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Article

Radiometric Calibration Methodology of the Landsat 8 Thermal Infrared Sensor

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Abstract: The science-focused mission of the Landsat 8 Thermal Infrared Sensor (TIRS) requires that it have an accurate radiometric calibration. A calibration methodology was developed to convert the raw output from the instrument into an accurate at-aperture radiance. The methodology is based on measurements obtained during component-level and instrument-level characterization testing. The radiometric accuracy from the pre-flight measurements was estimated to be approximately 0.7%. The calibration parameters determined pre-flight were updated during the post-launch checkout period by utilizing the on-board calibration sources and Earth scene data. These relative corrections were made to adjust for differences between the pre-flight and the on-orbit performance of the instrument, thereby correcting large striping artifacts observed in Earth imagery. Despite this calibration correction, banding artifacts (low frequency variation in the across-track direction) have been observed in certain uniform Earth scenes, but not in other uniform scenes. In addition, the absolute calibration performance determined from vicarious measurements have revealed a time-varying error to the absolute radiance reported by TIRS. These issues were determined to not be caused by the calibration process developed for the instrument. Instead, an investigation has revealed that stray light is affecting the recorded signal from the Earth. The varying optical stray light effect is an ongoing subject of evaluation and investigation, and a correction strategy is being devised that will be added to the calibration process.

Keywords: Landsat; TIRS; radiometric calibration

1. Introduction

The Thermal Infrared Sensor (TIRS) continues broadband, long-wave infrared measurements of the Earth onboard the Landsat 8 observatory. The instrument operates in a push-broom imaging mode to acquire image data of the Earth in two spectral channels and collects imagery coincident with the Operational Land Imager (OLI) instrument also onboard Landsat 8. TIRS was designed, built and tested at the NASA Goddard Space Flight Center (GSFC) and has been operationally collecting Earth scene thermal infrared imagery since its activation in March 2013.

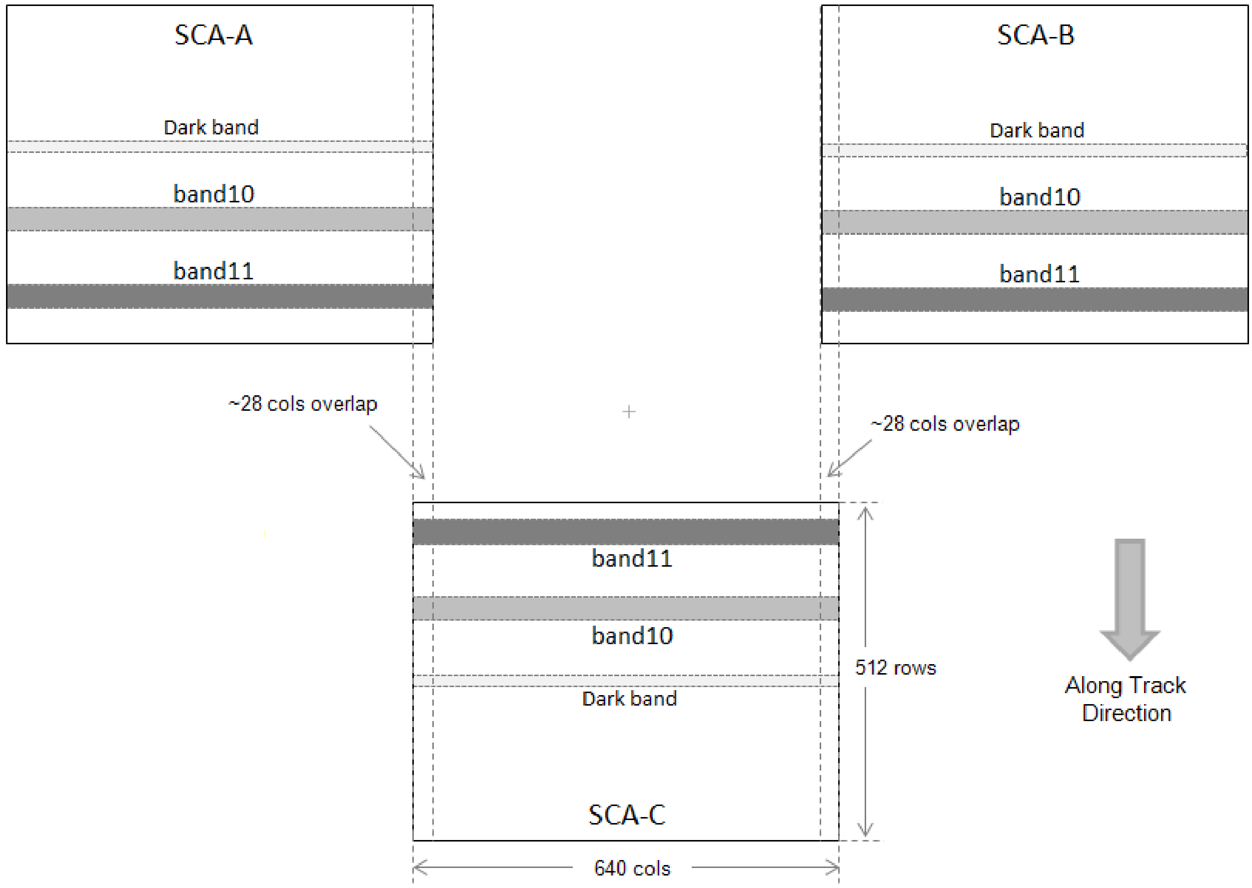
The radiometric calibration process, documented here, is an important aspect of the Landsat 8 mission. The process involves an understanding of how the signal is recorded by the TIRS detectors. Algorithms were developed to convert the raw output from the detectors into an at-aperture radiance. The methods and parameters developed during the pre-flight characterization and testing of the instrument were updated after launch to account for the actual on-orbit operating conditions of TIRS. An optical stray light issue has since been diagnosed that will require a correction to be applied to the calibration process in the future once a solution has been finalized [1]. The stray light affects certain aspects of the calibration, such as uniformity [2] and the absolute radiometric calibration [3].

1.1. Instrument Overview

The TIRS instrument is designed to detect and record long-wave infrared radiance emitted from the Earth. It consists of an optical system, focal plane, onboard calibration sources and the associated electronics and structures. The optical system is made up of a four-element refracting telescope, which produces an f/1.64 beam onto the focal plane. A flat mirror, known as the Scene Select Mechanism (SSM), attached to the front of the telescope is able to rotate through three preset positions. This mechanism allows the telescope to switch between viewing the Earth (nadir), a deep space calibration port or a variable temperature blackbody, known as the on-board calibrator (OBC). A mechanical cryocooler cools the focal plane detectors to less than 40 K. Excess heat from the focal plane is dissipated through a radiator attached to the side of the instrument structure. The telescope optics are held at approximately 186 K by heating elements and a passive radiator [4].

The focal plane is comprised of three Quantum Well Infrared Photodetector (QWIP) arrays, each having 512 by 640 detectors [5]. The imaging arrays are sometimes referred to as sensor chip assemblies (SCAs). Specially designed spectral interference filters are placed over two regions on each array to produce two spectral channels when combined with the QWIP spectral response. Areas of the arrays not containing a filter are masked, so that radiance from the telescope does not reach the detectors. There are approximately 30 rows of detectors in each spectral region. One spectral channel is centered at 10.9 μm with a bandwidth of 0.6 μm and is referred to as Landsat 8 Band 10 (sometimes called the 10.8 band or the 10.9 band). The other channel is centered at 12.0 μm with a bandwidth of 1.0 μm and is referred to as Landsat 8 Band 11 (sometimes called the 12.0 band).

Figure 1. Thermal Infrared Sensor (TIRS) focal plane. The three arrays are known as sensor chip assembly (SCA) -A through -C. For nominal operations, two rows from each of the filtered regions centered at 10.9 μm and 12.0 μm (Band 10 and Band 11, respectively) are read out along with two rows from the masked, or dark region. The final image product contains data from all three arrays stitched together. An optional diagnostic mode will read out all rows from each array.



