Radiometric Performance of the Landsat Thermal Infrared Sensor Instruments

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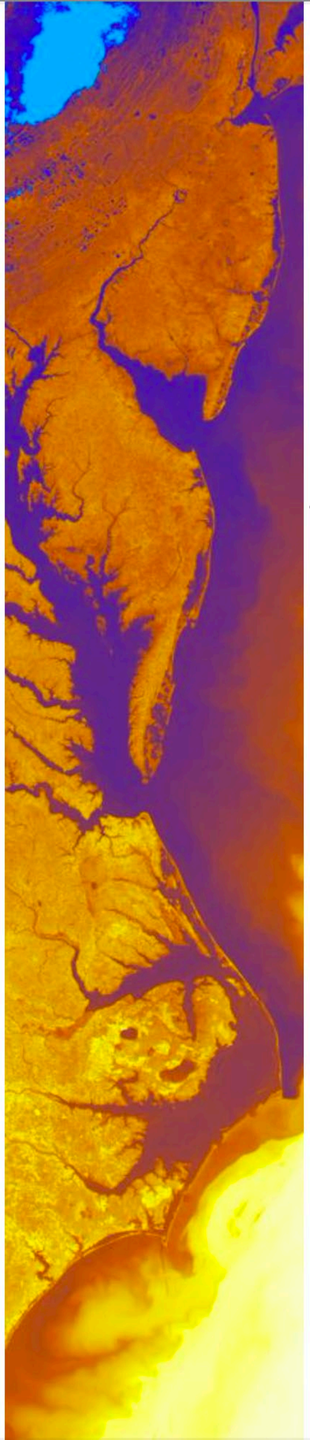


US Eastern Seaboard
Landsat-9 TIRS Band 10
2022-02-10

Outline

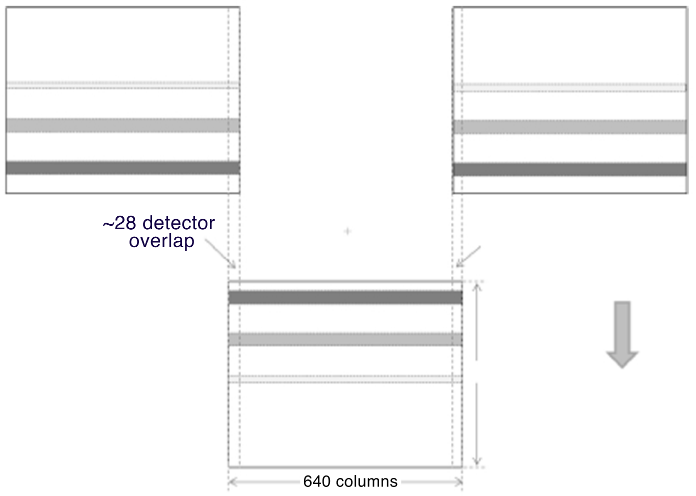
- Spacecraft and Instrument overview
- Stray light artifact
- Internal Radiometric Performance
  - Radiometric stability
  - Noise performance
- Vicarious Calibration

