Landsat 9 Thermal Infrared Sensor 2 On-Orbit Calibration and Initial Performance

Aaron Pearlman, Associate Member, IEEE, Boryana Efremova, Matthew Montanaro, Allen Lunsford, Dennis Reuter, and Joel McCorkel

Abstract—The Thermal Infrared Sensor 2 (TIRS-2) on Landsat 9 (L9) was launched on September 27, 2021, and underwent a variety of tests during its commissioning phase to establish its postlaunch performance. We report on the calibration updates performed to maintain its calibration and generate high-quality imagery. This is done by transferring the SI-traceable prelaunch calibration to on-orbit while accounting for changes in the TIRS-2 response as detected through on-board calibrator observations. Additional empirical corrections were implemented to mitigate image striping observed on-orbit. The detector arrays were monitored through its commissioning phase to ensure that stable detectors were chosen for operations. TIRS-2 has demonstrated ∼0.025% instability over its orbit, ∼80-mK noise equivalent delta temperature (NEdT), and an absolute radiometric uncertainty <1.4% in its nominal temperature range enabling a wide array of Earth science applications.

Index Terms—Calibration, Landsat, thermal infrared, traceability, uncertainty.

I. INTRODUCTION

THE Thermal Infrared Sensor 2 (TIRS-2) is one of two instruments on-board the Landsat 9 (L9) observatory. It continues the Landsat program’s legacy of long-wave infrared imaging capabilities enabling a host of Earth science applications [1], [2]. L9 launched on September 27, 2021, followed by four months of on-orbit commissioning tests to verify radiometric and geometric requirements. Throughout this phase, measurements of the on-board blackbody calibrator (OBC) and the Deep Space view port, along with Earth observations were acquired on multiple occasions to characterize the TIRS-2 calibration stability, repeatability, and noise performance, and to select the most stable, low noise detector elements for operational use. The radiometric uncertainty budget was also updated with on-orbit performance data. TIRS-2 is a functional copy of the TIRS on-board Landsat 8, its predecessor, but provides more electronic redundancy and improved stray light suppression [3]. It is a ±7.5° field-of-view push-broom imager that covers a swath of 185 km from a 705-km orbit. A four-element refractive telescope images onto a focal plane consisting of three 512-row × 640-column detector arrays, denoted as sensor chip assembly (SCA) A, B, and C, staggered to provide the necessary swath width (see Fig. 1) [4]. Each detector array has two spectral filters placed over roughly 70 pixel rows to provide two spectral channels centered at 10.8 and 12.0 μm in wavelength with bandwidths of 0.8 and 1.0 μm, respectively, [5], [6]. The rest of the array area is masked to provide dark pixels for trending purposes. Two rows of detectors, one termed primary and the other secondary (or redundant), in the two spectral regions are combined in the US Geological Survey (USGS) Landsat image product generation system to produce calibrated image products known as L9 band 10 and band 11, for the 10.8- and 12.0-μm channels, respectively. A so-called “detector swap list” based on the most stable, lowest noise detectors, determine whether a primary or secondary row detector is selected for a particular column to form the image. The detector arrays may also operate in a diagnostic mode in which nearly all pixel rows are read at a lower frame rate. This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/
This “transmit-all” mode is used to trend 2-D spatial changes on the detector arrays.

Before launch, TIRS-2 underwent a comprehensive testing program to ensure it met its prelaunch performance requirements [7], [8]. A key element of the radiometric characterization was to establish SI-traceability by performing the instrument-level calibration with a NIST-traceable blackbody referred to as the flood source (FS) [9] over the required radiance range by setting its temperature from 240 to 360 K (with additional measurements down to 200 K). During this testing, the instrument response to the OBC was also characterized over its more limited temperature range (270–320 K). Other key instrument parameters were derived during prelaunch testing such as the relative spectral response functions [5] and noise.

After launch, OBC observations over its temperature range were used to track any changes in the TIRS-2 response under the assumption that any change between the on-orbit OBC measurements and the prelaunch OBC measurements reflect a change in the instrument responsivity (not the blackbody). We then applied this change to the prelaunch FS measurements to transfer the NIST traceable calibration to actual on-orbit operating conditions. This philosophy maintains the absolute calibration while adjusting for instrument responsivity changes for each detector. Additional on-orbit tests included repeated measurements of the OBC and deep space port over its orbit to gauge response and background stability.

