refinement to avoid atmospheric absorption features, 12 bit data resolution to provide a larger dynamic range that limits the saturation level, a set of well-designed onboard calibrators to monitor the stability of the sensor. Some of these changes such as refinements in spectral bandpasses compared to earlier Landsats and well-designed on-board calibrator have a direct impact on the improved radiometric calibration performance of the instrument from both the stability of the response and the ability to track the changes. The on-board calibrator lamps and diffusers indicate that the instrument drift is generally less than 0.1% per year across the bands. The refined bandpasses of the OLI indicate that temporal uncertainty of better than 0.5% is possible when the instrument is trended over vicarious targets such as Pseudo Invariant Calibration Sites (PICS), a level of precision that was never achieved with the earlier Landsat instruments. The stability measurements indicated by on-board calibrators and PICS agree much better compared to the earlier Landsats, which is very encouraging and bodes well for the future Landsat missions too.

Keowords— Landsat, Operation Land Imager (OLI), Enhanced Thematic Mapper Plus (ETM+), Thematic Mapper (TM), radiometric calibration

1. Introduction

Landsat 8 (L8) was launched on 11 February 2013 and has two imaging sensors on-board: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). It has now joined the Landsat 7 Enhanced Thematic Mapper (ETM+) on orbit to provide a continued data record of the earth. The Landsat archive contains the longest continuous record of the Earth's surface, as viewed from space, with the Landsat 8 mission extending this record to more than 42 years (and counting). L8 OLI adopts a pushbroom technology with approximately 70,000 detectors which is a fundamental change (or upgrade) compared to earlier Landsat instruments which all used whiskbroom imagers and contained far fewer (≤136) detectors. Several other enhancements have been made with L8 OLI such as addition of extra spectral bands namely the Coastal Aerosol Band and Cirrus Band, refinements of the bandwidths to avoid some atmospheric absorption features, wider dynamic range that limits saturation, improved temperature stability, and the larger detector integration time and low noise level of the OLI detectors provide superlative Signal-to-Noise Ratio (SNR) compared to earlier Landsat instruments which used whiskbroom imagers and had a shorter integration time. OLI also has 3 primary on-board calibration devices: a shutter, lamps and diffusers which are employed periodically to track the stability of the instrument. Because of its temporal coverage (8 days with L7 and L8 combined), spatial resolution (30 m) at an appropriate scale for monitoring human activity, as well as the benefit of free access to the public, the Landsat data record is important for land cover change research and global climate change studies. A key precursor for these studies is consistent radiometric calibration and stability of the Landsat sensors.

The primary purpose of this paper is to assess the improved radiometric calibration of Landsat 8 OLI, particularly with respect to spectral bandpasses and its impact on vicarious calibration methods, as compared to on-board calibration systems. This will be done through comparisons with Landsat 5 TM and Landsat 7 ETM+ calibration performance and through briefly noting the impact that spectral bandpass changes have on common measurements and potential for further refinements in future Landsats.

2. Key OLI Design Improvements in L8 OLI

As stated earlier, OLI is a pushbroom instrument which essentially increases the integration time for each pixel. It has fourteen overlapping focal plane modules (FPMs) that cover a 185 km swath width [1]. The multispectral OLI bands have about 494 detectors per module and the panchromatic band has twice as many. Each of the FPMs has its own butcher block assembly of spectral filters. The low noise level of the detectors and a long integration time has significantly improved SNR compared to earlier Landsats which were whiskbroom instruments and had a shorter integration time. Figure 1 shows the comparison between L7 ETM+ and Landsat 8 OLI SNR at a typical radiance level [2] [3]. The figure shows that OLI SNR is 6 to 10 times better than ETM+ SNR for the different spectral bands.

One of the salient features of the OLI instrument is its set of well-designed on-board calibrator systems. OLI has multiple lamps and diffusers as on-board calibration sources to monitor the stability of the sensor system. The diffuser and lamp assemblies in the OLI instrument have been described in detail [1] [4]. The lamps and diffusers have been named as working, backup or pristine depending on the frequency of usage. The three sets of lamps are used daily, bi-monthly and every six months, respectively. The presence of these multiple sources can identify changes in the instrument response as opposed to changes in calibration sources. Similarly, a working diffuser is deployed every week and the pristine diffuser panel is used every 6 months. These diffuser panels are NIST traceable reflectance standards and were characterized prior to launch; trending these ensures that the changes in the OLI instrument are monitored and calibration correction can be incorporated in the data processing in the event of potential changes [1].

In general, L8 OLI spectral bands are similar to L7 ETM+ and L5 TM. OLI includes two additional spectral bands: a Coastal/Aerosol Band which allows estimation of the concentration of aerosols in the atmosphere and a Cirrus Band to aid in the detection of clouds. The spectral response function of OLI was well characterized during prelaunch testing and exhibits very minimal out-of-band response and cross-talk among bands [5]. Relative to TM and ETM+, enhancements have been made in the position of OLI bands in the electromagnetic spectrum too. Figure 2 compares the Relative Spectral Response (RSR) of L8 OLI (blue line), L7 ETM+ (red line) and L5 TM (green line) for matching bands together with a typical atmospheric transmittance profile (black line). It can be seen that, in general, the OLI bands are narrower than ETM+ and TM bands as OLI band edges have been refined to avoid atmospheric absorption features. The most significant change can be noticed in the Near InfraRed (NIR) band where OLI is substantially narrower than the other two to avoid the water vapor absorption features at 817 and 823 nm. Similarly, the SWIR-1 band is considerably narrower in OLI as compared to ETM+ and TM, and placed in a region where atmospheric transmittance is very high. A closer inspection of SWIR-1 band in TM indicates its proximity to the major water absorption features starting around 1800 nm where the transmittance is close to zero. A similar explanation holds true for the SWIR-2 band. It should be noted that the spectral resolution and SNR are generally trade-offs in optical design system and narrower bands in OLI were only possible because of the high SNR in OLI as discussed earlier. Atmospheric absorption features are an indication of the composition of the atmosphere and can vary temporally and spatially. This variability can add additional uncertainties in the datasets when vicarious sources such as PICS are trended to monitor the stability of the sensor. The impact of narrower bandpasses on radiometric calibration improvement will be described later explicitly when Pseudo Invariant Calibration Sites (PICS) based stability is discussed.

