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Article

On-Orbit Radiometric Performance of the Landsat 8 Thermal Infrared Sensor

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Abstract: The Thermal Infrared Sensor (TIRS) requirements for noise, stability, and uniformity were designed to ensure the radiometric integrity of the data products. Since the launch of Landsat 8 in February 2013, many of these evaluations have been based on routine measurements of the onboard calibration sources, which include a variable-temperature blackbody and a deep space view port. The noise equivalent change in temperature (NEdT) of TIRS data is approximately 0.05 K @ 300 K in both bands, exceeding requirements by about a factor of 8 and Landsat 7 ETM+ performance by a factor of 3. Coherent noise is not readily apparent in TIRS data. No apparent change in the detector linearization has been observed. The radiometric stability of the TIRS instrument over the period between radiometric calibrations (about 40 min) is less than one count of dark current and the variation in terms of radiance is less than 0.015 $W/m^2/sr/\mu m$ (or 0.13 K) at 300 K, easily meeting the short term stability requirements. Long term stability analysis has indicated a degradation of about 0.2% or less per year. The operational calibration is only updated using the biases taken every orbit, due to the fundamental stability of the instrument. By combining the data from two active detector rows per band, 100% detector operability is maintained for the instrument. No trends in the noise, operability, or short term radiometric stability are apparent over the mission life. The uniformity performance is more difficult to evaluate as scene-varying banding artifacts have been observed in Earth imagery. Analyses have shown that stray light is affecting the recorded signal from the Earth and inducing the banding depending on the content of the surrounding Earth surface. As the stray light effects are stronger in the longer wavelength TIRS band11 (12.0 μm), the uniformity is better in the shorter wavelength band10 (10.9 μm). Both bands have exceptional noise and stability performance and band10 has generally adequate uniformity performance and should currently be used in preference to band11. The product uniformity will improve with the stray light corrections being developed.

Keywords: Landsat; TIRS; performance; noise; stability

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1. Introduction

The Thermal Infrared Sensor (TIRS) is the thermal imaging instrument onboard the Landsat 8 observatory. The sensor was designed to continue broadband, long wave infrared measurements of the Earth for the Landsat program. In a change from previous Landsat instruments, TIRS operates in a push-broom mode to acquire image data of the Earth in two thermal channels. The instrument was designed and built at the NASA Goddard Space Flight Center to be incorporated as a payload on the Landsat 8 mission. TIRS has been operationally collecting Earth scene thermal infrared imagery since its activation in March 2013.

The radiometric performance of the instrument since activation on-orbit is documented here. Performance metrics for noise and stability were evaluated based on various data collects of the TIRS onboard calibration sources. Uniformity performance is more difficult to evaluate since banding artifacts have been observed in TIRS Earth scene imagery due to stray light effects [1]. Corrections for the stray light are currently being developed that are expected to greatly improve uniformity performance.

1.1. Instrument Overview

The TIRS instrument is comprised of a four-element telescope that directs an f/1.64 beam onto the focal plane. A flat mirror known as the scene select mechanism (SSM) is attached to the front of the telescope and rotates through three preset positions. This mechanism allows the telescope to switch between viewing the Earth, the deep space calibration port, or the variable temperature blackbody known as the on-board calibrator (OBC). The focal plane is actively cooled to less than 40 K by a mechanical cryocooler. The cooler dissipates excess heat through a radiator attached to the side of the instrument structure. The telescope optics are held at approximately 186 K and are passively cooled through a similar radiator [2].

The focal plane consists of three Quantum Well Infrared Photodetector (QWIP) arrays each containing 512 by 640 detector elements [3]. Spectral interference filters are placed over two regions on each array to produce two spectral channels when combined with the QWIP spectral response. One of the filters produces a band sensitive between roughly 10.6 and 11.2 μm while the other filter produces a band between 11.5 and 12.5 μm. The filtered regions result in approximately 30 rows of detectors on the array for each region that possess the desired spectral band shape. The rest of the array is masked so that radiance from the telescope does not reach the detectors.

For imaging in the standard push-broom mode, only two rows from each of the two filtered regions along with two rows from the masked or 'dark' region are read out at a frame rate of 70 Hz. The two rows of detectors from each region allow for a primary and redundant row of image data so that individual detectors from the primary row that do not meet specifications are swapped with the corresponding detectors in the redundant row. The row image data from all three arrays are combined during ground processing to produce an instrument swath width of approximately 185 km (15° field-of-view) with a detector ground sample distance of approximately 100 m. The image data are geo-rectified and located to the standard Worldwide Reference System 2 (WRS2) grid in the final product released to the public [4]. The TIRS band data are referred to as Landsat 8 "band10" and "band11", which correspond to the 10.9 μm and the 12.0 μm channels, respectively. All ground processing takes place at the USGS Earth Resources Observation Systems (EROS) Data Center [5,6].

1.2. Radiometric Calibration

The calibration process, summarized here, was developed during the pre-flight environmental testing to convert raw signal from the detectors into an accurate at-aperture radiance. A linearization step is performed first to ensure that the detected signal from the focal plane arrays is linear with photons. Next, a background frame is subtracted from Earth imagery to remove the effects of dark current and instrument self-radiance. Finally, the background-subtracted data is converted to radiance through the use of a look-up table that was constructed from pre-flight measurements of a uniform NIST-calibrated blackbody source. During the on-orbit checkout period immediately following launch, the TIRS relative calibration was updated to account for the actual on-orbit operating conditions. Trends in instrument performance are continuously tracked since the calibration process requires that the instrument is thermally and electrically stable. For a full treatment on the calibration of the TIRS instrument, refer to reference [7].

The basic on-orbit calibration procedure involves subtracting a background frame from Earth data in order to remove the self-emitted thermal signal and the dark signal from the instrument. TIRS uses the SSM to view the deep space port and the OBC before and after every Earth collection interval. The deep space collect serves as the required background frame since the only signal recorded on the detectors in this configuration is the background signal of the instrument (deep space has a near-zero temperature) and the dark current in the detectors. The space/OBC collect takes under five minutes to acquire whereas a typical Earth interval may be approximately 36 min in duration. 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 two background collects that bracket the Earth acquisition. This procedure depends on the stability of the instrument response between collections of the background frame. That is, the instrument background signal must not significantly change during an Earth collection interval. Otherwise the background frames obtained before and after the Earth interval would not be sufficient to properly remove the background signal from the Earth image data.

In addition, for every line of band10 and band11 image data obtained, a line of dark band data is also acquired simultaneously. The dark band data provides a means to track the stability of the dark current signal throughout the Earth collection interval. If the dark band is found to vary significantly during the Earth interval, the difference in dark band counts may be subtracted from the band10 and band11 image counts to compensate for the dark signal variation in the arrays.

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. TIRS also periodically performs special calibration acquisitions including collecting deep space and OBC data continuously for 36 min and collecting a series of space/OBC collects over the course of an orbit and a half. These special collects of the onboard sources provide an indication of the instrument response stability during an Earth collection interval.