For normal science imaging, a primary and redundant row of detectors from each filtered region and from the masked region are read off the arrays (six rows total per array) and transmitted to the ground for assembly into the final image product. The placement of the arrays and the spectral filters produce a 15° field-of-view in the across-track direction for each spectral channel. The layout of the focal plane is illustrated in Figure 1.

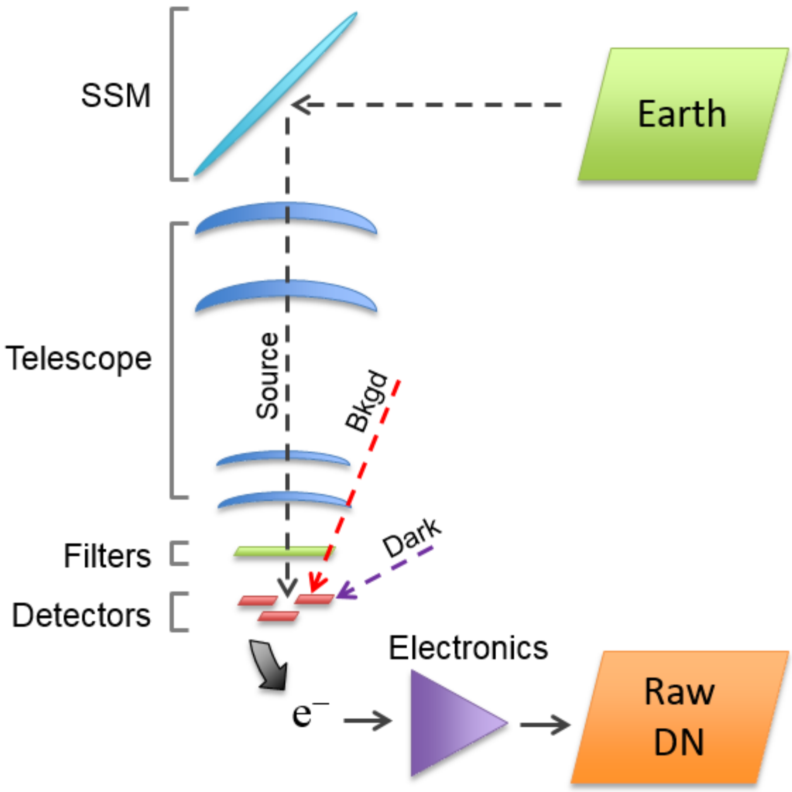
The focal plane also has a diagnostic mode in which nearly all rows from each array are read out instead of the usual six rows. The diagnostic mode is especially useful for the characterization and trending of the rows of detectors in each spectral region that are not used in the final science product. The performance of these detectors are tracked should the need arise to swap the primary row of detectors with another row in the spectral region.

1.2. Overview of the Detected Signal

In order to understand the TIRS radiometric calibration process, an understanding of the way a signal from the Earth is detected by TIRS is needed. The top-of-atmosphere (TOA) radiance from the Earth scene enters the aperture of the instrument and passes through the optical system. The radiance is reflected off the flat SSM mirror and then passes through the telescope, which focuses the incoming photons onto the focal plane. Radiance passes through one of the two spectral interference filters that transmit only photon wavelengths between roughly 10.6–11.2 μm for the Band 10 filter and 11.5–12.5 μm for the Band 11 filter. The filtered radiance then strikes the QWIP detector material, where electrons are produced and captured.

The instrument optics and structure will also emit photons according to the Planck function, since they have a non-zero temperature. The self-emitted radiance of the optical path impinges on the detectors and produces a measureable signal in the arrays. This represents a background signal that will always be detected, even when the at-aperture radiance is zero. In addition, the thermal energy of the detector and electronics will produce electrons in the detector material. This signal, known as the dark signal or dark current, is greatly mitigated by actively cooling the focal plane. The telescope optics are also thermally controlled in order to keep the background signal stable. The stability of the background and dark signals are essential to the calibration process.

Figure 2. Diagram indicating the three major energy paths (the source, the background and the dark signal) reaching the detectors and contributing to the recorded raw signal.



The electrons generated in the detector material from all three energy paths (Figure 2) are recorded by the read-out electronics of the detectors. The analog-to-digital converter and downstream electronics then condition and digitize the signal to produce 12-bit digital numbers to represent the recorded signal on each detector. Header information, such as acquisition time, integration time, *etc*., is added to each line of raw image data after which ancillary data is interleaved with the image data by the observatory. Ancillary data includes instrument temperatures, voltages, ephemeris data, attitude data and other instrument and observatory telemetry. TIRS science data, as this dataset is known as, is saved onboard the observatory and transmitted to Earth when in view of ground stations. Ground processing takes place at the USGS Earth Resources Observation Systems (EROS) Data Center [6]. Using the developed calibration algorithms, the image data from the arrays are combined and the raw digital values converted into spectral radiance for each detector. Image data are then geo-located to produce Worldwide Reference System 2 (WRS2) Earth scenes of an approximately 185 by 180-km area on the ground per scene [7]. The data product available to users is rescaled to 16-bit integers that can be converted back into spectral radiance using the coefficients available in the image metadata [8].

2. Radiometric Calibration Process

The radiometric calibration process involves converting the raw signal from a detector into the expected at-aperture spectral radiance. The raw signal is expressed as 12-bit digital numbers as a result of the focal plane electronics. The at-aperture radiance is the spectral radiance in units of W/m^2/sr/μm that enters the aperture of the TIRS instrument. The relationship between spectral radiance and digital number is found for every detector in both TIRS spectral bands. There is a three-step process to convert the raw signal in digital counts into spectral radiance.