In contrast to Landsat 8 OLI, Landsat 5 TM and Landsat 7 ETM+ had substantially different on-board calibration systems. Landsat 5 TM only used a set of three lamps for its on-board calibrators [6] This system only illuminated a portion of the optical path in the sensor but operated according to plan for its design life of three years [7]. After that vicarious methods were used to calibrate the instruments for its 27 year lifetime [8]. Conversely, Landsat 7 had 3 on-board calibrators – lamps, partial aperture solar calibrator (PASC) and full aperture solar calibrators (FASC). Each of these systems provided only a partial solution to the calibration problem and vicarious methods were again needed for a full solution [3] [8].

Figure 1. Signal-to-Noise ratio of L7 ETM+ & L8 OLI at typical radiance levels.

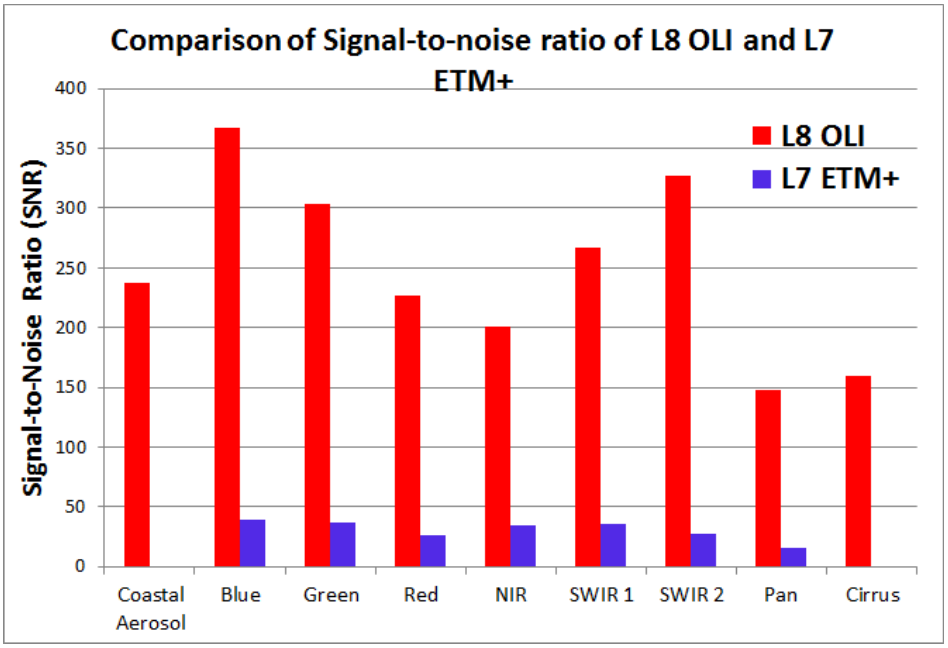
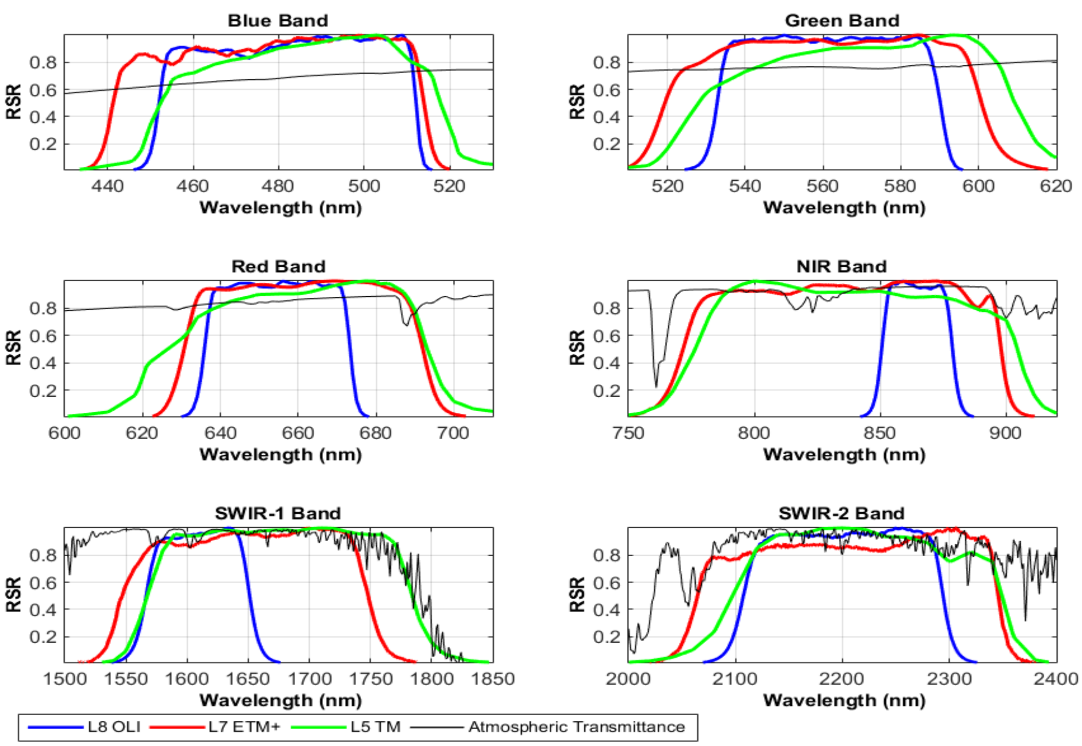


Figure 2. Relative Spectral Response (RSR) of L8 OLI and L7 ETM+ and L5 TM.



3. Landsat 5 TM & Landsat 7 ETM+ Gain Stability Monitoring

One of the primary issues with the on-board radiometric calibration is the constant need to demonstrate that the calibration of the systems hasn't drifted with time due to potential degradation of the source [9] [10]. This section briefly describes how the calibration on the earlier Landsats these instruments, L5 TM and L7 ETM+, have been a challenge over the years because as time progressed, changes were observed in these on-board calibrators and it was often difficult to determine whether these changes were due to the calibrators drifting or the degradation in the imaging system.