In this article, we describe the on-orbit calibration approach in detail with additional corrections that were implemented based on observed image artifacts. We then discuss the detector selection process. Finally, the uncertainty budget updates are described accounting for the calibration methodology and on-orbit performance data.

II. CALIBRATION OVERVIEW AND UPDATE METHODOLOGY

A. TIRS-2 Prelaunch Calibration

As detailed in our previous work on the prelaunch calibration methodology [7], the FS-based calibration established the SI-traceability of the instrument [9]. The calibration datasets involved TIRS-2 acquiring image data of the FS at various temperature set points between 200 and 360 K along with a background acquisition through the deep space viewport (viewing a <100 K cold source for prelaunch testing) for each FS acquisition. Similarly, image acquisitions of the OBC were made over its operational temperature range to be used as a transfer measurement after launch since the OBC, unlike the FS, is available on-orbit (see Section II-B). For each FS and Deep Space pair, the generated digital counts are linearized through an established linearization function [7]. This function was derived through an integration time sweep to reveal the piecewise linear electronic response of the system, indicating two different electronic gain regimes. The digital counts are linearized by transforming them so that they have the same electronic gain throughout their dynamic range [10]. The Deep Space linear counts are subtracted from the FS linear counts to obtain the delta counts, \( \Delta c \), for each detector (i.e., background-subtracted counts). The associated source radiance for each delta count is obtained by calculating the effective spectral radiance using the temperature of the FS, its emissivity (0.992), and the relative spectral response function for the appropriate channel. A polynomial fit is then derived to fit the radiance as a function of delta counts. For the previous analysis in [7], we assumed a second-order polynomial. Further analysis showed that a third-order polynomial fit was more appropriate and the prelaunch calibration was reestablished using this model. Fig. 2 shows the residuals of the second-order and third-order fits over the dynamic range for all detector columns in the primary row for the 10.8-\( \mu \)m channel. The cubic residuals have a more random shape compared to the quadratic residuals where there is structure particularly at lower radiance values. This same pattern is also evident in the 12.0-\( \mu \)m channel (not shown). Choosing an even higher-order polynomial would reduce the residuals further but could result in overfitting. Thus, we chose the lowest order polynomial that shows random residuals.

B. TIRS-2 On-Orbit Calibration Update

To account for instrument response changes through launch, the calibration methodology relies on measurements of the OBC to characterize such changes and derive updates to the SI-based calibration. The prelaunch calibration established with the FS measurements is adjusted using the ratio between pre- and post-launch OBC measurements as expressed in the equation

\[
L_{\text{update}} = L_{\text{FS}} \times \frac{L_{\text{OBC, on-orbit}}}{L_{\text{OBC, prelaunch}}}
\]  

(1)

where \( L_{\text{FS}} \) is the prelaunch FS-based calibration and \( L_{\text{OBC}} \) is a calibration function fit to the OBC measurements. The prelaunch OBC response model was derived similar to the FS calibration model. The main difference was that narrower temperature range of OBC operation (270–320 K) and its emissivity was assumed to be one. The OBC calibration model form was chosen so that the ratio between the FS calibration and OBC calibration was as close to a constant value with respect to source temperature as possible. We compared different polynomial fits for the OBC radiance versus delta counts (\( \Delta c \)) and calculated the ratio between \( L_{\text{FS}} \) and \( L_{\text{OBC}} \).
Fig. 3. Depiction of the Monte Carlo uncertainty derivation method for the model fit uncertainty. The plots show an example for the OBC-based calibration for a single detector.

We included fits from linear to third-order with either forcing the offset to zero or including it as a fit parameter. The quadratic form with a forced zero offset showed the flattest dependence with temperature from 240 to 360 K. The calibration transfer function then becomes

\[ L_{update} = (a_o + a_1 \Delta c + a_2 \Delta c^2 + a_3 \Delta c^3) \frac{m_1' \Delta c + m_2' \Delta c^2}{m_1 \Delta c + m_2 \Delta c^2}. \]  

(2)

The \( a \) coefficients correspond to the FS-based calibration model coefficients and the \( m \) and \( m' \) correspond to OBC-based calibration model coefficients for prelaunch and on-orbit data, respectively. The on-orbit OBC calibration coefficients are determined through the on-orbit observations of the OBC blackbody at temperatures from 270 to 320 K and Deep Space view observations.