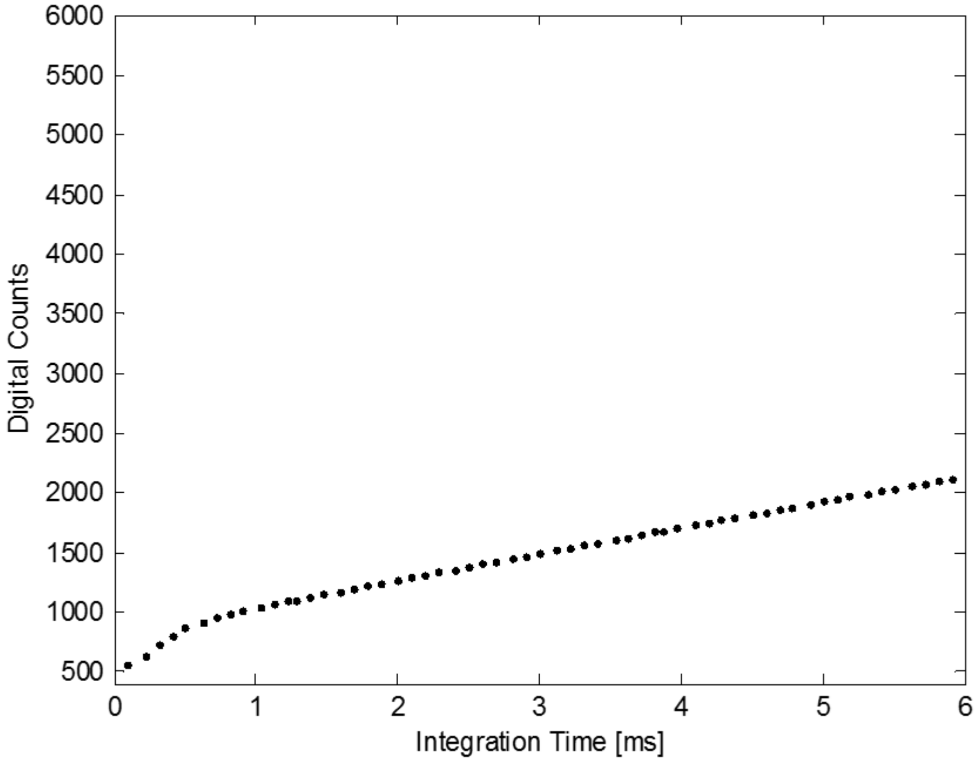
2.1. Linearization

The raw signal in terms of digital numbers is produced by electronics that have a non-linear response. This means that there is not a strictly linear relationship between the electrons in the detector and the output signal. The gain of the read-out electronics is dependent on how many electrons have been produced in the detector material. For TIRS, there are essentially two separate regimes where the gain is linear (*i.e.*, the read-out response is piece-wise linear), as illustrated with the integration time sweep data in Figure 3. As electrons are produced in the detector, the output signal is the result of a particular linear gain. Then, as the number of electrons in the detector material reach a certain point (about 10% of detector well capacity), the resulting output signal is produced by a different linear gain (roughly $\frac{1}{3}$ to $\frac{1}{4}$ of the original gain). In order to correctly compare two different signals detected from the two different gain regimes, the digital counts produced from one gain regime must be translated into counts that would have been produced by the other gain regime.

In the integration time sweep data from the instrument shown in Figure 3, the detector was integrated in time steps of 0.1 milliseconds. As time increases, background photons and dark current produce an increasing amount of electrons in the detector material. The time axis on the figure (representing electrons) is linear, while the digital number axis (representing the output signal) is roughly piece-wise linear. The change in response around the 1000 count level is due to the transition from the lower gain regime to the upper gain regime.

A linearization algorithm is necessary to transform the raw digital counts into "linearized counts" in which the ratio of a change in electron level to a change in output counts (*i.e.*, the gain) is constant over the dynamic range of the detector. All TIRS data must be linearized before any further processing.

Figure 3. Integration time sweep data for one detector. Three regions are noticeable in the data: a lower linear gain region, an upper linear gain region and a non-linear transition region between the two linear regions.



2.2. Background Removal

As described previously, the recorded digital number from the detectors represents the signal, not only from the desired Earth scene, but also the signal from the self-emitted radiance of the instrument and the signal from the thermal energy of the detectors and electronics. The background and dark current are undesirable signals that must be removed in order to isolate the signal produced by the at-aperture radiance.

The characterization of the background and dark responses can be accomplished by viewing a zero-radiance source. In such a configuration, the only signal recorded by the detector is the background signal from the instrument optical path and the dark current from the detector and electronics. If the instrument is thermally and electrically stable between the collection of the zero-radiance frame, known as the "background frame", and the source (Earth) image, then the change in the background and dark responses are zero, and the subtraction of the background frame is sufficient to remove the self-emitted signal from the instrument. The result of the background-subtraction calibration step will be digital counts that represent the source only. This can be expressed as,

$$\begin{aligned} Signal &= (Source\,frame) - (Background\,frame) \\ &= (source + background + dark) - (background + dark) \\ &= source - \Delta background - \Delta dark. \end{aligned} \tag{1}$$

Operationally, the stability of the background signal between the collection of background frames is checked periodically on-orbit through special calibration collections and through instrument temperature telemetry. In addition, a dark band line is read off the arrays for every image line from TIRS. This band is monitored for changes on a line-by-line basis in between collections of the background frames. A change in the dark band (*i.e.*, the dark signal) would be an indication of a similar change in the spectral bands. Should this be the case, the change in counts from the dark band may be subtracted from the counts in the spectral bands to remove the fluctuation in the dark signal from the spectral bands. For analyses on the stability of the background and dark signals, refer to [2].

2.3. Relation to Radiance

The result of the linearization and background removal steps is the at-aperture source signal represented as "linearized, background-subtracted counts". These counts must now be related to the absolute spectral radiance entering the instrument aperture. To develop such a relationship, the counts are recorded for a range of known spectral radiance entering the TIRS aperture. The counts-radiance dataset is a look-up table (LUT) that can be used to convert counts into the expected at-aperture radiance. A uniform blackbody-like source at a well-known temperature is sufficient to calculate a known spectral radiance to illuminate the instrument aperture. The spectral radiance of the source is calculated from the recorded temperature of the source (from temperature sensors on the source) along with the Planck blackbody function and known source emissivity to generate a spectral radiance curve for the given source temperature. The incident radiance on the detector is then given by the Planck radiance multiplied by the emissivity and then multiplied per wavelength by the relative spectral response (RSR) of the detector and integrated over the wavelength. This is expressed as,

$$L_i(T) = \frac{\int \epsilon(\lambda) \cdot B(\lambda, T) \cdot R_i'(\lambda) \cdot d\lambda}{\int R_i'(\lambda) \cdot d\lambda} \quad (2)$$

where $B(\lambda, T)$ is the Planck function, $\epsilon(\lambda)$ is the emissivity of the source, $R_i'(\lambda)$ is the relative spectral response of the detector and $L_i(T)$ is the integrated radiance in units of W/m^2/sr/μm.

The process of recording the detector counts (at a fixed integration time and detector bias voltage) for a given input radiance is repeated for a range of source temperatures. The result is an integrated incident spectral radiance per detector for each source temperature along with the associated measured linearized, background-subtracted count. This LUT is stored for every detector, and a linear interpolation may be used between the measured points in the table to convert the detected counts into the expected spectral radiance.

3. Pre-Flight Radiometric Calibration

TIRS was characterized during the pre-flight environmental testing campaign at NASA/GSFC. The instrument was placed in a thermal-vacuum (TVAC) chamber to simulate the expected range of environmental conditions that it would experience on-orbit. Calibration ground support equipment (CGSE) was incorporated into the pre-flight testing in order to assist in the pre-flight characterization of the instrument. The CGSE contained a wide-aperture blackbody source, known as the "Flood source", which filled the entire field-of-view of TIRS and provided the known at-aperture radiance for the instrument. The CGSE and the TVAC chamber were chilled to liquid nitrogen temperature (<100 K) to limit the environmental background signal entering the TIRS aperture. The optics and focal plane temperatures were held at the approximate values required for normal operation on-orbit. The primary purpose of the environmental testing was to demonstrate the functionality and survivability of the instrument for all expected on-orbit conditions. Science calibration datasets were obtained in between systems testing.

3.1. Radiometric Calibration Data

The raw signal from the detectors is a function of the integration time and the bias and offset voltages for the focal plane arrays. The integration time and voltages were set to values, such that the detectors would provide a sufficient signal without saturating for the required range of source temperatures (240 K–360 K) [9]. The nominal integration time for TIRS is approximately 3.4 ms.