On-board calibrators in TM consisted of internal lamps and a shutter to estimate gain and bias. L7 ETM+ had an internal lamp as well as the FASC. The PASC was determined to be unreliable as a calibration source early on [11]. Figure 3 shows the absolute calibration model for Landsat 5 TM where all the possible calibration sources have been integrated. Plot shows prelaunch gain (green triangle), cross-calibration with Landsat ETM+ (red circle), UAZ optimized calibration 2004-2005 (green star), vicarious calibration data collected by UAZ (pink triangle) throughout the lifetime of the instrument and that by SDSU (maroon stars) have been included in the plot for band 1 (blue band). The normalized Libyan PICS data represented by blue diamonds and the model "exponential plus constant" scaled to the Landsat 7 ETM+ cross-calibration is also shown on the plot. Finally, the IC models (exponential plus constant) scaled to the prelaunch as well as to the Landsat 7 ETM+ cross-calibration are also included in the plot. It can be seen that the Libyan site model, which had a precision of better than 1%, seems to agree well with the vicarious ground based data The IC data agrees to the Libyan site model in the first two years but there is a substantial difference, up to 13% after the initial years. Two independent sites, once in Africa and one in North America showed similar results suggesting that changes in IC data after three years were probably due to the calibrators degrading over time rather than the actual changes in the imager. The Libya 4 model was scaled to cross calibration to ETM+ in 1999 and yet still shows very good agreement to the gains derived by in-situ vicarious calibration performed by UAZ (1.225 and 1.215) to within about 0.9%. Although the in-situ vicarious data shown in the figure has a major advantage in that they allowed for independent knowledge of absolute accuracy, but did not have enough precision coupled with low frequency of data collects to implement a calibration model to account for the imager degradation. The PICS approach had the advantage of having sufficient data precision to build a model by making repetitive measurements for a temporally stable target and the PICS model, shown in Figure 3, was used to tie all the available calibration together process together. Currently this PICS model is being used to calibrate the Landsat 5 archive. Thus the lifetime calibration of Landsat 5 was achieved only through combination of on-board and vicarious calibration.

Switching to Landsat 7, figure 4 shows both FASC trending and trending for Libya 4 (181/40), Sudan 1 (177/45), Algeria 3(192/39), Mauritania 1(201/46) and Saudi Arabia (165/47) PICS. The ETM+ PICS data were anchored to prelaunch gain to compare with the solar panel data. It shows that PICS and the FASC had very good agreement for first one and half year since launch (within 2%). After that the solar panel started to diverge from the PICS measurements. The gain change indicated by FASC steadily grew in a linear fashion while PICS showed essentially no change in gain. Decay of the FASC is probably due to use of a paint that degraded with the exposure of the UV light. These observations led to the conclusion that the changes from the FASC panel were like due to degradation in the panel itself rather than real changes in the imager system and the detectors. Table 1 compares the estimated drifts derived using PICS measurements and the solar panel for different solar reflective bands. Solar panel measurements showed that the gain changes are as high as 0.94% per year (for NIR band) which was not conceivable as PICS measurement indicated that gains were changing by no more than 0.21% per year. The gain changes observed by PICS were statistically significant at 2-sigma level (95% confident interval) for all the solar reflective bands. In order to account for these changes, L7 ETM+ calibration gains were updated in the calibration parameter file (CPF) in the USGS image archive in 2013 [12]. Once again, it is clear that both on-board calibration and vicarious calibration was required to ensure that ETM+ performance was well understood.

Figure 3. Lifetime calibration data and models for Landsat 5 TM, Band 1 (from [13])

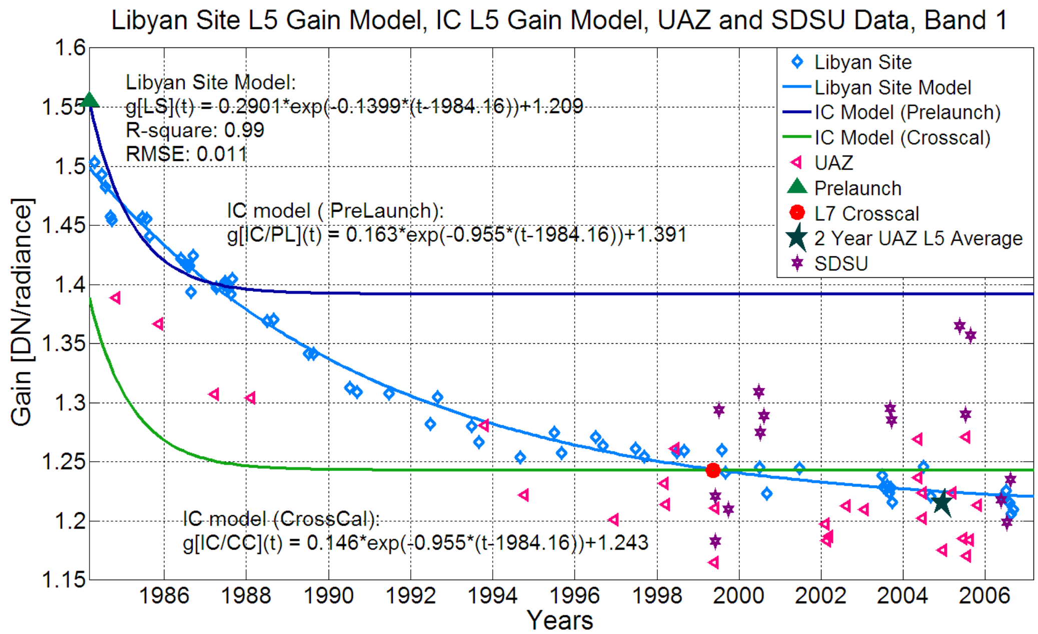


Figure 4. Estimated Gain for Landsat 7 ETM+ Band 3 using PICS and the full-aperture solar calibrator