C. Uncertainty Evaluation

The uncertainty budget is assessed using the same general methodology as was done prelaunch to account for both systematic and random uncertainties. These uncertainty contributions are combined using the sum uncertainty method (SUMU) described in [11] to form a confidence interval to denote the uncertainty. An individual uncertainty component’s contributions to the radiometric uncertainty was calculated using a Monte Carlo approach where we applied a Gaussian distribution to generate random numbers with the mean measured value and standard deviation corresponding to its \( k = 1 \) (1 − \( \sigma \)) uncertainty. We then propagated them through the updated calibration equation [see (2)] to establish an output distribution of the radiance values. The standard deviation of these values was defined as the radiometric uncertainty. Fig. 3 illustrates this process for a single detector with the OBC model. This process was used for both the OBC-based (prelaunch and on-orbit) and FS-based calibration model fit uncertainties for all detectors. Note that the uncertainty budget derived previously did not assume a specific approach for updating the calibration on-orbit. Thus, the difference between OBC-derived radiances and FS-derived radiances were used to calculate the uncertainty. Here, we implemented an approach that removes this term and substitutes an additional on-orbit OBC model fit uncertainty term.

The updated uncertainty budget also used on-orbit observations for noise and reproducibility terms. The calibration model coefficients were derived using separate OBC calibration datasets, where the OBC temperature was changed from 270 to 320 K in 5 K increments with a deep space view at each temperature. This sequence was repeated >16 days apart enabling the calibrations to be compared. We also added an additional short-term repeatability term by monitoring the OBC response over 1.5 orbits. This radiometric uncertainty budget only applies to uniform scenes; it does not include contributions from stray light, which is the subject of a separate work [3].

III. ON-ORBIT UPDATE

The on-orbit calibration update is meant to correct for response changes to each detector element to allow Earth image data to be as accurate as possible while minimizing any image artifacts. On-orbit characterization consists of repeated OBC measurements, including three temperature sweeps from 270 to 320 K, with comparisons to prelaunch results. Independent observations of the OBC at its nominal value of 295 K were generally used for quick-look verification after calibration updates. Then a combination of on-orbit tests were used to find and adjust for any artifacts found. Fig. 4 shows the steps in the calibration update process throughout the commissioning phase and will be described in detail below.

The first step in the on-orbit update involved checking the established linearization function. Image data were generated from viewing the OBC and the deep space port while varying the detector integration time to characterize the nonlinear response behavior of the system as shown in the left panel of Fig. 5. This was corrected with a linearization process used previously for TIRS [10] and TIRS-2 prelaunch utilizing integration time sweep data to derive a function that corrects for the piecewise linear response of the detectors [see Fig. 5 (Right)]. Deriving the linearization function using on-orbit data and comparing with the prelaunch values revealed a negligible difference. Comparing two separate on-orbit integration sweeps found a negligible difference in their derived linearization functions (<0.2 counts).

The next step in the on-orbit update process involved establishing the OBC radiometric function. Similar to prelaunch
datasets, image data were acquired of the OBC between 270 and 320 K in increments of 5 K along with a Deep Space acquisition to pair with each OBC acquisition. After linearization, delta counts were calculated for each OBC and deep space pair. A quadratic function with no offset term was then fit to the OBC count and radiance data, and the prelaunch FS-based calibration was adjusted per (2).

The updated calibration functions were then applied to Earth imagery and the scenes were assessed for uniformity. Although results showed an overall reduction in striping in stripeing, several artifacts were still evident. The first involved a persistent area of banding on one edge of the field of view that was observed in nearly all scenes. Since this artifact was not corrected by the pre-to-post-launch OBC ratio correction, the cause was most likely an unnoticed spatial nonuniformity in the FS measurements due to the view geometry between the instrument and the FS in the thermal vacuum chamber. To account for this, an adjustment to the FS data was made by comparing the prelaunch FS and OBC data. The relative per-detector ratio between the FS-based calibration and the OBC-based calibration revealed the across-track profile of this banding artifact which was then folded into the FS-based calibration to remove the banding effect. The correction shape is illustrated in Fig. 6 for both bands.