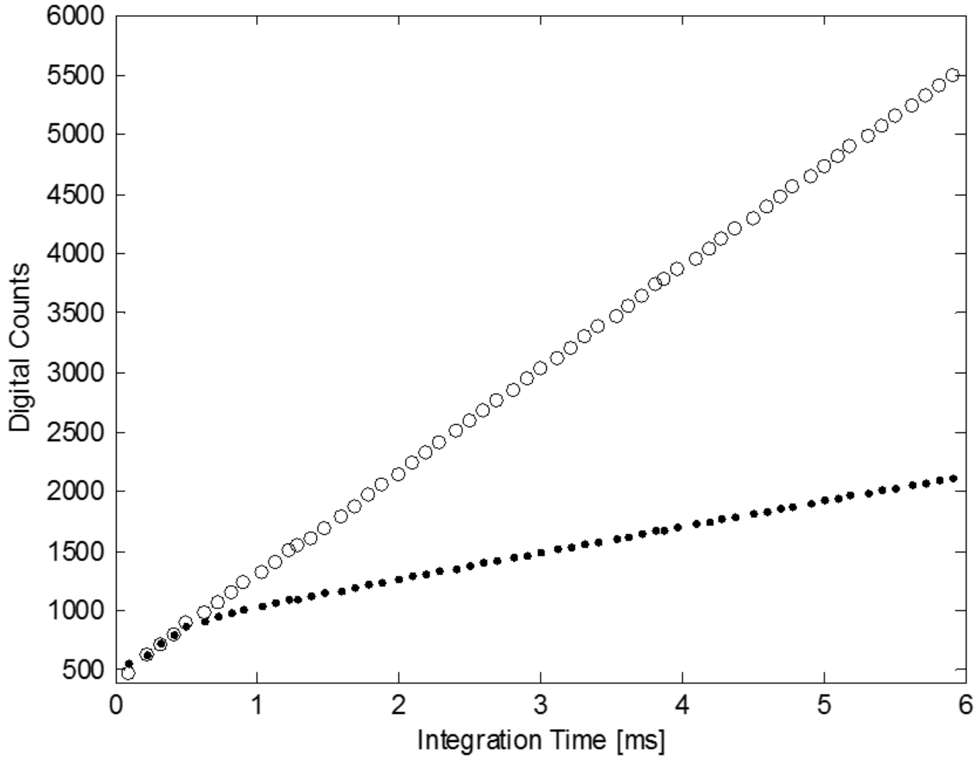
The first required dataset in the calibration process is a set of parameters required for linearization. The goal of the linearization process is to convert the two detector gain regimes into a single regime in which the gain (or change in digital number with change in signal) is the same regardless of the source signal. Integration time sweep data provides the necessary dataset for the linearization process. Data observed from a low radiance source (the CGSE background) was sufficient to observe the change from the lower gain regime to the upper gain regime in both TIRS spectral channels.

The linearization algorithm accepts raw digital counts for a detector and transforms the data, such that a change in count value is constant over the dynamic range of the detector. The integration time sweep data has three distinct regions: a lower linear region, an upper linear region and a transition region between the lower and upper regions. The data points in each region are fit with a quadratic function that relates raw counts into the new linearized count space. The linearization algorithm will determine the appropriate quadratic function to use based on the value of the raw count to be linearized. The application of the algorithm to integration time sweep data for one detector is shown in Figure 4.

The lower gain region was chosen as the regime to be held fixed in the linearization process, since it is the region that is common across the two spectral bands and the dark band. The low signal in the dark band only produces counts in the lower gain region. Should it become necessary to use the dark band counts to correct the two spectral bands (recall Section 2.2), the counts from all bands must be in the same gain regime. As such, all raw data from the detectors are linearized before any further processing utilizing a set of quadratic coefficients.

The second half of the calibration process involves the removal of the instrument background and the development of the radiance LUT. The deep space view port serves as the near-zero radiance source to characterize the background signal. While operating on-orbit, the SSM mirror turns so the instrument views deep space, which has a temperature of approximately 0 K. The signal on the detectors is therefore only the background and dark signal. In the TVAC chamber, a liquid nitrogen-cooled plate served as a substitute for deep space. The cold plate, with a temperature of less than 100 K, produces a signal that is less than 0.005% of the signal of a 300-K blackbody source in the TIRS spectral channels. This signal is negligible for TIRS.

Figure 4. Example of applying the linearization algorithm to integration time sweep data for one detector. The original raw digital counts are shown as black dots, while the associated linearized counts are shown as open circles. The linearization algorithm transforms the detector gains into the gain of the lower response region.



The CGSE Flood source served as the known at-aperture radiance for TIRS. A typical data collection would involve obtaining a deep space collection followed by an acquisition of the Flood source at a specified temperature. All image data of the Flood source is linearized and then background-subtracted with the associated deep space frame (nearest in time to the Flood source collection). These linearized, background-subtracted counts exist for ten Flood source temperatures of 240 K, 250 K, 270 K, 290 K, 300 K, 310 K, 320 K, 330 K, 345 K and 360 K, which span the required sensitivity range of TIRS [9].

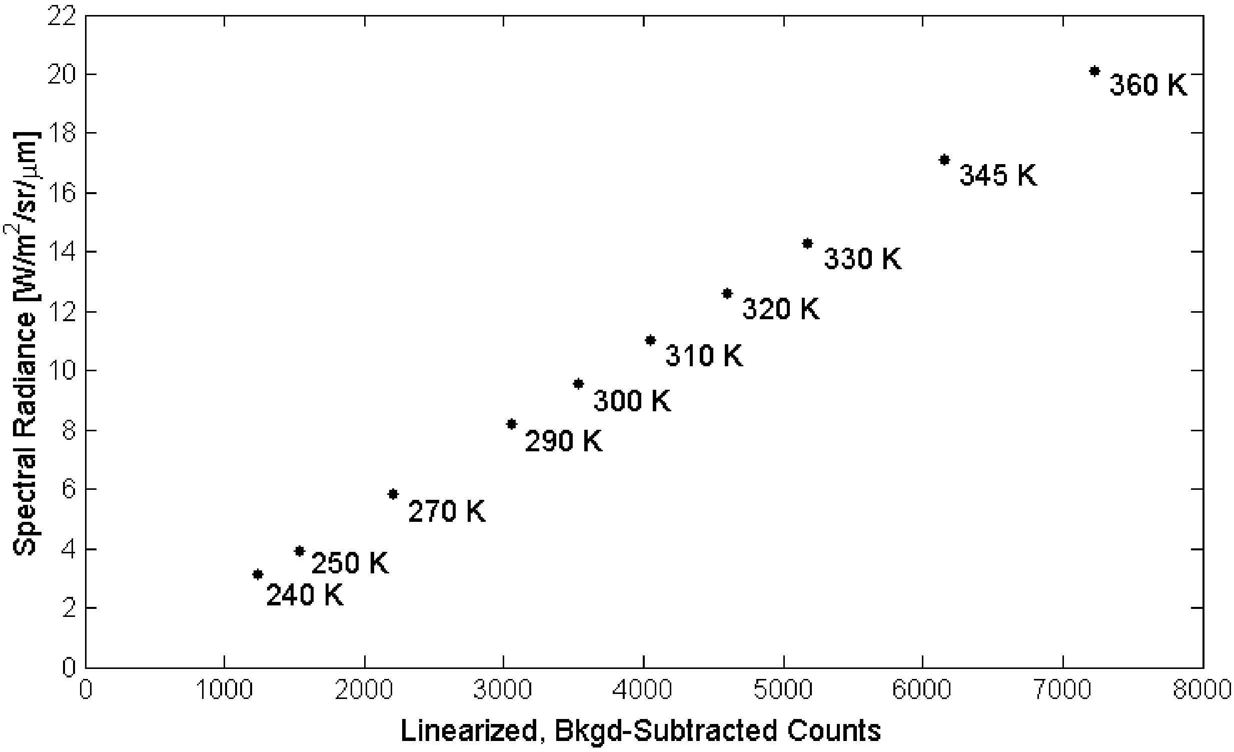
To obtain a relationship between counts and spectral radiance, the expected spectral radiance of each of these Flood source measurements must be calculated for every detector. The Flood source was subsequently calibrated to a National Institute of Standards and Technology (NIST) standard at the Space Dynamics Laboratory (SDL) in Logan, UT, in the fall of 2012. The results of that calibration campaign revealed that the Flood source behaved as a blackbody with a 0.992 emissivity that was spatially and spectrally invariant over the spectral range of the two TIRS bands (approximately 9.0 μm to 13.0 μm). The calculated uncertainty in the radiance output of the Flood source at a given temperature is 0.3% [10].