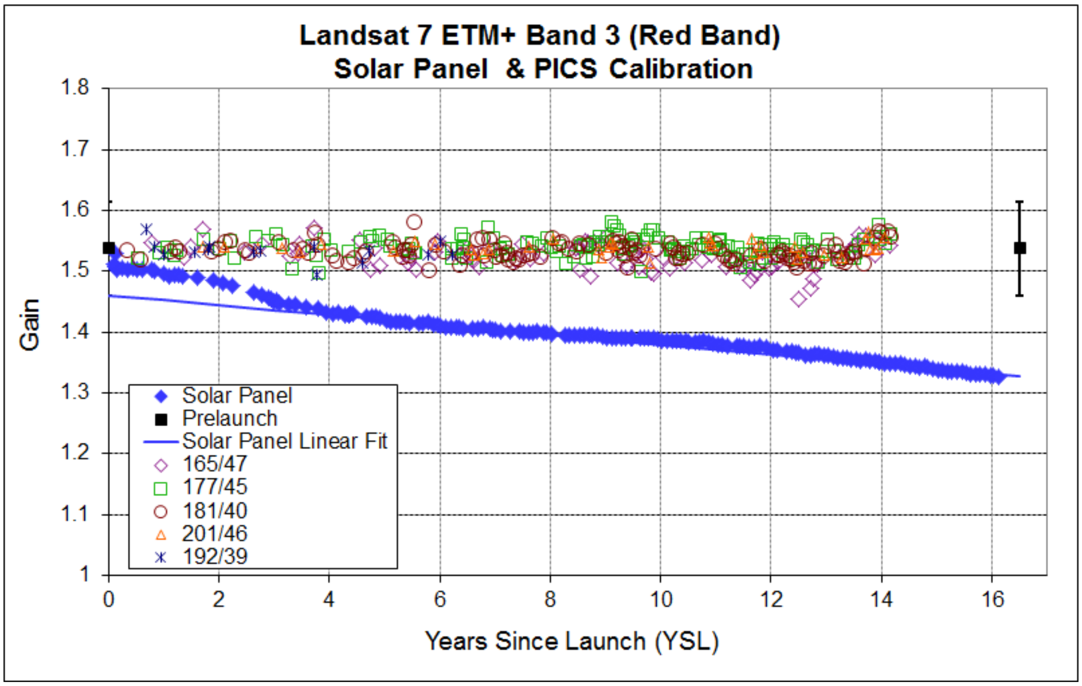


Table 1. Estimated gain changes observed with Solar Panel and PICS at 2-sigma level uncertainty.

	Landsat Bands	Gain Change (%per year ± 2-sigma)	
		Solar Panel	PICS (Libya 4)
1	Blue	-0.62+/-0.02	-0.21+/-0.09
2	Green	-0.58+/-0.02	-0.09+/-0.07
3	Red	-0.68+/-0.02	-0.06+/-0.05
4	NIR	-0.94+/-0.04	-0.13+/-0.09
5	SWIR-1	-0.20+/-0.01	-0.18+/-0.07
7	SWIR-2	0.12+/-0.01	-0.21+/-0.13

4. Improved Gain Stability Monitoring in OLI

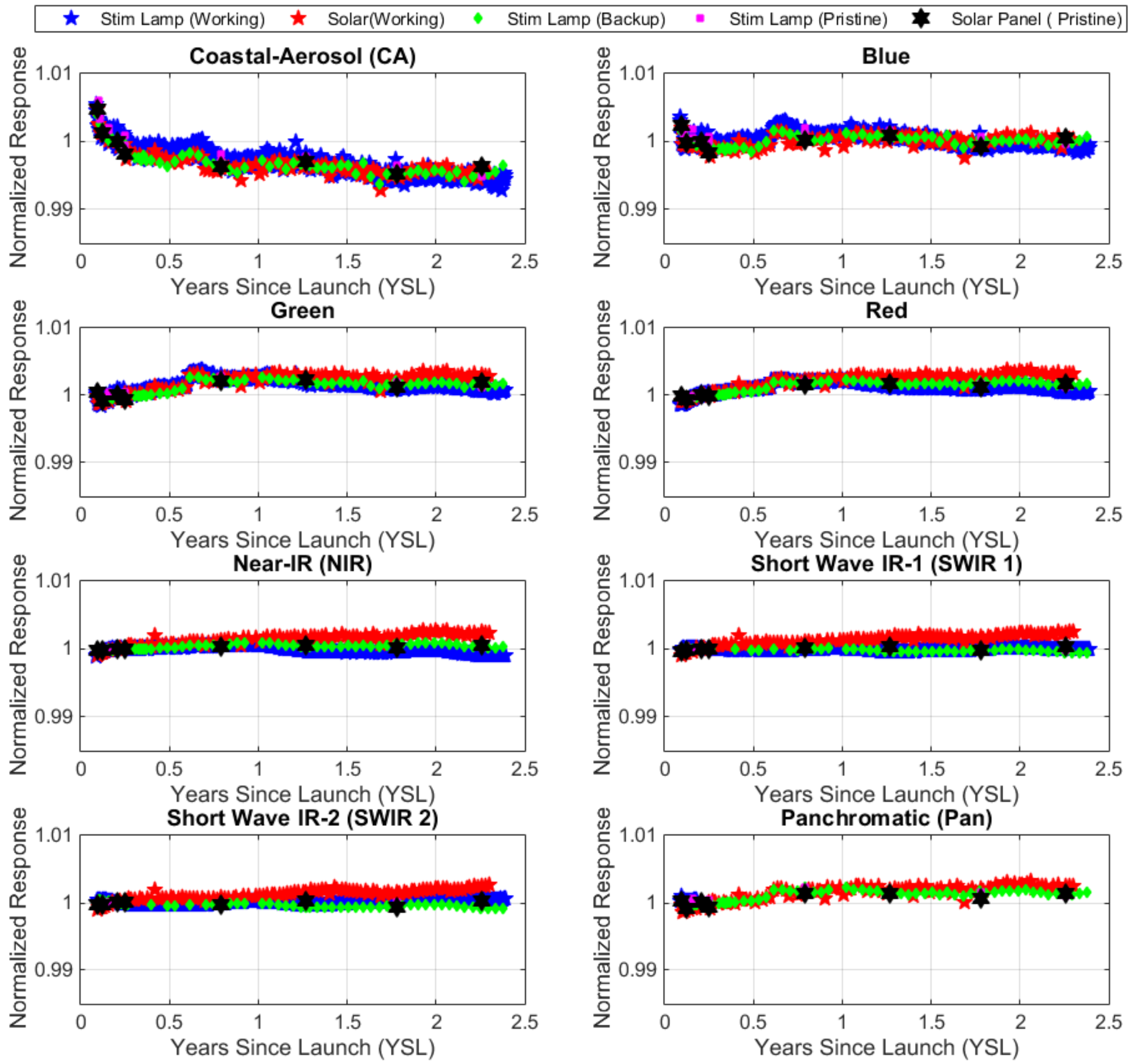
The stability of a sensor is important to users as it allows the users to quantify smaller changes on the earth's surface. Stability of a satellite sensor is assessed by making repetitive measurements of stable sources and trending these measurements to identify any potential drifts. The potential sources can include on-board sources such as lamps and diffusers and vicarious sources such as PICS, the Moon, Deep Convective Clouds (DCC) and other celestial objects for measuring gain stability [8] [9] [14] [15] [16]. On the other hand shutter collects and/or dark ocean collects are primarily used for monitoring bias stability [17]. Two independent methods of OLI gain stability monitoring will be described in this section. The first one uses on-board lamps and diffusers, and the second one uses the vicarious PICS based method. Since OLI is a relatively new satellite sensor on-orbit, the onboard calibrators are primarily being used to track the stability of OLI to meet the mission repeatability requirements. The PICS-based method acts as a backup to complement the on-board hardware or, in the case of unexpected failure of the on-board hardware, as a primary means of absolute calibration. PICS based method also has the benefit of being full-aperture stable source and independent of the instrument.