After the FS correction was implemented, another image artifact was investigated that involved a small discontinuity in the transition region between detector arrays SCA-A and SCA-C. Calculating the magnitude of the discontinuity over a number of uniform scenes revealed a dependence on radiance, where, for instance, the largest discontinuity was \( \sim 0.4\% \) or 0.16 K for the coldest scene. A correction was derived as a function of radiance by fitting these data and applying the fit to the on-orbit calibration using SCA-C as the reference (see Fig. 7). The amount of scatter in the graph is a consequence of the differing levels of uniformity in the scenes. The 10.8-\( \mu \)m channel results are shown here, but the 12-\( \mu \)m channel results have a similar dependence but lower magnitude. SCA-B to SCA-C discontinuities did not show a significant trend. The figure also shows an example of imagery before and after this correction was applied. Note that other improvements in the image example were caused by selecting detectors in the redundant row in several columns.

The final adjustments to the image calibrations involved updating the detector swap list to account for new out-of-spec detector elements. As mentioned previously, a primary and a redundant row of pixels are read from the focal plane arrays for each spectral region. Pixel data from the primary row that are considered out-of-spec can be swapped with the corresponding pixel data from the secondary row so that the combined row data meets performance requirements. The process of optimizing the detector swap list for operational imaging
was based on the prelaunch characterization and postlaunch detector stability. Detectors were selected prelaunch based on dynamic range, radiometric sensitivity, precision, uniformity, and stability requirements. Postlaunch, additional detectors were swapped based on: visual assessment of striping artifacts and streaking metric trending in image data; comparisons of detector response derived from two sets of OBC calibration acquisitions, taken 36 days apart; and trending the detector response using OBC (at 295 K) data, taken as part of the routine on-orbit operations. The streaking metric \( S \) was calculated for Earth images acquired over the first-month on-orbit

\[
S_i = \left| \bar{L}_i - \frac{1}{2}(\bar{L}_{i-1} + \bar{L}_{i+1}) \right| / \bar{L}_i.
\]

This metric captures the amount of striping (or streaking) by comparing the average radiance in the along-track direction corresponding to a detector, \( \bar{L}_i \), to the average radiance corresponding to the adjacent detectors \( \bar{L}_{i\pm1} \). Detectors that had streaking metric values of 0.3% or higher, or showed detector response change of 0.3% or higher between the two OBC calibration acquisitions were tagged as potential candidates for swapping and investigated further (The 0.3% threshold is equivalent to a 0.19 or 0.21 K change in brightness temperature for the 10.8- and 12.0-\( \mu \)m channels at 295 K, respectively).

The per-detector 10.8-\( \mu \)m channel radiance, relative to the average, is shown in the top panel of Fig. 8 for all images of the first OBC calibration data acquisition. The images are calibrated using parameters derived from the second OBC calibration acquisition; thus, any detector response change between the two events appears as a spike in the figure. The 0.3% selection threshold is marked with dashed lines. An example of the selection process is shown in the bottom panel of Fig. 8. The OBC is kept at nominal temperature, we expect the radiance measured by individual detectors to be also constant (within the noise and OBC stability). For the majority of the detectors this is the case, while for a small number of detectors there are jumps in the detected radiance, which we interpret as response change. The response of detectors 1553 and 1657 relative to the first observation is trended (using OBC data at 295 K) over about 30 days (the first observation is selected to be after the instrument temperatures had reached their final, nominal values). Their secondary row counterparts show stable response. Detector 1657 experienced frequent response changes (five–ten days) and was selected to be swapped with the secondary row. Detector 1553 experienced a jump around day 5 but then stabilized, and the response change is corrected by the latest calibration.

The resulting calibration update, incorporating the pre-to-post-launch OBC ratio, the FS banding adjustment, the SCA boundary discontinuity correction, and the updated detector swap list, was the final on-orbit calibration parameter delivery to the USGS Landsat image product generation system. The calibration parameters are used to radiometrically calibrate the raw detector image data from both of the TIRS-2 spectral bands into the standard L9 band 10 and band 11 Level 1 product available to users. Overall, the on-orbit calibration adjustment accounted for \( \sim 2\% \) change at 295 K (or \( \sim 1.3–1.4\)-K temperature difference) in the instrument response through launch. The flat dependence of the radiance ratio between the on-orbit calibration derived from each OBC temperature sweep and the prelaunch calibration is shown in Fig. 9 for both channels at radiance levels associated
with selected brightness temperature values. The ratio is not constant across temperatures due to the nonlinearity in the calibration equation. This relationship establishes a baseline for trending any degradation during operations. An example of an Earth scene acquired by TIRS-2 and processed with the prelaunch calibration compared with the updated on-orbit calibration is given in Fig. 10 and demonstrates the improvement in image artifacts. Over the lifetime of L9 and TIRS-2, the Landsat calibration and validation team will continuously monitor the onboard calibration sources and in situ Earth calibration sites to track the absolute and relative response of the instrument. Regular calibration updates to the ground processing system will be implemented to account for any future response changes.