The expected radiance is calculated by computing the spectral radiance of the Flood source at the given temperature through the Planck blackbody function. The temperature sensors on the Flood source give the temperature of the source. The emissivity of the Flood source (as measured by SDL) is taken as 0.992 for all wavelengths. The band relative spectral response (see Section 3.2) is then multiplied per wavelength and integrated to arrive at the expected radiance for the band for the given source temperature. The appropriate values are inserted into Equation (2) and are expressed as,

$$L_b(T_{Flood}) = \frac{\int 0.992 \cdot B(\lambda, T_{Flood}) \cdot R_b'(\lambda) \cdot d\lambda}{\int R_b'(\lambda) \cdot d\lambda} \quad (3)$$

where $L_b(T_{Flood})$ is the integrated incident spectral radiance for the spectral band at a given Flood source temperature, $R_b'(\lambda)$ is the relative spectral response of the band and $B(\lambda, T_{Flood})$ is the Planck radiance at the given blackbody (Flood source) temperature. The integrals are calculated by the trapezoid numerical integration scheme. An example of the relationship between counts and radiance for the range of recorded source temperatures is shown in Figure 5. The LUT for each detector provides the means to convert linearized, background-subtracted counts into an at-aperture spectral radiance.

Figure 5. Calculated incident spectral radiance for ten source temperatures as a function of the measured source signal (linearized background-subtracted counts) for one detector in the 10.9 μm band (Band 10) on the center focal plane array (SCA-C) from measurements taken during the instrument pre-flight thermal-vacuum (TVAC) campaign.



3.2. Spectral Response

For Equation (3), the band average relative spectral response (RSR) is needed to calculate the predicted integrated radiance from the blackbody calibration source. The RSR for TIRS was constructed from component-level measurements of the various elements of the optical system and the focal plane arrays and verified during instrument-level testing on a small sample of detectors. This section focuses on the combined spectral responses of the science row detectors.

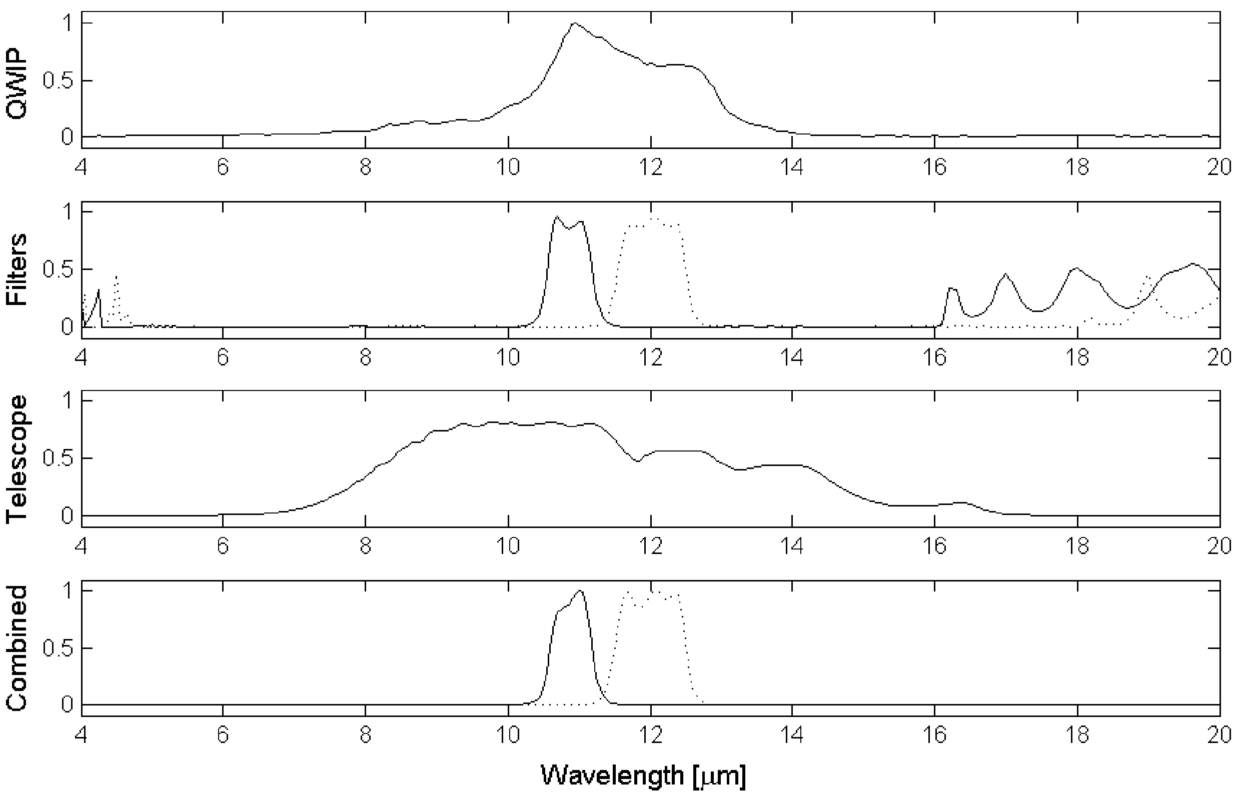
The relative conversion efficiency of each QWIP array was measured by the Detector Characterization Laboratory at NASA/GSFC. The in-band response of every detector was measured over a wavelength range of 7–15 μm at operational cryogenic temperature. The out-of-band response was measured for the average of all detectors on each array over a wavelength range of 1.8 μm to 20 μm. For the RSR measurements needed for the TIRS calibration process, the in-band responses of the detectors that make up the primary and redundant science detectors in the image product are taken from the measured dataset.

The filter spectral transmissions were designed to produce the desired band shape for the two TIRS spectral channels when combined with the QWIP spectral response. The filter vendor then constructed the transmission of the filters to match the desired design as close as possible. Iterations between the manufacturer and the TIRS project continued until the transmission spectrum was agreed upon. The design of the filter was based on only the QWIP response and did not take the telescope transmission into account.

The transmission of the spectral interference filters were measured and provided by the filter vendor. The spectral transmission at five locations on the wafer from which the individual filters were cut were measured at ambient temperature. These measurements were scaled to the spectral transmissions at the operational cryogenic temperature based on measurements from a witness sample at ambient and cryogenic temperatures. Subsequent measurements at NASA/GSFC of the witness sample at ambient and cryogenic temperatures confirmed the vendor measurements.

The spectral transmission of the separate telescope lenses were measured at NASA/GSFC at their operational temperature of approximately 185 K. The product of the measurements from the three

Figure 6. Spectral responses of the TIRS system. From top to bottom: average peak-normalized response of the Quantum Well Infrared Photodetectors (QWIPs); average peak-normalized transmission of the two spectral interference filters; transmission of the telescope lenses; combined average peak-normalized response of each TIRS spectral channel.