4.1. Using on-board calibrators

The data from the lamps and diffusers, processed through the USGS Image Assessment System (IAS), are bias subtracted, linearized and normalized to obtain an average response as shown in Figure 5. Figure 5 illustrates the agreement between the different calibration sources is close to a few tenths of a percent. The lamp and diffuser trends are generally in the same direction. There is a "hump" in the data around 0.6 years since launch, likely related to the power cycling of a spacecraft safe hold event; the responsivity of all bands changed suddenly by 0.1 to 0.2% for unknown reasons, but responsivity recovered to each band's original level within several weeks for unknown reasons [4].

The Coastal Aerosol Band has changed the most, with an exponential drop of about 0.5% in responsivity early in the mission life (~2 months) and a linear decay since then of about 0.1%/year. The change in the Coastal Aerosol band is likely real instrument change as it appears in all the calibrators. The decrease in responsivity can be corrected by adjusting the calibration gain in the processing system to reflect the change. Assuming an exponential plus linear model for the decay, removing the trend from the working lamp data decreases the variability from 0.16% to 0.08%, which is inline with all the other bands. The drift observed due to onboard calibrators will be analyzed further in section 4.3. However, to put things into better perspective, L7 ETM+ had three onboard calibration systems to monitor the stability of the reflective bands. However, each calibration system was subject to its own instability as time progressed which complicated the understanding of the behavior of the instrument and vicarious methods had to be used to assess its long term stability [8] as discussed earlier. On the contrary, in the case of L8 OLI, all the onboard systems have shown changes in the same direction and magnitude which strongly suggests that changes in the on-board systems are not confused with changes in the imager.

Figure 5. OLI on-orbit radiometric calibration trend for solar reflective bands.



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4.2. PICS Trending

As discussed earlier, enhancements have been made in the spectral bandpasses of the OLI instrument as compared to earlier Landsat instruments, and OLI bands are narrower than the corresponding ETM+ bands. Spectral resolution describes the ability of a sensor to define wavelength intervals and higher spectral resolution results in narrower spectral bandwidth. Generally, the SNR decreases with increase in resolution as signal strength is smaller in narrower bands. But this limitation has been overcome by implementing a pushbroom imager in OLI, allowing longer dwell time and greater range of sensed signal. Thus, the achievable SNR is very high in OLI, as shown in Figure 1, which has allowed narrowing down its spectral bandpasses to avoid some of the atmospheric absorption features.

The differences in RSRs of OLI and ETM+ would also mean that even while both sensors are looking at the same general region of the electromagnetic spectra at the same time, they may report different values of at-sensor radiance depending on the spectral signature of the target. It is also indicative of the fact that if both these sensors image a stable target of the earth's surface, such as PICS, better precision in the observed trend can be achieved in the OLI data as atmospheric variation is less in OLI bands. OLI images from North African PICS are processed through the USGS Image Assessment System (IAS) and trended continuously for stability monitoring. PICS-based radiometric trending has been employed for several years now to assess the stability of Earth Observation (EO) satellite sensors that may or may not be equipped with on-board calibrators [10] [14] [18] [19]. PICS trending provides an independent assessment of the stability of the instrument to complement the on-board lamps and diffusers. Figure 6 shows the TOA reflectance trending of OLI spectral bands over the Libya 4 (Lat/Lon +28.55, +23.39) test site. Libya 4 has been long regarded as the most invariant target by several researchers [10] [15] [19].The standard region of interest (ROI) is band averaged and adjusted for solar zenith angle and earth-sun distance for images acquired from launch to May, 2015. It can be seen that the spread in the data is minimal in the spectral bands which avoid atmospheric absorption features such as red, NIR and SWIR-1 bands. The spread in the data is largest in SWIR-2 because this band includes several atmospheric absorption features (Figure 2).

The temporal uncertainty (1-sigma standard deviation/mean) of the TOA reflectance is quantified in Table 2 for Libya 4 and two other additional sites, Libya 1(+24.42, +13.35) and Sudan 1 (+21.74, +28.22) which have earlier been identified as one of the top PICS [10]. As can be seen, the uncertainty in measurement generally is about 1.0% for the Coastal Aerosol, Blue and Green bands. The variability in the red, NIR and SWIR-1 bands is generally hovering near 0.5%. The uncertainties are higher in SWIR-2 and approach 2% for the reasons discussed earlier. The OLI data record is compared against its predecessor instrument, L7 ETM+, over the same time frame as shown in Table 2. On comparison, it can be seen that for all 3 PICS, OLI temporal uncertainty is better than ETM+ for every band. The most noticeable differences can be seen in the NIR and SWIR-1 bands. For NIR bands, the ETM+ uncertainties are hovering around 1.7% whereas the OLI uncertainties are around 0.5% which is a pleasing improvement of more than

1%. Similarly, for the SWIR-1 band, the ETM+ uncertainties are around 1.2% whereas OLI uncertainties are around 0.6% or better which shows improvement of more than 0.5%. SWIR-2 also exhibits a similar story where the temporal uncertainties in OLI are less than ETM+ by about 0.5%. This reduction in variability is a direct outcome of the spectral enhancements in OLI design whereby narrower bandpasses were possible in OLI because of the high SNR of the instrument.