IV. UNCERTAINTY BUDGET UPDATE

To give confidence in the TIRS-2 image product accuracy after the calibration updates, we reevaluated the radiometric uncertainty budget with on-orbit data. The overall radiometric uncertainty budget is a combination of the components detailed in Table I. The values are defined for a nominal temperature range, 260–330 K, and for an extended temperature range, 240–260 K and 330–360 K for comparison to the required source temperature ranges. Those components not addressed here were taken from [7]. The updated parameters, the FS-based fit uncertainty (based on a cubic model), and additional parameters for the OBC-based on-orbit model fit, short-term repeatability, noise, and reproducibility are shown. The uncertainties for systematic and random terms are added to obtain a total uncertainty interval defining the $k = 1$ uncertainty interval (or having a 68.27% probability of falling in the interval). For convenience, we also took the largest deviation from zero as a $k = 1$ conservative uncertainty estimate for comparison to the requirements. The uncertainty is well within the 2% and 4% requirement for both channels in the nominal and extended regions, respectively. The following discussion provides details on the updated parameters.

The uncertainties were derived for all detector fits for the prelaunch OBC-based model, the on-orbit OBC-based model, and the FS-based (cubic) model parameters (see Fig. 11). For both the nominal and extended brightness temperature ranges in each band, we used the values at the brightness temperature with the highest uncertainties and averaged over all detectors. For instance, in the nominal range, this usually meant using the uncertainties at 330 K. Generally, the fit uncertainties varied from approximately 0.1%–0.3%. As expected, the prelaunch OBC and postlaunch OBC fits had similar uncertainties showing the consistency in TIRS-2 response and suitability of the model.

The difference of calibration curves derived from two independent OBC sweeps acquired >16 days apart are compared to yield the reproducibility uncertainty term. Fig. 12 shows the radiometric difference between the two OBC datasets as a function of OBC temperature for all detectors in each channel. The random contribution is the standard deviation across detectors and the systematic contribution is the mean difference across detectors as reflected in Table I by the two terms in the table.

A short-term repeatability term was included in the budget that reflects the changes in response throughout the orbit. This was derived through a test where TIRS-2 acquires image data of the OBC and the deep space port every 8 min over 1.5 orbits. The TIRS-2 measured radiance (from the calibration) is normalized with the average measured radiance over all calibrations. This trend is then divided by the predicted radiance given by the blackbody temperature and channel relative spectral response functions. Fig. 13 shows that this trend stays below 0.1% demonstrating that background emission over the orbit has a negligible impact on the TIRS-2 response.
TABLE I
UNCERTAINTY BUDGET (%)

| Parameter | 10.8 μm | 12.0 μm |
|-----------|---------|---------|
|           | Nominal | Extended | Nominal | Extended |
| Spectral Response | 0.050 | 0.060 | 0.10 | 0.15 |
| Flood Source Temperature | 0.067 | 0.082 | 0.059 | 0.072 |
| Flood Source Calibration | 0.20 | 0.20 | 0.20 | 0.20 |
| Linearity | 0.30 | 0.70 | 0.040 | 0.10 |
| Fitting (Flood Source) | 0.33 | 0.32 | 0.22 | 0.30 |
| TIRS-2 Radiometric Reproducibility Bias | 0.20 | 0.20 | 0.26 | 0.26 |
| TIRS-2 Radiometric Reproducibility | 0.22 | 0.20 | 0.091 | 0.091 |
| TIRS-2 Noise | 0.0046 | 0.0054 | 0.0071 | 0.0084 |

$k = 1$ Confidence Intervals

| OBC Based | $U_9 - U_1$ | $U_1 + U_9$ | $U_1 - U_9$ | $U_1 + U_9$ |
|-----------|-------------|-------------|-------------|-------------|
| OBC Temperature | 0.21 | 0.36 | 0.19 | 0.35 |
| Fitting (OBC), pre-launch | 0.18 | 0.18 | 0.11 | 0.14 |
| Fitting (OBC), post-launch | 0.27 | 0.28 | 0.14 | 0.18 |
| OBC Angular Variability | 0.020 | 0.020 | 0.020 | 0.020 |
| TIRS-2 Radiometric Reproducibility Bias | 0.054 | 0.059 | 0.035 | 0.035 |
| TIRS-2 Radiometric Reproducibility | 0.019 | 0.023 | 0.018 | 0.022 |
| TIRS-2 Radiometric Short-Term Repeatability | 0.025 | – | 0.027 | – |
| TIRS-2 Noise | 0.00096 | – | 0.0012 | – |