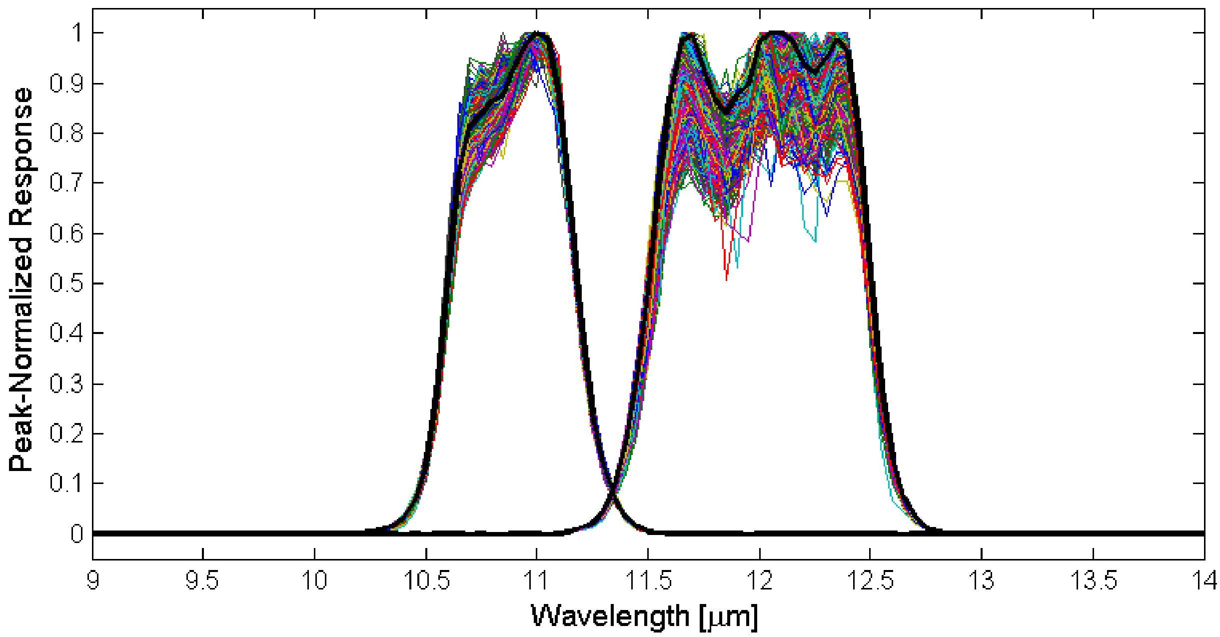


germanium (Ge) lenses and the one zinc selenide (ZnSe) lens yields the combined transmission of the telescope.

The spectral responses of the various elements in the optical system are shown in Figure 6. The QWIP response curve is the average response for all detectors. The QWIP and filter responses have been normalized to the peak response. The telescope transmission is the combined product of the transmissions of the four lenses. Finally, the average combined response of the two TIRS channels are shown. These combined band responses are used as the relative spectral responses for the two TIRS channels in the radiometric calibration calculations (Equation (3)) and are also made available to the user community [11].

The relative spectral response varies slightly from detector to detector. The RSR of all detectors in both bands are shown in Figure 7. The average peak-normalized response of the bands is also illustrated in the figure. The variation of band shape for each detector can be quantified by calculating the integrated radiance of each band shape from a blackbody at a typical Earth temperature. The radiance can be compared to the integrated radiance calculated by using the band average response. From a 300 K blackbody, the maximum variation of an individual detector from the band average response is approximately 0.05% in Band 10 and 0.2% in Band 11.

Figure 7. Relative spectral responses of all detectors that make up the primary and redundant science rows in the final TIRS image product. The black curves indicate the band average relative responses used in the radiometric calibration process. Data values for the band relative spectral responses are available to users on the NASA Landsat website [11].



3.3. Radiometric Calibration Uncertainties

The uncertainty in the conversion process can be estimated from the uncertainties of several components of the radiometric process. Performing a linear interpolation between counts in the counts-to-radiance LUT will produce radiance accuracy of approximately 0.4% in the worst case. The

NIST traceability of the Flood source radiance is accurate to within 0.3%. The count data in the look-up table is slightly sensitive to the temperature of the focal plane electronics. Over the maximum temperature range expected on-orbit, the counts may change by 0.4%. The error introduced by the slightly different spectral band shapes for each detector produces an uncertainty of about 0.2% in the worst case. Combining these uncertainties yields an overall radiometric uncertainty for the ground-based measurements of approximately 0.7%.

3.4. Implementation of Calibration Method

The calibration process is implemented in the USGS/EROS ground processing system. All raw image data is first linearized. The average of the deep space data collected before and after an Earth collection interval is used as the background frame for that interval. To facilitate processing, the aforementioned LUT is separated out into separate processes. A linear function is fit to each detector's LUT. The slope, intercept, and residuals of this fit are known as the gain, the gain-offset, and the second-linearization, respectively. The second-linearization is a LUT of linearized counts; the gain-offset is in units of linearized counts, and the gain is in units of radiance per linearized count. In the processing flow, the linearized counts from the background frame (deep space) are subtracted from the linearized counts from the Earth scene. The gain-offset is then added, followed by the counts from the second linearization LUT. Finally, the gain is applied to convert the adjusted counts into radiance. The radiance data is then geo-located and rectified to the WRS2 grid [12]. The standard Landsat Earth scene images available to users are expressed as 16-bit integer numbers and must be rescaled to spectral radiance using the provided coefficients in the image metadata.

4. On-Orbit Operation and Post-Launch Adjustments

For normal on-orbit operation, TIRS uses the SSM to view the deep space port and the OBC before and after every Earth collection interval. The space/OBC collection takes under five minutes to perform, whereas a typical Earth interval may last up to approximately 36 minutes. The background frame is updated every time the deep space port is viewed. Any changes in the instrument background that might occur will therefore be subtracted out in the ground processing using the average of the deep space collections that bracket an Earth acquisition interval. The image data from the OBC are used to monitor the stability of the radiometric response of the instrument. The OBC is normally fixed around 295 K, but can be set to temperatures from roughly 270 K to 320 K. The stability of the background and dark signals, as well as the response stability to the OBC are continuously monitored on-orbit [2].

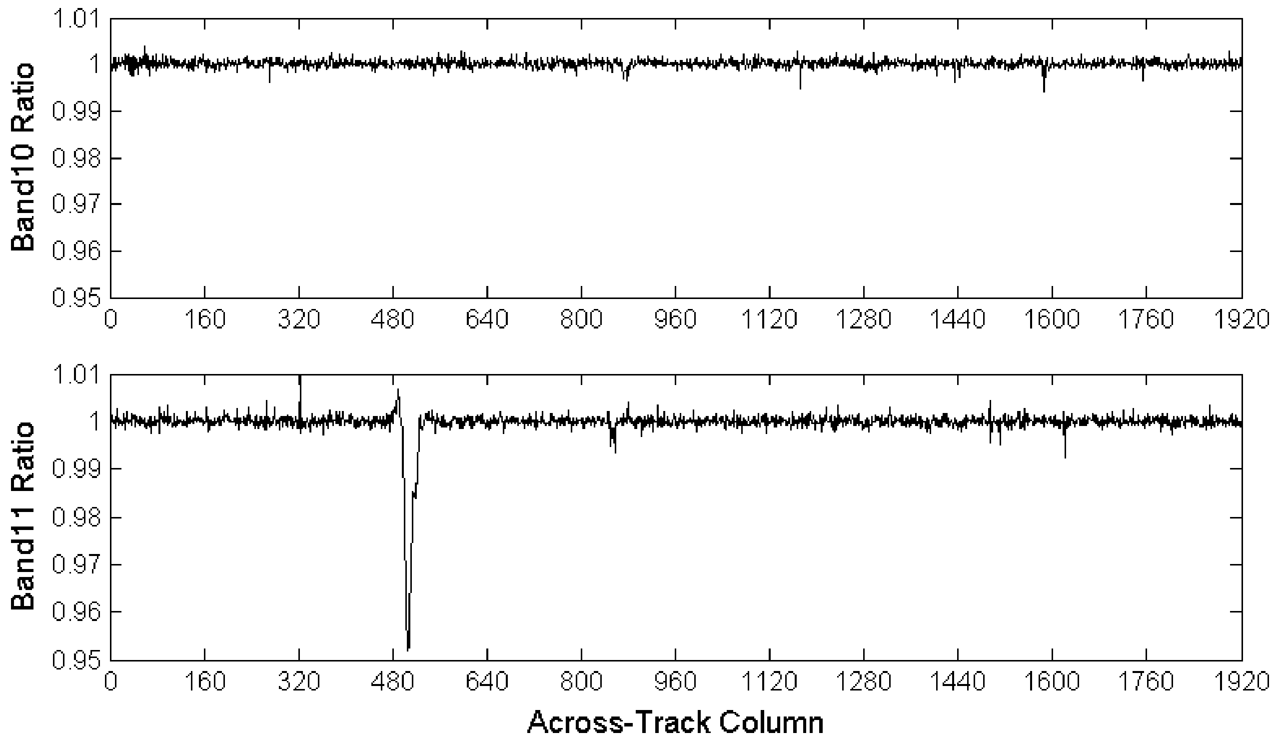
Following launch and activation in February 2013, the calibration of the instrument was evaluated. The actual operating conditions on-orbit, such as the instrument electronics temperatures, structure temperatures, *etc*., were slightly different than the conditions in the thermal-vacuum chamber during pre-flight testing, as expected. Therefore, the calibration parameters derived from the pre-flight measurements required modification for the actual on-orbit performance.