Similarly, figure 7 shows the temporal uncertainties of Landsat 5 TM, Landsat 7 ETM+ and L8 OLI using Libya 4 over instrument lifetime. As can be seen, the temporal uncertainties of L8 OLI bands are least, followed by ETM+ and TM across all bands. Significant improvement can be seen in green, red, NIR and SWIR-1 band of L8 OLI where the uncertainties are below half of one percent whereas for ETM+ and TM, the uncertainties are higher than 1%. It should be noted that the SWIR-1 band of TM saturates over Libya 4 and hence is not used for analysis. The improvement in precision in L8 OLI is an outcome of spectral refinements in OLI as discussed earlier. The larger bandwidths of TM and ETM+ sample more atmospheric features. Absorption features are not temporally and spatially uniform and this lack of uniformity leads to larger uncertainties in the trending. Thus, more precise trending is achieved with OLI over PICS while monitoring the long term stability of the sensor. Also seen from the figure is that the uncertainties for the SWIR-2 band are comparable for all the three Landsats which means that there is potential for enhancements and refinements in the future Landsats regarding the placement of this spectral bandpass in the electromagnetic spectrum.

Figure 6. Temporal Trending of L8 OLI over Libya 4 PICS.

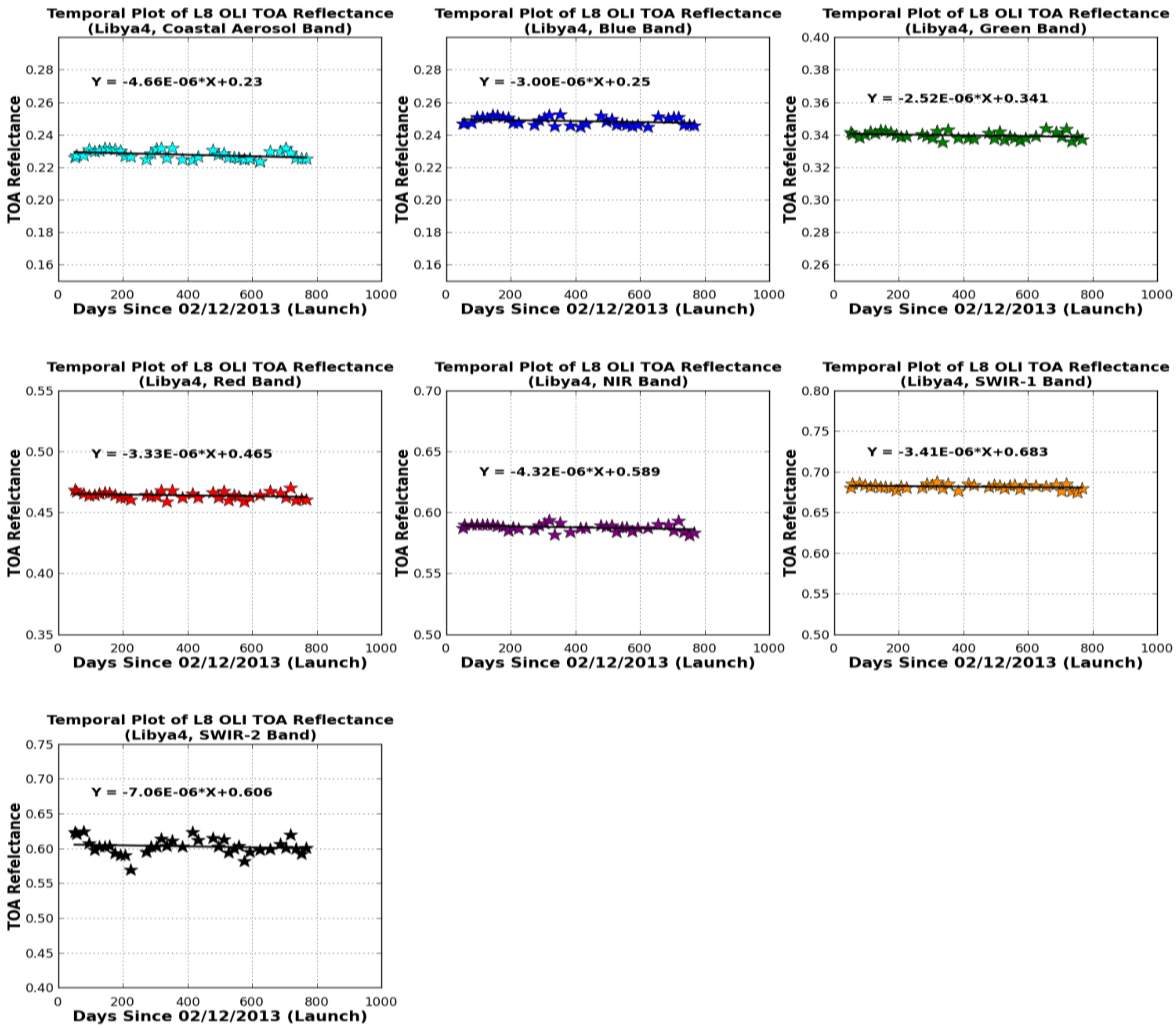
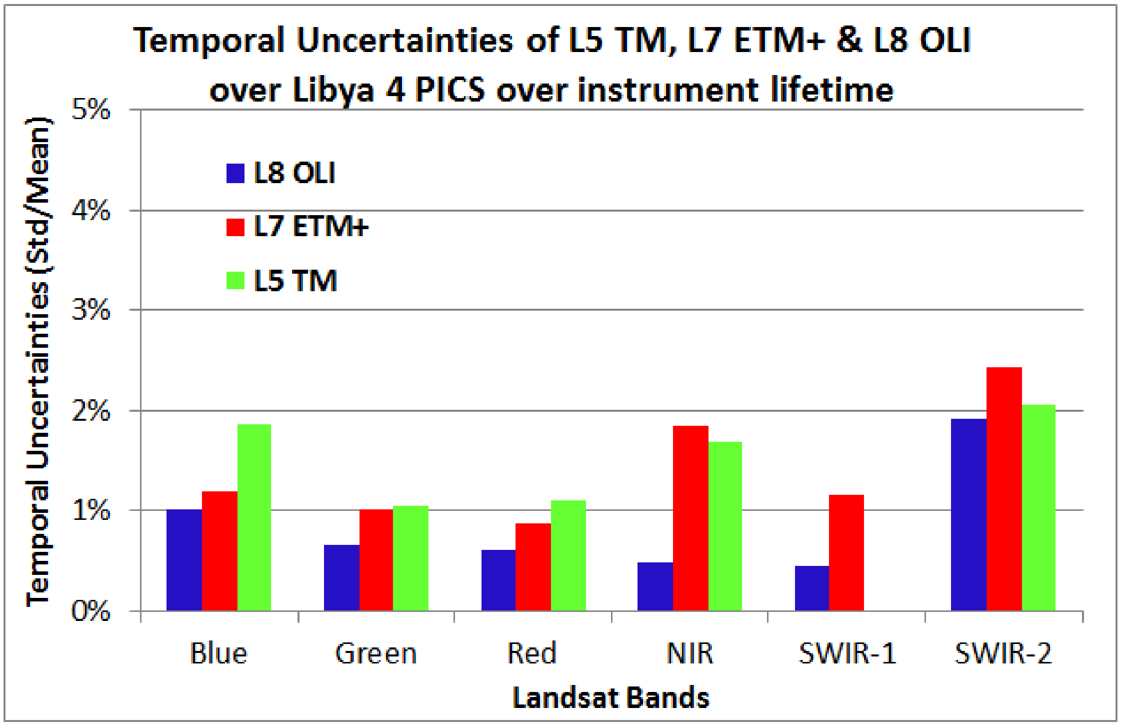