2. Instrument On-Orbit Performance

The noise and stability performance of TIRS are of particular interest since the accuracy of the calibration process depends on the stability of the instrument. Any instability in the instrument response might manifest itself as unwanted variations or artifacts in the final image product.

2.1. Noise

The variation of a detected signal over time while viewing a stable source is generally referred to as noise. Although noise can be evaluated several ways, three different metrics are discussed here.

2.1.1. Noise Equivalent Change in Radiance/Temperature

A common way to express the noise is in terms of a change in radiance, known as the noise equivalent change in radiance or NEdL. The NEdL requirement for TIRS is that the detector standard deviation in terms of radiance over a uniform WRS2 scene (about 25 seconds of image data) must be ≤0.059 $W/m^2/sr/\mu m$ for band10 and ≤0.049 $W/m^2/sr/\mu m$ for band11 [8]. The noise can also be expressed as a temperature change known as the noise equivalent change in temperature (NEdT) by converting the radiance data into a brightness temperature and computing the standard deviation.

The NEdL and NEdT for TIRS were calculated from OBC collects at temperatures of approximately 270 K, 300 K, and 320 K. Each frame of the OBC acquisition is converted to radiance using the standard calibration routine implemented in the ground processing system [7]. The NEdL is taken as the standard deviation of 1750 frames (or 25 seconds of image data) for a particular detector. Figure 1 shows the result of the NEdL calculations at a source temperature of 300 K along with the requirement limit. Data from all on-orbit OBC source temperatures exhibited similar performance to the 300 K result. Additionally, although the OBC is only able to operate between temperatures of roughly 270 K to 320 K on-orbit, during pre-flight thermal-vacuum testing of the instrument the NEdL (and similarly the NEdT) was measured with an external blackbody in the vacuum chamber at a low temperature of 240 K. The NEdL value for this case along with the OBC computations obtained on-orbit are summarized in Table 1. The NEdL is less than approximately 0.008 $W/m^2/sr/\mu m$ for all cases.

Figure 1. NEdL for all detectors in each band calculated from OBC data at a temperature of 300 K. The requirement limits of 0.059 and 0.049 $W/m^2/sr/\mu m$ for band10 and band11, respectively, are indicated on the graph.

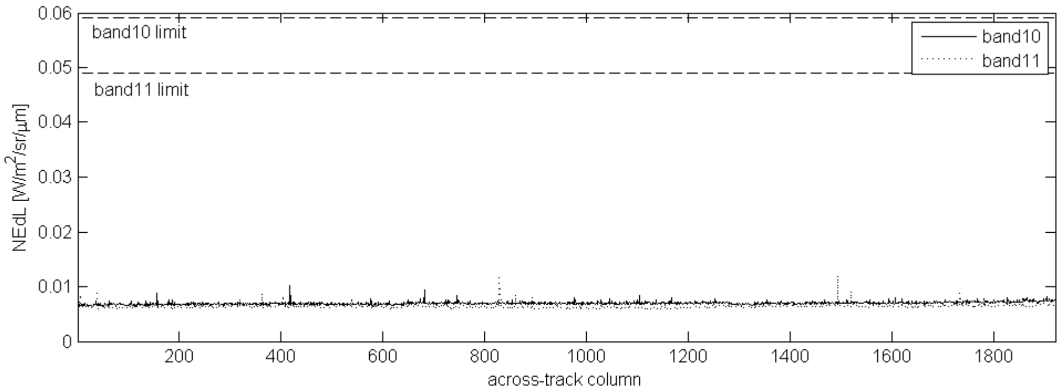


Table 1. Average NEdL for all detectors calculated for the source temperatures indicated. All NEdL values are in units of radiance ($W/m^2/sr/\mu m$). * Note that the NEdL values for the 240 K source temperature are based on pre-flight external blackbody measurements.

Source	Band 10		Band 11	
Temperature	Measured	Requirement Limit	Measured	Requirement Limit
240 K *	0.0054	0.059	0.0053	0.049
270 K	0.0062	0.059	0.0058	0.049
300 K	0.0070	0.059	0.0064	0.049
320 K	0.0075	0.059	0.0072	0.049

Similarly, the radiances of each frame of the OBC collects are converted to a brightness temperature and the standard deviation of 1750 frames for a particular detector is taken as the NEdT. Figure 2 shows the results of the NEdT calculation for a source temperature of 300 K. The other source temperatures yielded similar results and are summarized in Table 2. The data demonstrate that the NEdT of TIRS is approximately 0.05 K (@ 300 K) for all detectors across the field of view, which is well below the requirements.

Figure 2. NEdT for all detectors in each band calculated from OBC data at a temperature of 300 K. The requirement limit of 0.4 K is indicated on the graph.

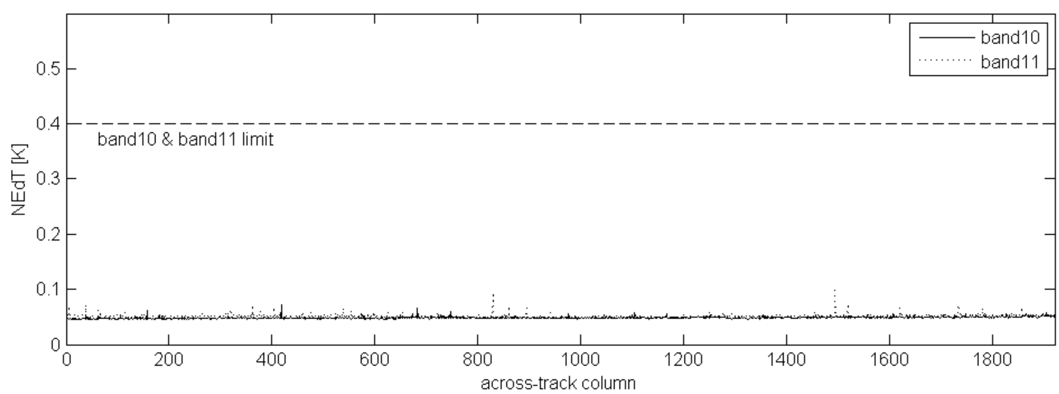


Table 2. Average NEdT for all detectors calculated for the source temperatures indicated. All NEdT values are in units of temperature (K). * Note that the NEdT values for the 240 K source temperature are based on pre-flight external blackbody measurements.