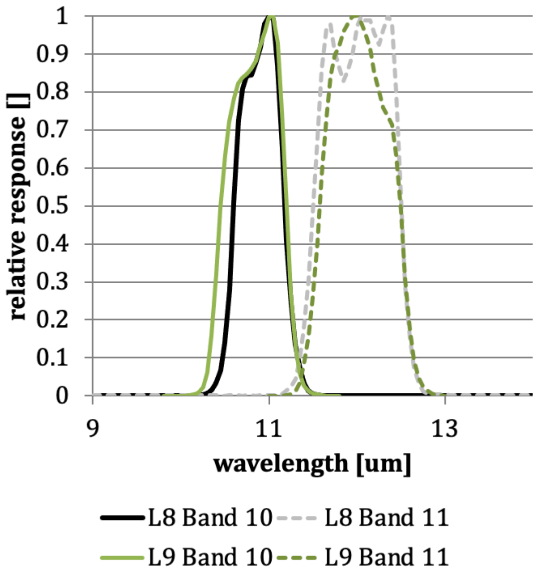
The Landsat Spacecraft

- Spacecraft
  - Landsat-8 launched February 11, 2013
  - Landsat-9 launched September 27, 2021
- Orbiting at 705km with 16-day revisit time
  - Satellite orbits are 8-days offset, so together, they have an 8-day revisit time
- Includes two instruments
  - Operational Land Imager (OLI) – eight spectral bands between 440 and 2500nm
  - Thermal Infrared Sensor (TIRS) – two spectral bands, 10um and 12um

Thermal Infrared Sensor

- 15-degree, 185km field of view covered by 3 different Sensor Chip Assemblies (SCAs)
- SCAs are 512x640 pixel Quantum Well Infrared Photodetectors (QWIP)
  - Spectral filters cover ~30 unvignetted rows on each chip
  - Science data (earth imagery) comes from one of two rows for each band
- 100m spatial resolution
- Two spectral bands chosen to optimize a split-window atmospheric correction
  - Not quite identical spectral shape between instruments

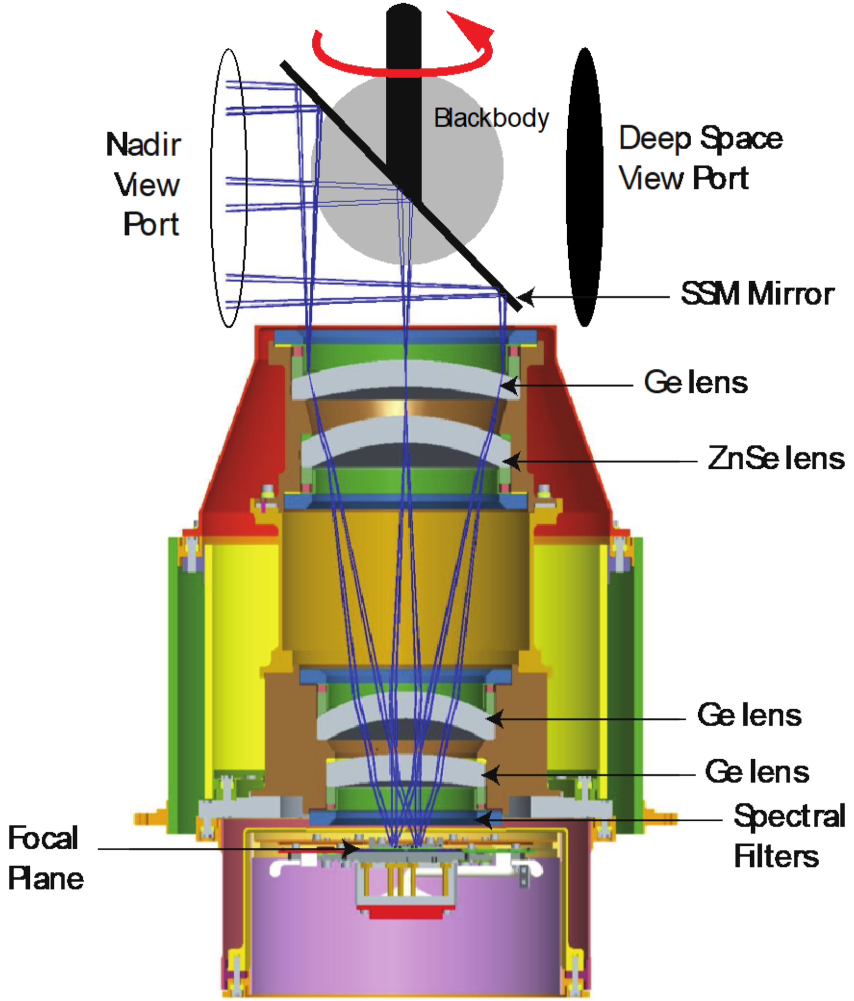




https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-instruments/tirs-2-design/tirs-2-relative-spectral-response/
https://landsat.gsfc.nasa.gov/satellites/landsat-8/spacecraft-instruments/thermal-infrared-sensor/spectral-response-of-the-thermal-infrared-sensor/