Table 2. Temporal Uncertainty of OLI over different PICS.

Landsat Bands	OLI Temporal Uncertainty since launch			ETM+ Temporal Uncertainty since Feb 2013		
	Libya 4	Libya 1	Sudan 1	Libya 4	Libya 1	Sudan 1
Coastal Aerosol	1.16%	1.20%	1.04%			
Blue	1.01%	1.76%	0.88%	1.12%	2.50%	1.65%
Green	0.66%	1.08%	0.72%	0.92%	1.35%	1.28%
Red	0.61%	0.65%	0.83%	0.91%	0.89%	0.97%
NIR	0.49%	0.40%	0.55%	1.84%	1.68%	1.72%
SWIR-1	0.45%	0.58%	0.37%	1.22%	1.22%	1.15%
SWIR-2	1.91%	1.14%	1.72%	2.40%	1.94%	2.11%

Figure 7. Temporal Uncertainties of L5 TM, L7 ETM+ & L8 OLI using Libya 4 PICS



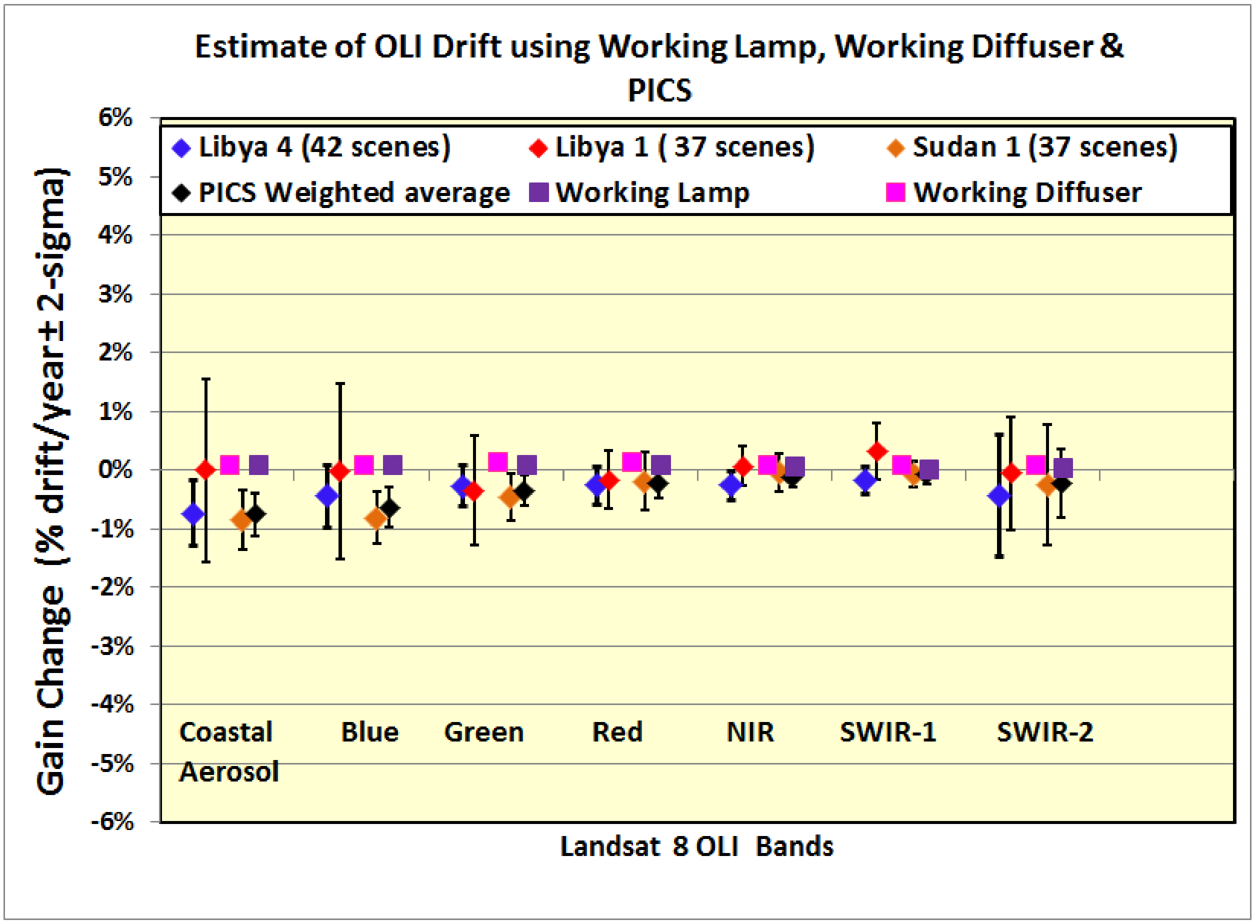
4.3. Comparing the on on-board and PICS data for OLI