Source	**Band 10**		**Band 11**	
Temperature	**Measured**	**Requirement Limit**	**Measured**	**Requirement Limit**
240 K *	0.074	0.80	0.078	0.71
270 K	0.057	0.56	0.060	0.53
300 K	0.049	0.40	0.052	0.40
320 K	0.045	0.35	0.051	0.35

2.1.2. Coherent Noise

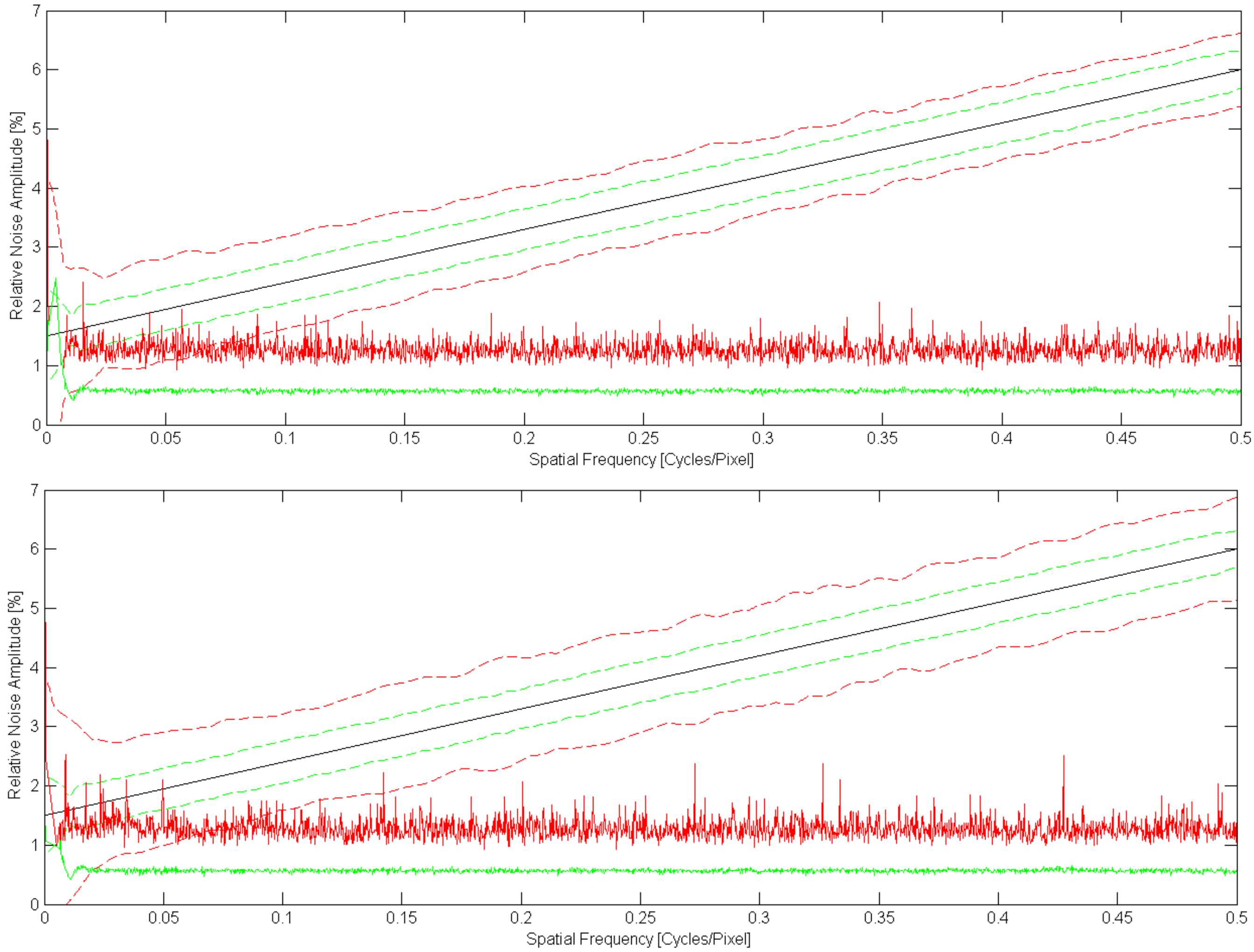
Coherent noise (CN) appears as a repeating artifact in imagery particularly noticeable in dark uniform scenes [9]. The artifact is usually caused by a susceptibility of the instrument electronics to either themselves or to external electromagnetic sources. The CN for TIRS is monitored on-orbit utilizing deep space and OBC data. A frequency domain analysis is performed on the data to determine what spatial frequencies exhibit amplitudes above the artifact visibility threshold. The analyses report the level of the coherent noise as a relative noise amplitude expressed as a percentage from the 3σ response. The 3σ response is an approximation for half of the dynamic range in the scene evaluated.

The baseline artifact visibility threshold is a linear function with frequency that is derived from the human visual sensitivity function known as the contrast sensitivity function [10]. It is defined as

$$Threshold\,(f) = 9 \cdot f + 1.5 \tag{1}$$

where f is the spatial frequency in units of cycles per pixel. The worst cases of the CN relative magnitude for each frequency are shown in Figure 3. These results were computed from the OBC data from all detectors. The two solid lines in the figure represent the best (green) and worst (red) case noise level among frequencies that were suspected to hold coherent noise (frequency components above the noise floor). Those best and worst case CN curves were produced by condensing the results from all 1920 detectors in each band after finding for each frequency sample the maximum and minimum CN levels from all individual sets of frequency domain responses from multiple collects throughout the year. The locus of all maximum points at all frequencies from all detectors and datasets represents the worst CN and the locus of all minimum points at all frequencies from all detectors and datasets represents the best CN. The solid black line represents the artifact visibility baseline threshold (from Equation (1)). The two dotted lines above the baseline threshold are the noise-floor-adjusted artifact visibility thresholds and the two dotted lines below the baseline threshold are the noise-floor-adjusted invisibility threshold lines based on the best (green) and worst (red) noise floor between all the detectors. The CN that will result in a visible artifact in the data would require multiple detectors with the noise amplitude above the upper two noise-adjusted threshold lines. Analysis of the TIRS data over the first year of operation has not revealed any concern for coherent noise.

Figure 3. Best and worst case coherent noise over all detectors for band10 (**top**) and band11 (**bottom**). The red solid line represents the worst case coherent noise and the green solid line represents the best case noise. The solid black line represents the artifact baseline (via Equation (1)). The upper two dotted lines are the noise-floor-adjusted *visibility* thresholds for the best case (green) and the worst case (red). The lower two dotted lines are the noise-floor-adjusted *invisibility* thresholds for the best case (green) and the worst case (red).



2.2. Stability

The radiometric stability of TIRS depends on the stability of the background and dark signals during Earth imaging. As mentioned in Section 1.2, the background-subtraction step of the radiometric calibration process depends on the background and dark signals remaining constant between the collections of space/OBC data. To monitor this on-orbit, special collects are obtained in which deep space port data is recorded continuously for 36 min (151,200 frames in total). This time interval is a typical length of time between the space/OBC collects. The variation of the space (*i.e.*, background) signal and of the dark band (*i.e.*, dark current) signal over this time would be an indication of the induced radiometric error added to an Earth collection due to background and dark current drift.

2.2.1. Dark Band Variation over 36 Min

The dark band for TIRS serves as an indication for the variation of dark current during an Earth image collection interval. The standard deviation of the dark band counts over the field-of-view for the 36 min deep space collection is shown in Figure 4. The 1σ variation of the dark band is approximately 0.55 counts, which implies a stable dark current. Figure 5 illustrates the deviation of the average dark count over time. Each data point represents the difference between the average dark count for the frame versus the average dark count for the first frame and indicates that there is no discernable trend in the dark counts over the 36 minutes. As mentioned previously (Section 1.2), a trend in the dark band counts over an Earth collection interval would imply a trend in the dark current that similarly affects the illuminated bands in which case the dark band information may be used to adjust the counts in band10 and band11. The dark data seen during the on-orbit operation of TIRS thus far indicate that this correction is not necessary.