Instrument Design

- Four-lens telescope
- Scene Select Mechanism (SSM) at the end of the telescope switches the view
- On-board calibration capabilities with blackbody and deep space view
  - Variable temperature blackbody allows for rigorous on-board calibrations



Reuter, D.C.; Richardson, C.M.; Pellerano, F.A.; Irons, J.R.; Allen, R.G.; Anderson, M.; Jhabvala, M.D.; Lunsford, A.W.; Montanaro, M.; Smith, R.L.; Tesfaye, Z.; Thome, K.J. The Thermal Infrared Sensor (TIRS) on Landsat 8: Design Overview and Pre-Launch Characterization. *Remote Sens.* **2015**, *7*, 1135-1153. https://doi.org/10.3390/rs70101135

Montanaro, M.; Gerace, A.; Lunsford, A.; Reuter, D. Stray Light Artifacts in Imagery from the Landsat 8 Thermal Infrared Sensor. *Remote Sens.* **2014**, *6*, 10435-10456. https://doi.org/10.3390/rs61110435

Stray Light Artifact

- In Landsat-8 TIRS, a stray light feature was discovered in imagery soon after launch
  - Confirmed by off-axis scans of the moon and by high-fidelity optical modeling
  - Out-of-field radiance was scattering in the optical system
- Stray light affects every pixel differently
- An algorithm was developed to estimate the per-pixel contribution of stray light to the earth imagery
  - Applied to Landsat-8 TIRS data starting in Collection-1 (2016)
- Design changes to the baffles in Landsat-9 TIRS reduced the total stray light contribution by >10x
  - No need to use the correction algorithm on Landsat-9 data