The existing linearization algorithm was first checked with the on-orbit measurements. Integration time sweeps collected on-orbit were linearized with the pre-launch linearization routine. It was determined that no update was required for the linearization function, since the pre-launch algorithm successfully linearized the on-orbit data.

A series of relative corrections were then made to the pre-flight counts-to-radiance LUT in order to correct for striping in the imagery without affecting the absolute calibration of the instrument. The OBC served as a convenient means to track changes in the TIRS performance through launch, as similar data collections of the OBC were obtained both pre-flight and on-orbit. Linearized, background-subtracted counts were collected for the OBC at six set point temperatures between approximately 270 K and 320 K in steps of 10 K. For the pre-flight collections, the deep space views of the TVAC cold plate served as the background frames. For the on-orbit collections, the nominal collection of the deep space port served as the background frames. In both cases, the actual temperature of the OBC was slightly different due to the different environmental conditions between the TVAC chamber and on-orbit (the differences were less than one degree). The on-orbit OBC collections were interpolated to the same source temperature as the pre-flight collections to minimize signal differences due to blackbody temperature.

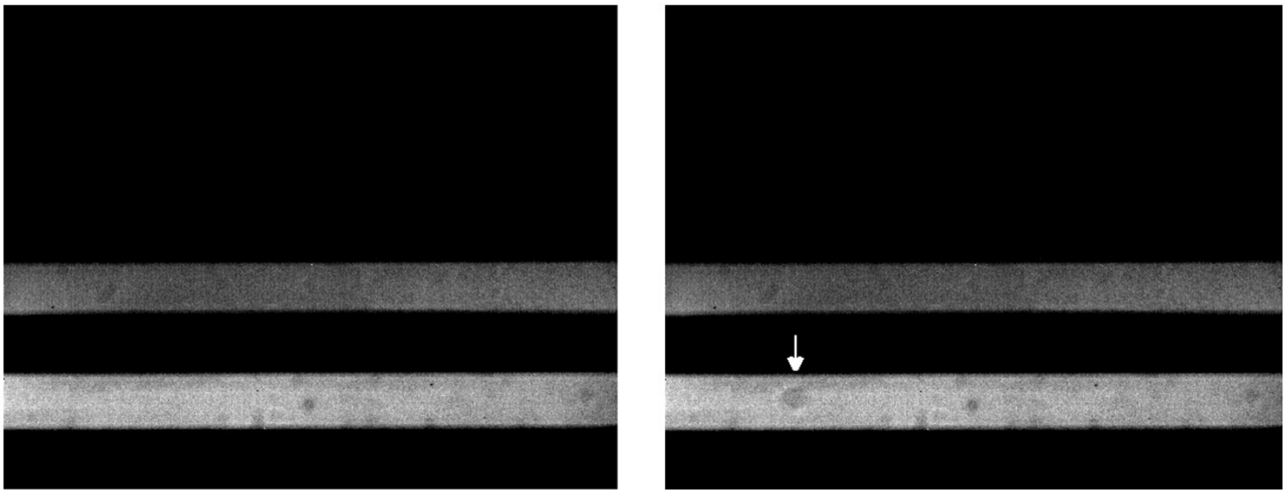
For each OBC temperature, the difference between the on-orbit and the TVAC collection was calculated for every detector. The difference, or offset, was removed from the on-orbit OBC collections, and the ratio of the offset removed on-orbit collection to the TVAC collection was computed. This ratio (Figure 8) represents the relative differences between the pre-flight and on-orbit response of TIRS, meaning that a given detector has become either more or less sensitive than its neighbor.

Figure 8. Ratio between the pre-flight on-board calibrator (OBC) measurement in TVAC and the on-orbit OBC data for Band 10 (**top**) and Band 11 (**bottom**). The 5% drop in the ratio on Band 11 around Column 500 is due to contamination that developed on the Band 11 spectral filter.



The large decrease in the average ratio value in the Band 11 graph in Figure 8 is due to contamination discovered on the Band 11 filter that occurred sometime between the last pre-flight measurements and activation on-orbit. It was checked by comparing a diagnostic collection of the arrays pre-flight and post-launch (Figure 9). The effect of the contamination will be continuously tracked over time and, so far, has remained unchanged.

Figure 9. Diagnostic readout of SCA-A from pre-flight (**left**) and on-orbit (**right**). Each image contains the 640 columns of the detectors for the array. The upper bright band is the detectors illuminated by the Band 10 spectral filter, while the lower bright band is the detectors illuminated by the Band 11 spectral filter. The dark areas are detectors that are masked out and do not receive light from the telescope. The arrow indicates the area of contamination on the Band 11 filter that appeared after launch.



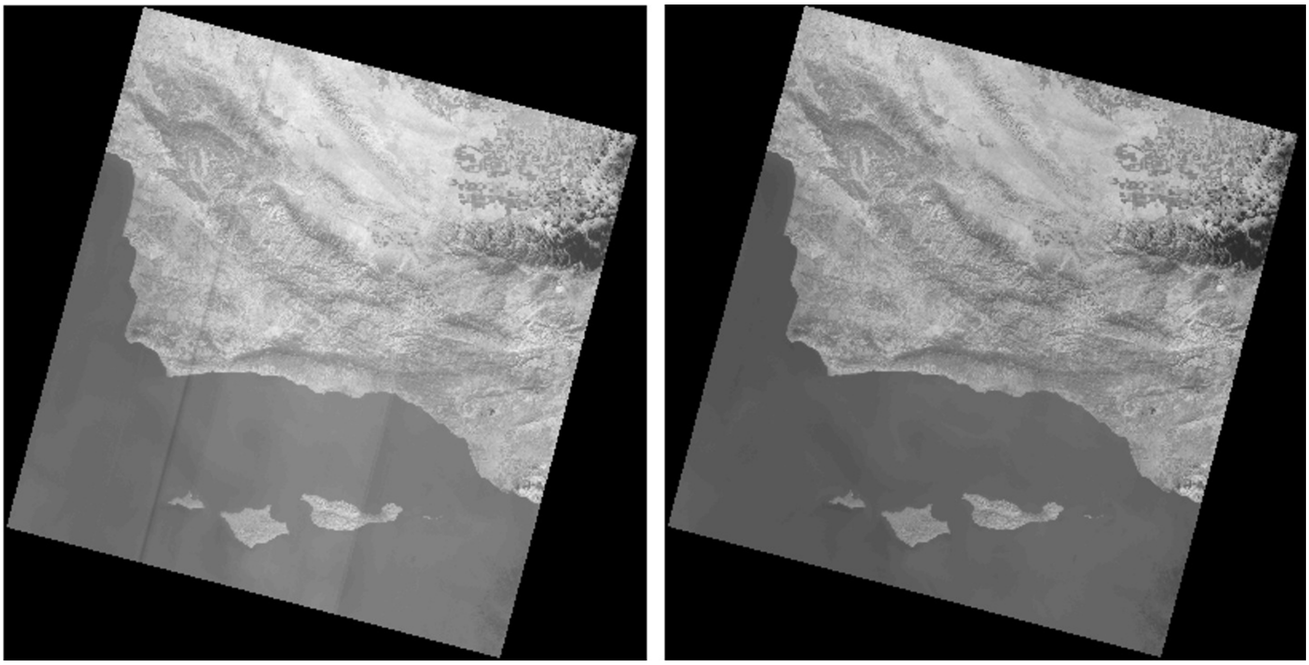
To adjust the calibration to compensate for the contamination and other detector relative differences, the OBC ratio is applied to the counts in the counts-to-radiance LUT, while keeping the radiance values in the table constant. The adjustment serves to cancel out any large relative changes of the TIRS response between pre-flight and on-orbit.