Figure 4. Standard deviation for all detectors in the dark band in terms of counts over continuous 36 minutes of image collection.

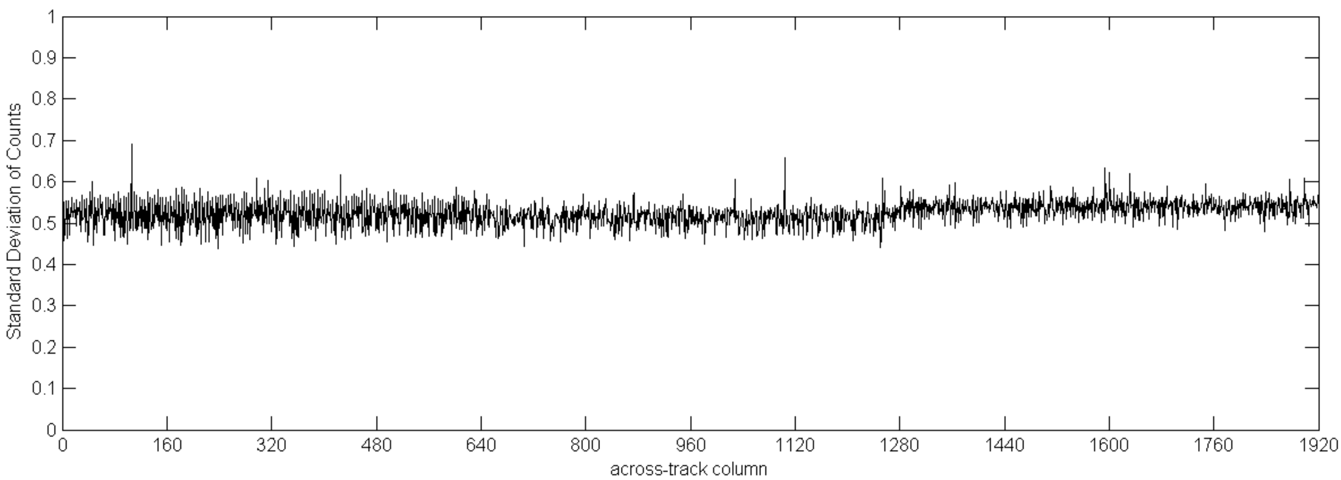
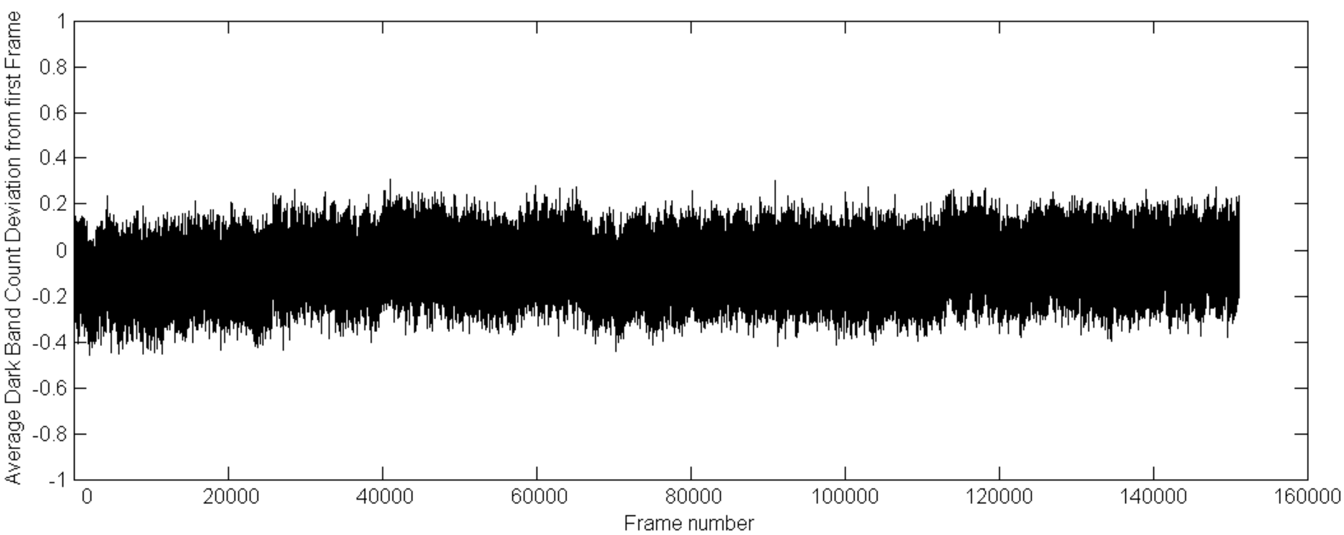


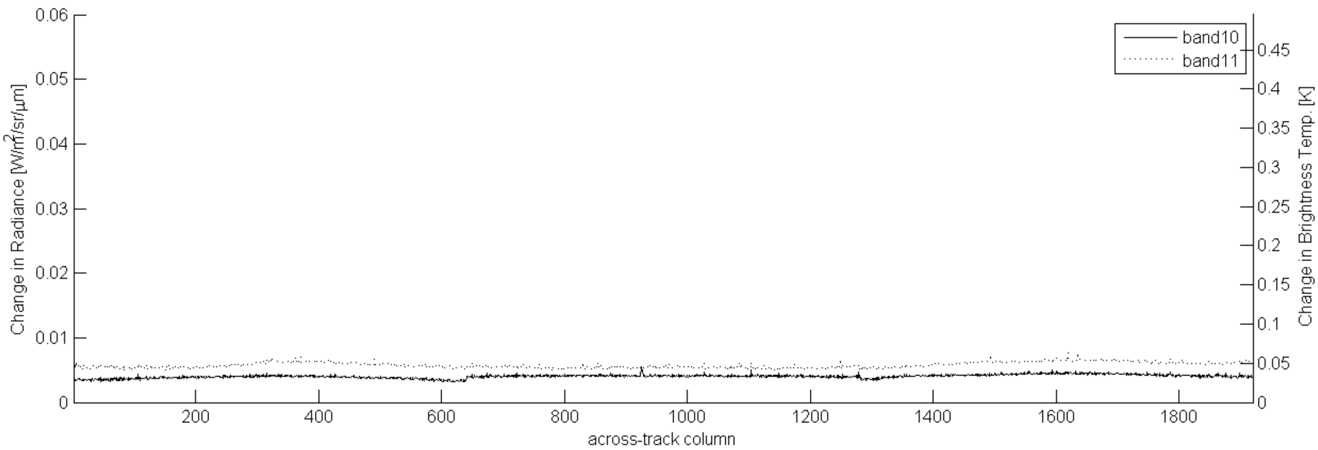
Figure 5. Average counts for the entire dark band over continuous 36 minutes of image collection (151,200 frames).