$k = 1$ Confidence Intervals

| Total Interval | $U_9 - U_1$ | $U_1 + U_9$ | $U_1 - U_9$ | $U_1 + U_9$ |
|---------------|-------------|-------------|-------------|-------------|
| Pre-launch Total | -0.87 | 0.33 | -1.1 | 0.62 |
| On-board Calibration Total Interval | -1.3 | 0.74 | -1.6 | 1.09 |
| On-board Calibration Total* | 1.3 | 1.6 | 1.4 | 1.6 |

Nominal refers to a brightness temperature range of 250-330 K and extended range refers 240-250 K and 330-360 K. Each bias term is followed by a bias uncertainty term.

*This is a conservative uncertainty estimate generated by taking the largest deviation in the confidence interval from zero.

The on-orbit noise performance is summarized in Fig. 14 where the noise equivalent delta radiance (NEdL) is expressed when viewing the OBC at each temperature. The measured NEdL is well below the noise requirements of 0.059 and 0.049 W/m²/sr/μm for the 10.8- and 12.0-μm channels, respectively, for all detectors. These values correspond to 80-mK NEdT. It also contributes a negligible amount to the on-orbit calibration uncertainty. The values in the table were calculated as standard deviation of the mean using the 320-K NEdL mean value.

V. SUMMARY AND CONCLUSION

Since its launch, the TIRS-2 instrument on-board L9 has demonstrated stable performance and produced high-quality
imagery after on-orbit calibration updates. This update approach transferred the SI-traceable prelaunch calibration to on-orbit while accounting for any response changes using the OBC as the transfer source. Two empirical corrections were also applied to account for streaking observed on-orbit, one using the relationship between the prelaunch OBC and FS data, and the other through analysis of the image artifact as a function of Earth scene radiance. The uncertainty budget was updated based on the early on-orbit tests of TIRS-2 repeatability and reproducibility and found to be <1.4% (or <1.0 K at 295 K) in its nominal temperature range meeting its 2% (or ≈1.4 K at 295 K) absolute radiometric requirements. TIRS-2 showed a 1σ instability of ~0.025% over its orbit and NEdT of ~80 mK. TIRS-2 radiometric calibration and validation efforts will be ongoing throughout the lifetime of the instrument to ensure the user community receives the most accurate thermal image data to support Earth science applications.

ACKNOWLEDGMENT

The Landsat 9 (L9) Flight Operations and Mission Planning Teams planned and executed the on-orbit TIRS-2 calibration acquisitions that were used in these analyses. The Landsat Calibration and Validation Team helped to implement the calibration updates and supported technical discussions. The opinions expressed here are entirely that of the authors.

REFERENCES

[1] J. G. Masek et al., “Landsat 9: Empowering open science and applications through continuity,” Remote Sens. Environ., vol. 248, Oct. 2020, Art. no. 111968.
[2] J. A. Sobrino, F. Del Frate, M. Drusch, J. C. Jiménez-Muñoz, P. Manunta, and A. Regan, “Review of thermal infrared applications and requirements for future high-resolution sensors,” IEEE Trans. Geosci. Remote Sens., vol. 54, no. 5, pp. 2963–2972, May 2016.
[3] M. Montanaro et al., “Landsat 9 thermal infrared sensor 2 (TIRS-2) stray light mitigation and assessment,” IEEE Trans. Geosci. Remote Sens., vol. 60, pp. 1–8, 2022.
[4] M. Jhabvala, D. Reuter, K. Choi, C. Jhabvala, and M. Sundaram, “QWIP-based thermal infrared sensor for the Landsat data continuity mission,” Infr. Phys. Technol., vol. 52, no. 6, pp. 424–429, 2009. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1350449509000619
[5] B. Efremova et al., “Landsat 9 thermal infrared sensor 2 subsystem-level spectral test results,” in Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS), Jul. 2018, pp. 8849–8852.
[6] A. J. Pearlman, B. Efremova, A. Lunsford, J. McCorkel, A. Simon, and D. Reuter, “Landsat 9 thermal infrared sensor 2 spectral response test: Updates and perspective,” in Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS), Aug. 2019, pp. 8534–8537.
[7] A. Pearlman et al., “Prelaunch radiometric calibration and uncertainty analysis of landsat thermal infrared sensor 2,” IEEE Trans. Geosci. Remote Sens., vol. 59, no. 4, pp. 2715–2726, Apr. 2021.
[8] J. McCorkel et al., “Landsat 9 thermal infrared sensor 2 characterization plan overview,” in Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS), Jul. 2018, pp. 8845–8848.
[9] “TIRS flood source 2018 calibration report,” Space Dyn. Lab., North Logan, UT, USA, Internal Rep. SDL/18-877, Aug. 2018.
[10] M. Montanaro, A. Lunsford, Z. Tesfaye, B. Wenny, and D. Reuter, “Radiometric calibration methodology of the Landsat 8 thermal infrared sensor,” Remote Sens., vol. 6, no. 9, pp. 8803–8821, Sep. 2014.
[11] S. Phillips, K. Eberhardt, and B. Parry, “Guidelines for expressing the uncertainty of measurement results containing uncorrected bias,” J. Res. Nat. Inst. Standards Technol., vol. 102, no. 5, p. 577, Sep. 1997.