In addition to the relative correction derived from the OBC comparison, other relative corrections were implemented that were based on Earth imagery in an attempt to removal residual striping. The first utilized data was obtained during the Earth-calibration maneuver. During this collection, the entire spacecraft is yawed 90° such that the across-track direction of the focal plane is now parallel to the direction of travel, as opposed to being perpendicular to the direction of travel in normal push-broom imaging [13]. Thus, each detector is theoretically scanned over the same spot on the ground, which in effect presents a uniform field to the detectors. A relative correction can then be derived from this dataset and was applied on top of the relative correction derived from the OBC comparison.

Further minor relative corrections were derived from Earth scene data. Detector image data were averaged over uniform Earth scenes to produce relative corrections on the order of less than 0.5% on top of the previously performed adjustments. An additional modification was made to the mean level of each focal plane array to force them to report the same value when viewing a uniform scene at different radiance levels.

The net result of the relative calibration adjustments was to remove the large differences that occurred through launch (e.g., the effect of the contamination on the Band 11 filter) and to make TIRS image data as uniform as possible over uniform Earth scenes. A comparison of an Earth scene processed with the pre-flight calibration parameters *versus* the adjusted parameters from the on-orbit checkout is shown in Figure 10.

Figure 10. TIRS Band 11 scene of WRS2 Path/Row 042/036 (25 September 2013) calibrated with the pre-flight calibration parameters (**left**) and with the adjusted parameters based on the characterization data collections during the on-orbit checkout (**right**). The on-orbit calibration adjustment removed large striping effects in the TIRS imagery.



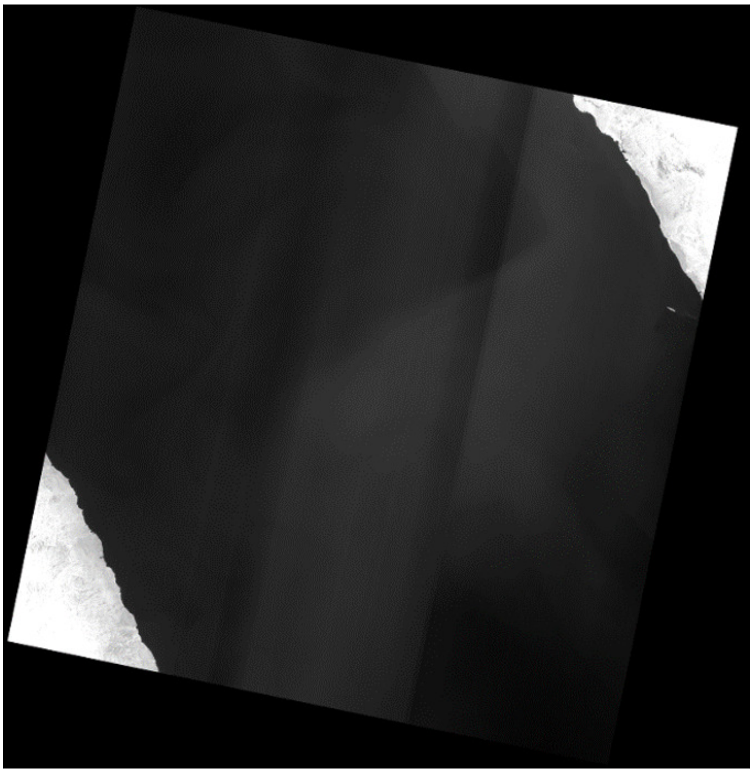
5. Current Status

The radiometric response stability of the instrument has been tracked continuously since activation using the on-board calibration sources. All indications from this dataset are that the TIRS instrument is thermally and electrically stable [2]. There have been, however, two anomalies that have been observed that require further investigation.

5.1. Uniformity

The relative calibration adjustment discussed previously has removed large striping artifacts in most TIRS Earth scenes. However, other Earth scenes have exhibited a particular artifact, known as banding, which refers to low frequency variation in the across-track direction from scenes that are expected to be uniform. Prime examples of Earth scenes expected to be essentially uniform are open water scenes in which the water near the overlap between adjacent focal plane arrays should have nearly the same temperature and should therefore report the same radiance on both arrays if properly calibrated. A representative Earth scene where this is not true is the Red Sea in the Middle East (WRS2 Path 173, Row 41), as shown in Figure 11.

Figure 11. TIRS Band 11 image of Path/Row 173/41 (14 August 2013) in the Red Sea. The image data from the three focal plane arrays is evident due to banding in the across-track direction that varies in the along-track direction.



The non-uniform effect across the field-of-view (FOV) is 2.5% or greater and also varies in the along-track direction. This variation is not caused by any internal instability within TIRS, since all indications are that the noise and radiometric stability is well behaved. Furthermore, no relative adjustment to the calibration would successfully remove the varying banding in the along-track direction.

It has been determined that stray light is the cause of the banding issues. Unwanted signals from outside the FOV are entering the optical system and add to the direct line-of-sight signal recorded by the focal plane arrays. The stray light produces a non-uniform signal across the arrays depending on the strength of the source from outside the FOV. The investigation of the stray light issue is ongoing, and possible correction strategies are being explored. For a detailed description of this issue, see [1].

5.2. Absolute Radiometric Response

The absolute radiometric response of TIRS is assessed through the use of *in situ* temperature measurements of water bodies. The top-of-atmosphere (TOA) radiance from the water bodies is calculated from the temperature measurements and from atmosphere profile knowledge at the time of data acquisition along with radiative transfer models [14]. The calculated TOA radiance from the water bodies is compared with the TIRS-derived image radiance of the water bodies. An overall difference between the TIRS data and the 'ground truth' is considered an error in the absolute TIRS radiometric calibration.

From data over the first year on-orbit, a varying bias error of approximately 0.29 $W/m^2/sr/\mu m$ in Band 10 and 0.51 $W/m^2/sr/\mu m$ in Band 11 has been observed. The source of the absolute calibration error is now understood to be the same stray light issue mentioned previously. The extra stray light radiance is adding a varying signal to the focal plane. Until a complete correction has been devised, an interim adjustment to the absolute calibration has been implemented to partially correct for this bias error for typical Earth scenes during the mid-latitude growing season. For a detailed treatment of the absolute calibration for TIRS, refer to [3].

6. Summary

To ensure the scientific objectives of the Landsat 8 mission, the TIRS instrument was calibrated pre-flight and adjusted post-launch. A calibration methodology was developed pre-flight to convert the raw output from the instrument into an accurate at-aperture spectral radiance. TIRS requires a detector linearization step followed by a background subtraction step and, finally, a conversion to radiance through the use of a calibration look-up table. Measurements to support the calibration procedure were obtained from component-level characterization during the build-up of the instrument and from instrument-level characterization during the pre-flight environmental TVAC testing.

During the instrument checkout period following launch, on-orbit calibration data was obtained, which allowed for the adjustment of the pre-flight calibration parameters to match the actual on-orbit operating conditions. This adjustment, based on comparisons of the OBC and on Earth image data, served to remove large differences that are observed as striping artifacts in Earth imagery. Subsequently, a season-varying absolute calibration error was noticed from vicarious calibration data that could not be explained by standard calibration adjustments. Furthermore, banding artifacts observed in certain Earth scenes could also not be accounted for by usual calibration adjustments. Ensuing analyses have concluded that stray light has been affecting the TIRS instrument, which has caused the banding and absolute calibration errors. Once the stray light issues have been corrected for, the relative adjustments described in this document will be reassessed and an update to the overall calibration of TIRS will be implemented.

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Author Contributions

All authors contributed to this text.

Conflicts of Interest

The authors declare no conflict of interest.

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