2.2.2. Background Variation over 36 Minutes

Whereas the dark band serves as an indication of dark current variation, the image data from the 36 min deep space collect serve as an indication of the stability of the instrument response to low background signals. Figure 6 illustrates the variation of the background in band10 and band11 expressed as a radiance change at 300 K. Similarly, this variation can be expressed as a change in brightness temperature at 300 K. The data indicate that the background variation during the time interval between typical space/OBC collects is about 0.005 $W/m^2/sr/\mu m$ for the worst case. This value is roughly the same as the calculated value of the NEdL.

Figure 6. The variation of radiance (1σ) in both bands while viewing deep space continuously for 36 minutes of image collection. The approximate change in brightness temperature is shown on the right hand axis.



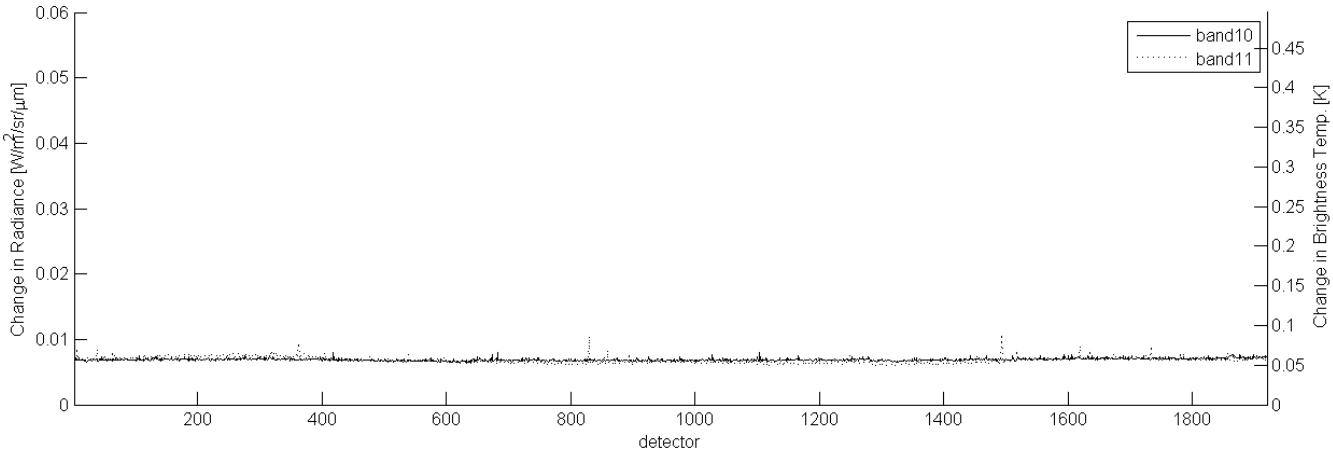
2.2.3. OBC Signal Variation over 36 Minutes

The radiometric stability also involves the variation of the TIRS response to a constant source. A second special collection consisted of staring at the OBC at a temperature of 270 K for 36 minutes continuously. Each frame of the 36 min collect is converted to radiance. The response variation is illustrated in Figure 7 in terms of the standard deviation of the radiance and in terms of the standard deviation of the equivalent brightness temperature. The variation in response while viewing the OBC is in the order of the NEdL of the instrument (approximately 0.007 $W/m^2/sr/\mu m$). Expressed another way, the 1σ variation in signal in terms of percent of the average radiance is approximately 0.1%. The TIRS requirement states that this variation should not exceed 0.7% [8].

2.2.4. Orbital Stability

Another special collect performed routinely deals with examining the variation of the background and of the response to the OBC over 1.5 orbits (approximately 150 min). Characterizing the amount of background variation is important to the radiometric accuracy of TIRS since any variation of the background signal during the Earth interval will cause the derived radiance of the Earth to vary by the same amount. Since image data of the deep space port cannot be collected simultaneously with the Earth data, this special collect allows for the characterization of the background through multiple Earth intervals.

Figure 7. The variation of radiance (1σ) in both bands while viewing the OBC at a temperature of 270 K continuously for 36 minutes of image collection. The approximate variation in brightness temperature is shown on the right hand axis.



For this collection, a standard space/OBC collect is obtained roughly every eight minutes for 1.5 orbits, which yields 18 space datasets along with 18 OBC datasets. The OBC temperature is held at approximately 295 K over the 1.5 orbits. The variation of the background over the 1.5 orbits was found by taking the mean count (over the one minute of data collection) for each of the 18 space collects. The minimum and the maximum variation of these 18 collects relative to the mean of the 18 collects is calculated in terms of the equivalent change in radiance at 300 K. This variation represents the maximum change of the background for an orbit and is illustrated in Figure 8 for band10 and band11. The variation of the background over the 1.5 orbits is approximately $\pm 0.015\ W/m^2/sr/\mu m$ or ± 0.13 K or $\pm 0.2\%$ for the worst case. Since the background signal can be expected to vary by this amount, the calibrated radiance from the Earth scene can be expected to vary over this range between the collection of background frames (recall Section 1.2).

The variation of the background signal is due to the solar heating and cooling of the instrument over the course of an orbit. Figure 9 demonstrates the average background error for each band as a function of the WRS2 row. In general for this dataset, WRS2 rows 1 through 124 are roughly on the daytime side of the orbit, and rows 125 through 248 are roughly on the nighttime side of the orbit. The data in the graph indicate that the background signal is higher than the average during the day pass of the orbit and is lower on the night pass. This effect is correlated with the temperature of the structure assembly that secures the SSM mirror in place. The solar loading heats the structure, which causes an increase in the optical background signal since the structure is in the optical path and is viewed by the detectors. This increased signal is detected differently by the three focal plane arrays due to their geometry relative to the optical boresight and the SSM structure. This non-uniform background signal variation is evident in the across-track variation seen in Figure 8. Additionally, the magnitude of the variation is greater in band11, again due to the geometry of the detectors viewing the optical system and structure.

Figure 8. The minimum and maximum variation of the band10 (**top**) and band11 (**bottom**) background response of 18 space collects over 1.5 orbits expressed as a difference in radiance from the mean. The approximate change in brightness temperature is shown on the right hand axis.