Aaron Pearlman (Associate Member, IEEE) received the B.S. degree in electrical engineering from Tufts University, Medford, MA, USA, in 2001, and the M.S. and Ph.D. degrees in electrical engineering from the University of Rochester, Rochester, NY, USA, in 2003 and 2006, respectively.

He became an IC Post-Doctoral Research Fellow with the National Institute of Standards and Technology, Gaithersburg, MD, USA, to conduct research on single photon generating and detecting technologies for quantum information applications. He has provided prelaunch testing support and technical oversight and coordination for a validation field campaign for National Oceanic and Atmospheric Administration’s (NOAA’s) new generation of satellite sensors. In 2017, he joined the NASA Goddard Space Flight Center’s Calibration Team, Greenbelt, MD, USA, to support prelaunch testing and postlaunch support for the Landsat Program’s Thermal Infrared Sensor-2. He is currently the Chief Scientist of GeoThinkTank LLC, Miami, FL, USA. His work focuses on developing next-generation satellite sensors and applying novel methods for validating on-orbit satellite sensor performance.

Boryana Efremova received the Ph.D. degree in astronomy and astrophysics from Sofia University, Sofia, Bulgaria, in 2009.

She has been working in the field of remote sensing instrument calibration since 2011, supporting the prelaunch and/or on-orbit calibration, instrument monitoring, and validation of sensors such as Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi NPP spacecraft, the Advanced Baseline Imager (ABI) onboard the geostationary GOES-16 and GOES-17 satellites, and the prelaunch calibration and testing of the Landsat 9 Thermal Infrared Sensor 2 (TIRS-2).

Matthew Montanaro received the B.S. degree in physics and the Ph.D. degree in imaging science from the Rochester Institute of Technology (RIT), Rochester, NY, USA, in 2005 and 2009, respectively.

He is currently the Senior Research Scientist involved in the calibration of the thermal infrared imaging instruments for the NASA Goddard Space Flight Center, Greenbelt, MD, USA, and the U.S. Geological Survey. He is also specialized in the calibration of the Thermal Infrared Sensor (TIRS) onboard Landsat 8, both preflight and on-orbit. He serves as the Deputy Calibration Lead for the upcoming Landsat 9/TIRS-2 instrument and serves on the Landsat Calibration and Validation Team. In addition, he has supported and advised a number of Imaging Science graduate and undergraduate students through RIT.

Allen Lunsford, photograph and biography not available at the time of publication.

Dennis Reuter, photograph and biography not available at the time of publication.

Jared McCorkel received the B.S. degree in optical engineering and the Ph.D. degree in optical sciences from The University of Arizona, Tucson, AZ, USA, in 2005 and 2009, respectively.

He is currently the Physical Research Scientist of the Biospheric Sciences Laboratory, NASA’s Goddard Space Flight Center, Greenbelt, MD, USA, where his current work involves development and characterization of the next-generation environmental monitoring and Earth observing sensors. He serves as the GOES-R Flight Project Scientist, the Landsat 9 TIRS-2 Deputy Instrument Scientist leading the prelaunch instrument characterization, and the principal investigator of the Goddard Laser for Absolute Measurement of Radiance (GLAMR) Calibration Facility.