The purpose of this section is to quantify short-term drift (OLI is a relatively new instrument) of OLI monitored from different calibration sources. The response of OLI to lamps, diffusers and PICS were regressed over time to determine the presence of temporal drift. The drift calculated from these calibration sources is shown in Figure 8. For comparison, only working diffusers and lamps have been used in the analysis. Recall from figure 5 that the overall drift in the Coastal Aerosol band is approximately 0.3% per year. This drift has been modeled as exponential plus linear decay and the model has been applied to the data. As results, the decay recorded in this band in figure 8 is essentially zeroed out for the on-board calibration sources. This is the only band that has a corrections applied to it. The figure also indicates that the observed drifts, marked with squares, in the remaining bands from blue to SWIR-2 are quite small and range from 0.05% to 0.2% per year indicating excellent stability. The drifts observed with PICS are marked with diamonds and range from 0.2% to 0.8% per year, with higher drifts observed in coastal aerosol and blue bands and lower drift observed in SWIR-1. In order to reduce noise associated with measurement uncertainties over PICS, the drifts observed with PICS are weighted inversely with their uncertainty to derive a weighted average drift as indicated by the black diamonds in the figure. Based on the observed drifts derived using on-board systems and PICS, the following observations can be made:

1) The observed drift is higher in the coastal aerosol band using both methods and in the same direction. PICS exhibit drift of around 0.7% per year and prior to correction the onboard calibrators showed a drift of around 0.3% per year but are within the uncertainties of PICS based drifts.
2) In blue bands, PICS based numbers are higher than the on-board measurements and differ by around 0.5% with the disagreement almost within the PICS based uncertainties. PICS uncertainties are dominated by atmospheric aerosols in both the Coastal Aerosol and blue bands.
3) For cleaner spectral bands such as green, red, NIR and SWIR-1 bands, the onboard numbers and PICS-based numbers show closer agreement. PICS show a drift of around 0.1 to 0.2% per year whereas diffuser and lamp exhibit a change of around 0.05 to 0.2% per year and are within the uncertainties of PICS measurements. These numbers are very small and not statistically significant. These results show PICS are an attractive complement to onboard systems for gain stability monitoring. Also, the longer wavelength bands (green through SWIR-1) suggest what level of uncertainties could be achieved in the short wavelength bands if aerosols are accurately modeled. This work is currently under progress.
4) For the SWIR-2 band, the uncertainties associated with PICS-based measurements are higher because of the location in the electromagnetic spectrum as discussed in earlier. But, it can be seen that the changes observed with on-board systems are within the uncertainties of PICS-based observations and these drifts are not statistically significant at 95% confident interval.

Thus, the comparative analysis shown in this section indicates that with the design improvements made to OLI with careful placement of spectral bandpasses, the degree of performance exhibited by vicarious methods can equal on-board methods. However, although solar diffusers provide a reference to a convenient and mostly invariant source without the need to account for an atmosphere, they are prone to degradation over time due to repeated ultraviolet exposure and therefore a vicarious technique is needed not only to complement the on-board systems but also as a backup in case of failures in the on-board systems. The history of Landsat instruments has shown that on-board systems have been subject to their own drifts, and PICS-based observations have been used to validate their performance, especially Landsat 5 TM and Landsat 7 ETM+. With OLI design improvements, the level of precision for gain stability as monitored by vicarious sources such as PICS is much better than any of the earlier Landsats and has made PICS based methods more attractive than ever.

Figure 8. Estimated Gain change in OLI using different methods.



5. Conclusion

Radiometric calibration of the reflective bands of Landsat sensors has improved steadily since the program began in 1972. This paper has outlined the improvements that have occurred with the workhorse sensors of the system – Landsat 5, 7 and 8. Initially, efforts focused on the development of onboard systems as the sole capability for calibration as shown with the Landsat 5 TM. However, it soon became clear that an independent system for calibration was necessary for success and this has routinely been employed with later Landsats. A greater degree of success has been achieved with Landsat 8 than the other sensors—all calibration sources, both onboard and vicarious, are in good agreement. Both onboard systems and vicarious methods have a fundamental difficulty that needs to be overcome. Onboard systems have achieved greatest success through use of full aperture diffuser systems. However, these systems are subject to degradation from UV exposure. This has been at least partially overcome by using multiple panels such that a working panel is used regularly and a pristine panel is used sparingly to better monitor and understand degradation. Vicarious calibration methods, in this case those that use Earth targets, suffer from needing to deal with atmospheric propagation issues which add to the uncertainties inherent in these methods. Thus, in order to overcome limitations in both methodologies, it is strongly advised that both approaches be routinely employed to assure the highest possible quality for the image data recorded by these sensors.

Results shown in this paper indicate that the level of precision possible with vicarious methods such as PICS is similar to that of onboard calibration systems. This has been made possible by judicious selection of spectral bandpasses and the use of pushbroom technology which results in much higher SNR than previous whiskbroom scanners. Current state of the art suggests that 0.5% precision is possible in all Landsat spectral bands with proper modeling of aerosols at the shorter wavelengths. Thus, a second recommendation from a calibration perspective is to maintain the current spectral bandpasses to achieve this goal along with consideration for an improved narrower bandpass for the SWIR-2 band given the excellent SNR that exists (see Figures 1 and 7). While the outlook is good for Landsat 8 OLI to achieve both the longest lifetime and most accurate calibration of any Landsat sensor, it remains to be seen how the technology in this instrument degrades over time. However, the approach used for radiometric calibration of this instrument remains a major step forward for the program and will serve as an excellent model for future Landsat sensors.

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