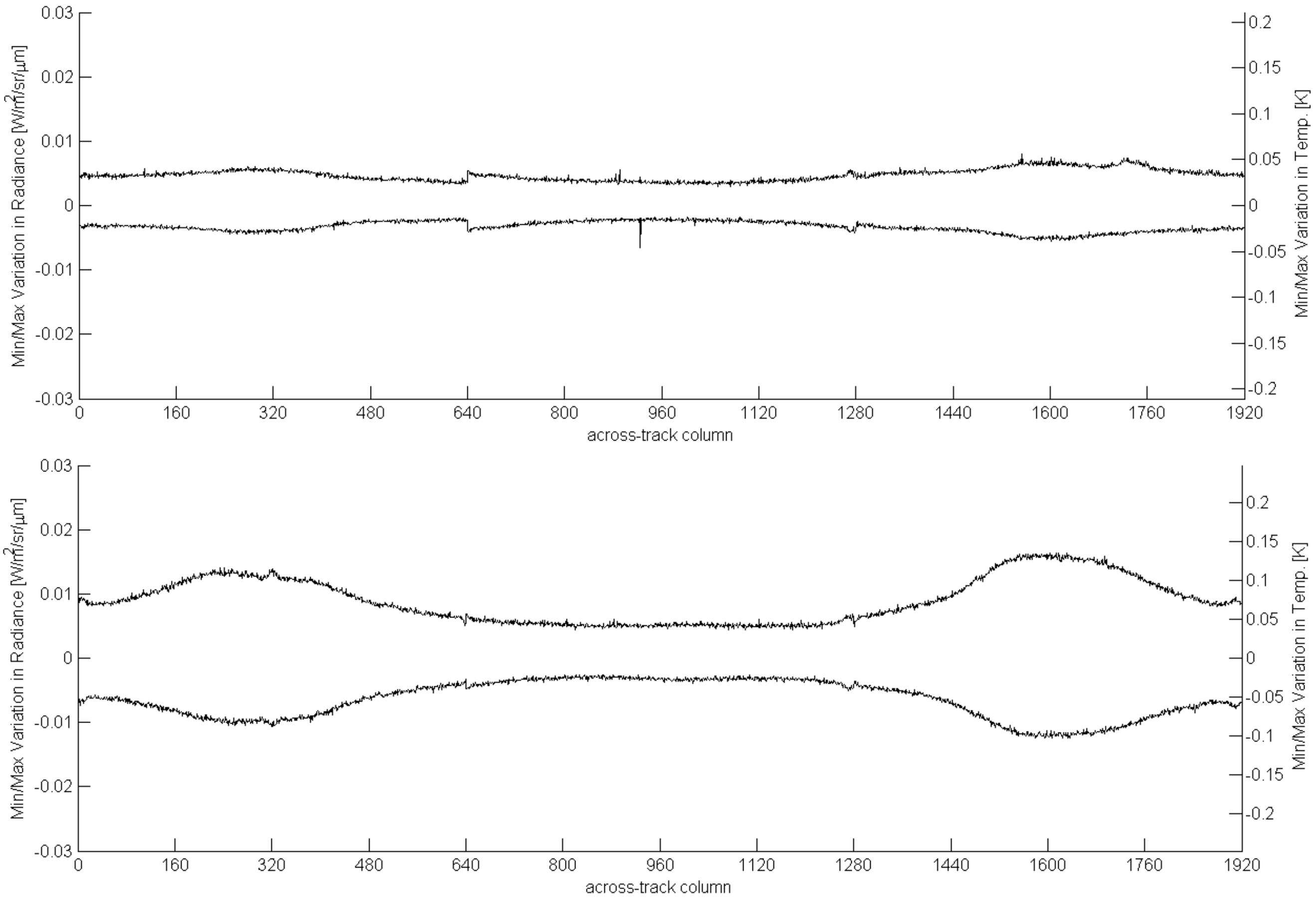
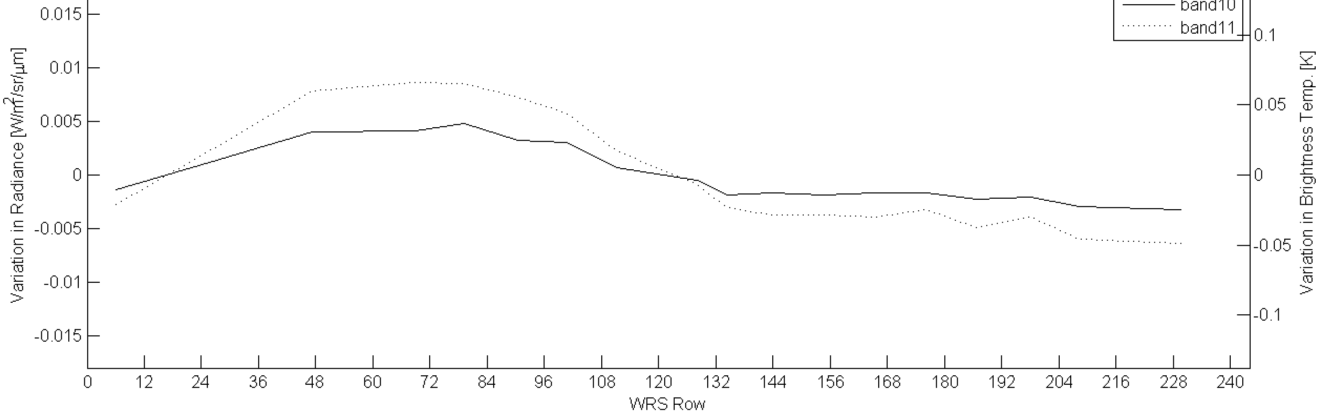
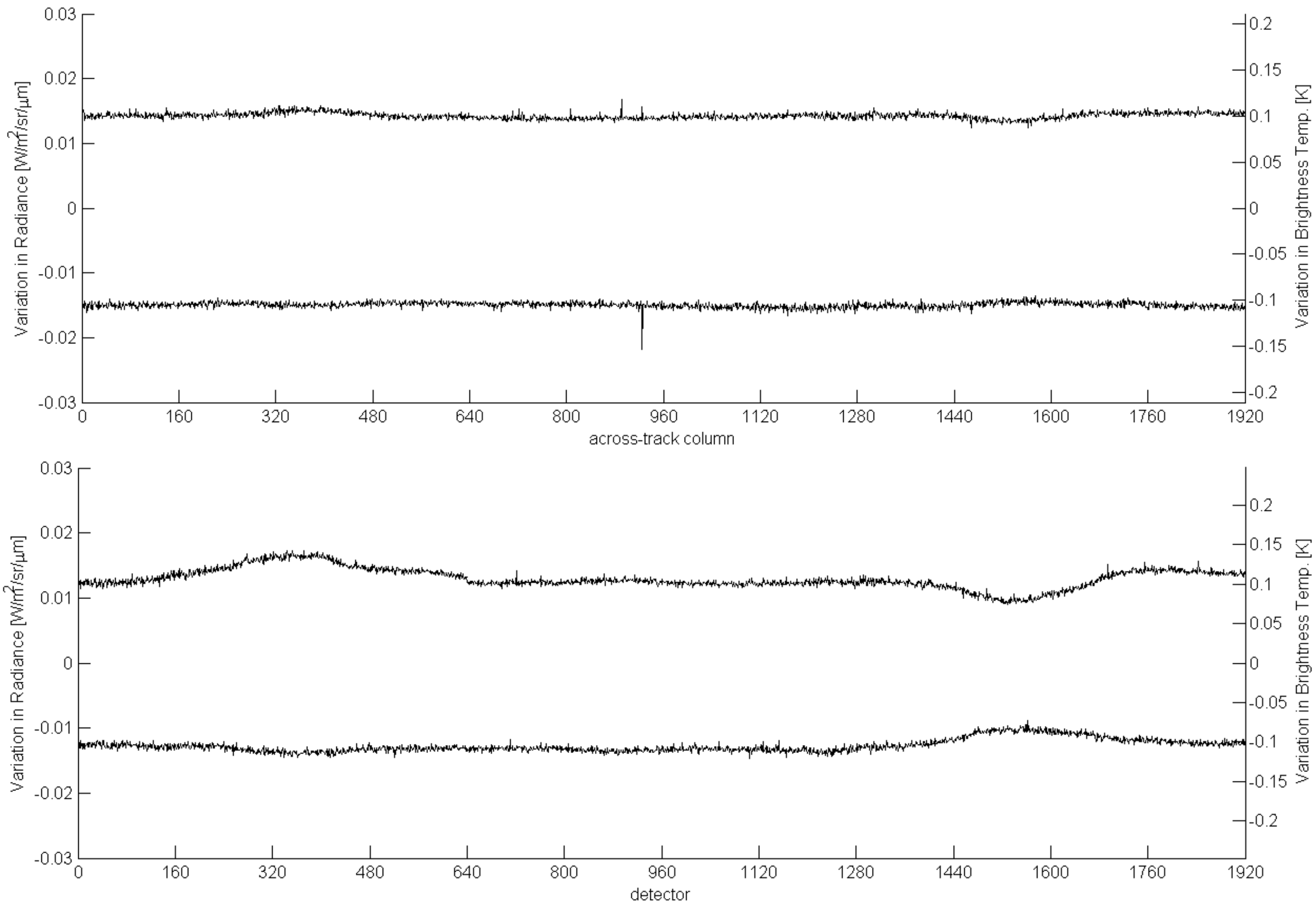


Figure 9. Variation from the average background signal for both bands as a function of WRS row. Orbital day is approximately rows 1–124 while orbital night is approximately rows 125–248. The effect is correlated with the temperature of the SSM structure assembly. An increase in structure temperature produces a higher optical background signal that is detected on the focal plane.



The OBC data from the space/OBC 1.5 orbit collects provide an indication of the stability of the radiometric response of TIRS over the course of an orbit. The variation of the instrument response to the OBC over the 1.5 orbits was found by subtracting the associated space data from the OBC data and converting the mean of each background-subtracted OBC collect into radiance. The minimum and the maximum variation of these 18 collects relative to the mean of the 18 collect were then calculated. The variation is illustrated in Figure 10 for band10 and band11. The variation is approximately ±0.015 $W/m^2/sr/\mu m$ or ±0.13 K or ±0.2% for the worst case and represents the total change of the response of TIRS due to changes in the electronics temperatures, power voltage, *etc*., caused by the environmental conditions as TIRS travels in orbit.

Figure 10. The minimum and maximum variation of the band10 (**top**) and band11 (**bottom**) response of 18 OBC collects over 1.5 orbits expressed as a difference in radiance from the mean. The approximate change in brightness temperature is shown on the right hand axis.



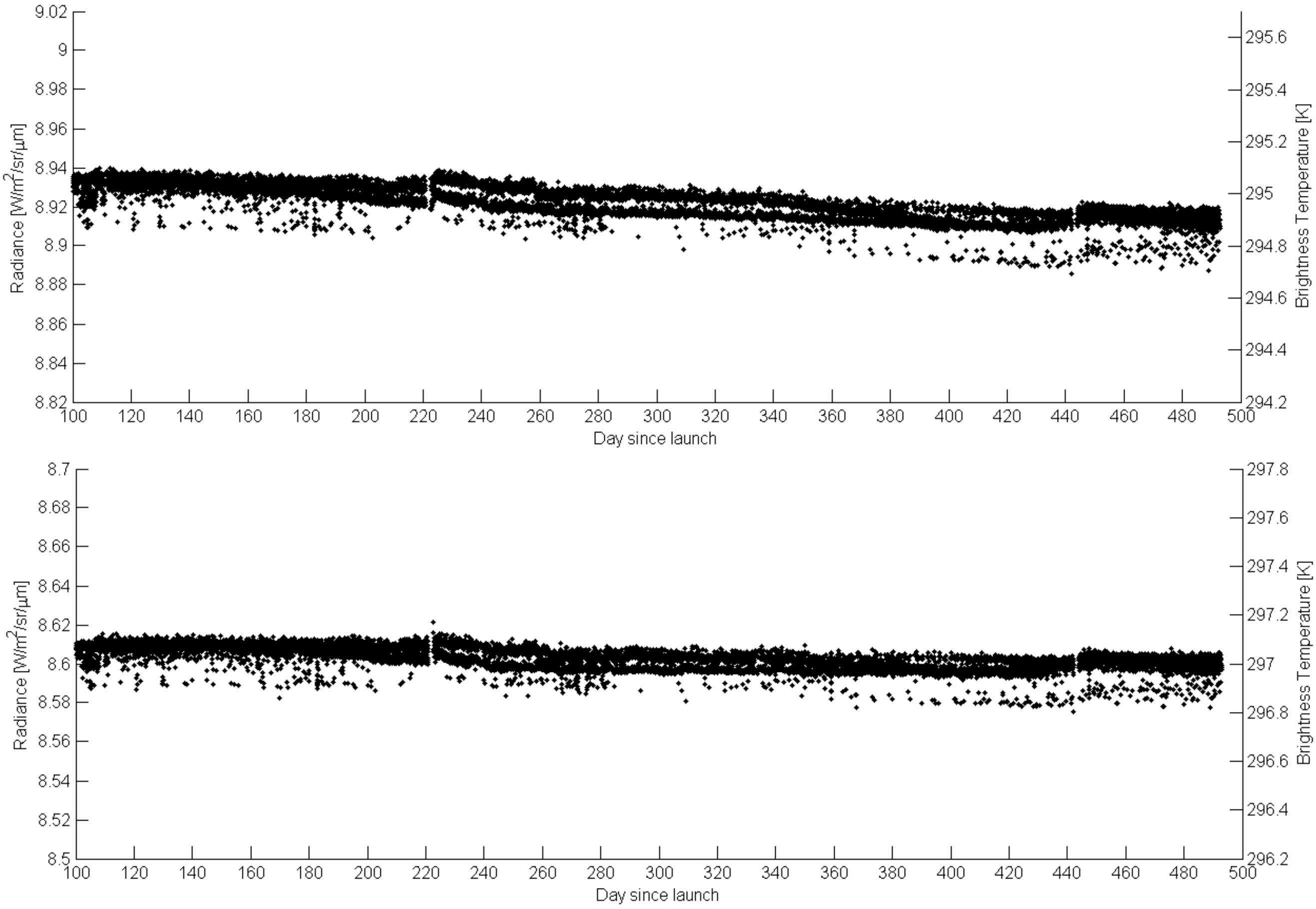
2.2.5. Long Term Stability and Trends

The long term stability of the instrument response is also important to characterize. An overall trend in the TIRS response might necessitate an update to the radiometric calibration in order to compensate for the trend. Since a space/OBC collect is obtained before and after every Earth interval, a large dataset of these collects exists, which allows for the long term trending of the radiometric response.

For each space/OBC collect, the background-subtracted counts from the OBC (at a set point temperature of 295 K) are converted to radiance using the standard radiometric calibration process.

The average observed radiance of the OBC over time is shown in Figure 11 for band10 and band11. The jumps and discontinuities in the data are due to several factors: temperature fluctuations of the OBC; observatory safehold events in which the instrument was turned off and no data was taken; and day/night heating of the SSM baffle assembly causing a fluctuation in background signal levels (see Section 2.2.4). In general, a very slight downward trend is noticed in the data. Over the course of a year, the band10 response to the OBC has dropped by approximately 0.018 $W/m^2/sr/\mu m$ and the band11 response has dropped by approximately 0.009 $W/m^2/sr/\mu m$. The apparent trend may be due to either an actual change in the sensitivity of the detectors, or due to a degradation of the output radiance of the blackbody. In either case, the effect is so far negligible.

Figure 11. The average instrument response of band10 (**top**) and band11 (**bottom**) to the OBC at a set point temperature of 295 K over the course of one year. The discontinuities are due to factors such as temperature fluctuations of the OBC, suspension of imaging activities, and day/night fluctuations in background signal levels. In general there is a 0.2% per year trend in band10 and a 0.1% per year trend in band11.

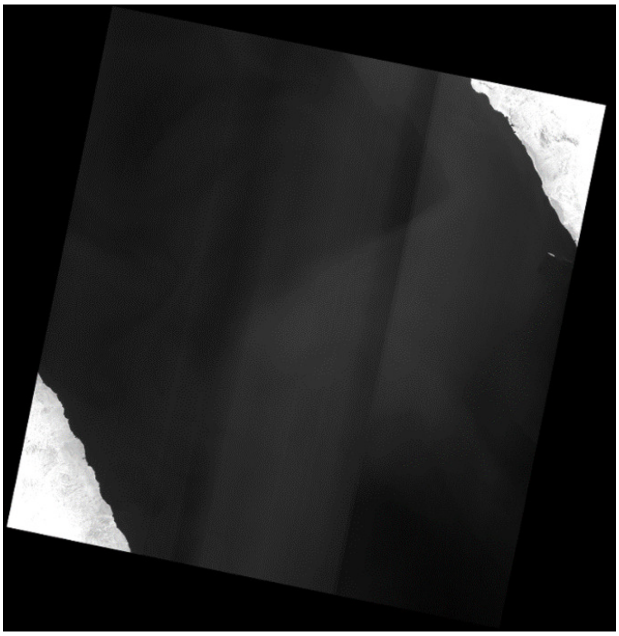


Vicarious absolute radiometric data is used in addition to the trending of the blackbody data to determine if the TIRS response is indeed changing. However, due to the stray light effects (see Sections 2.3 and 2.4), the radiometric errors induced by the stray light must be compensated for before it can be determined with reasonable accuracy whether the instrument response is degrading [1]. If so, a calibration update will be applied to the ground processing system to compensate for the degradation in the final image product. These datasets will be continuously monitored throughout the lifetime of the instrument to determine future calibration updates as necessary.

2.3. Uniformity

The pixel-to-pixel uniformity is an important element of the push-broom sensor design of TIRS. The calibration algorithms are designed to produce a uniform radiance across the field-of-view (FOV) when observing a spatially uniform source [7]. However, a particular artifact known as banding has been observed in certain Earth imagery since launch. Banding in general refers to low frequency variation in the across-track direction in the image data from scenes that are expected to be uniform. Examples of Earth scenes expected to be essentially uniform are open water scenes where it is assumed that the area of water near the overlap between adjacent focal plane arrays is at a uniform temperature and will 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 12. The non-uniform effect across the FOV is as high as 2.5%. Furthermore, the banding effect varies in the along-track direction as well. This variation is not caused by any internal instability within TIRS since all indications are that the noise and radiometric stability is well-behaved.

Figure 12. TIRS band11 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.



Stray light has been determined to be the cause of the banding issues in TIRS Earth imagery. Unwanted signal from outside the FOV is entering the optical system and adds 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 and also on the view geometry of the detector. The band11 detectors have shown a greater magnitude of the stray light effects than the band10 detectors. The investigation of the stray light issue is ongoing and possible correction strategies are being explored. For a detailed description of this issue, see reference [1].

2.4. Absolute Radiometric Response

The absolute radiometric response of TIRS is assessed through the use of vicarious calibration data. Water buoys provide *in situ* measurements of the temperature of water bodies at locations around North America. The top-of-atmosphere (TOA) radiance from the water bodies is calculated from the *in situ* temperature measurements and from atmosphere profile knowledge at the time of data acquisition along with radiative transfer models. The calculated TOA radiance from the water bodies is compared with the TIRS-derived image radiance of the water bodies and the differences between the two values are considered to be an error in the absolute TIRS radiometric calibration.

From data over the past year on-orbit, a varying bias error of approximately (0.29 ± 0.12) $W/m^2/sr/\mu m$ in band10 and (0.51 ± 0.20) $W/m^2/sr/\mu m$ in band11 has been observed. The source of the absolute calibration error is now understood to be the same stray light issue mentioned previously. The stray light signal from outside the FOV 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 reference [11].

3. Summary

The on-orbit performance of the TIRS instrument is continuously monitored through the calculation of performance metrics (such as noise and stability) to ensure the radiometric integrity of the data product. These metrics are evaluated through multiple observations of the onboard calibration sources. The NEdL of the instrument has been approximately 0.008 $W/m^2/sr/\mu m$ for both channels at 300 K. The equivalent NEdT at 300 K is approximately 0.05 K for both channels. The noise metrics are well within the design requirements. From a stability standpoint, the fluctuation of the dark current signal is less than one digital count, which indicates a very stable dark signal. Since no trends are observed in the dark signal over the course of an Earth collection interval, no dark correction to the two spectral channels is needed as had been prepared prior to launch as an option. The variation of the response to the background and to a stable source (the OBC) over an Earth collection interval is in the order of the NEdL (0.008 $W/m^2/sr/\mu m$). The very low variation indicates that TIRS is producing a stable signal while imaging the Earth. The variation of the background signal over the day/night cycle of an orbit is approximately ±0.015 $W/m^2/sr/\mu m$ or ±0.13 K or ±0.2% for the worst case in both channels. This is the expected error in the calibrated Earth scene imagery as the result of using the deep space collects obtained before and after the Earth interval as the background frame to be subtracted out to remove the instrument self-emitted signal. The long term stability of the instrument response to the onboard sources has shown negligible trends (0.2% degradation or less) in the response. By combining the data from two active detector rows per band, 100% detector operability is maintained for the instrument.

While stability was confirmed with onboard sources and instrument telemetry, a non-uniform banding effect has been observed in Earth imagery. In addition, vicarious *in situ* measurements have indicated time-varying errors in the absolute radiometric calibration of the instrument. The cause of the banding and absolute calibration issues was determined to be stray light entering the optical system and producing an additional non-uniform signal on the focal plane arrays. Evaluations of the stray light are currently being performed and a correction strategy is being developed for implementation. Until the correction has been implemented, band10 image data should be used in preference to band11 since band10 has in general exhibited adequate uniformity performance.

The standard noise and stability metrics will be continuously monitored throughout the lifetime of the instrument and updates to the calibration will be performed as needed. A correction for the stray light will be applied to the TIRS data products, which is expected to greatly improve uniformity performance.

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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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