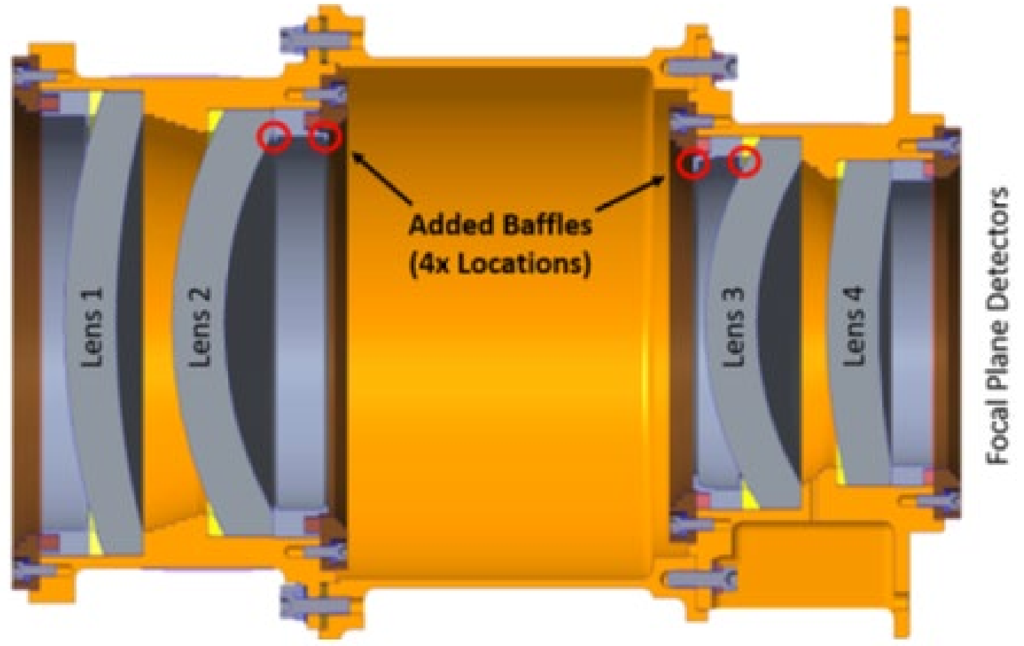
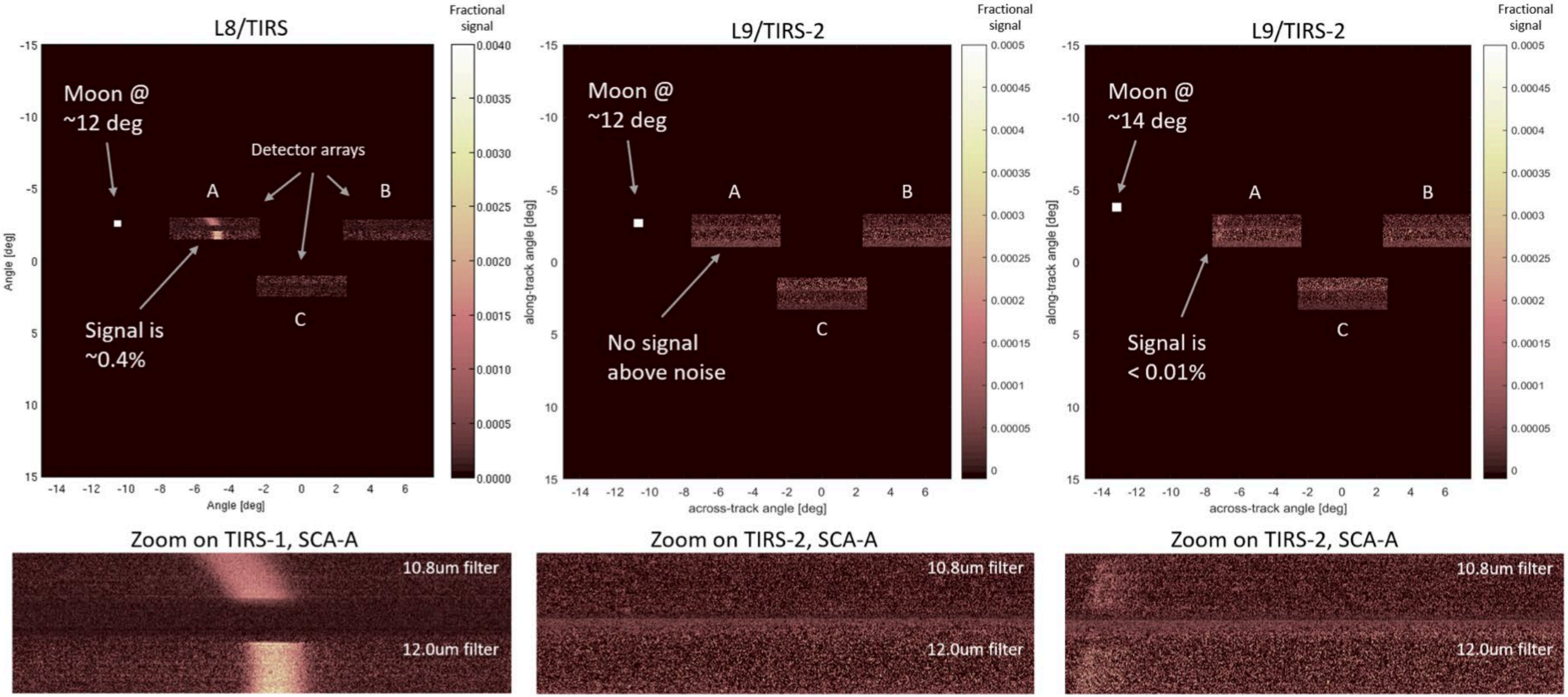


Fig. 1. Cross-section of the TIRS-2 telescope assembly indicating the locations of the added baffles to reduce the effect of scattering over the baseline design.

Matthew Montanaro, Joel McCorkel, June Tveekrem, John Stauder, Eric Mentzell, Allen Lunsford, Jason Hair, and Dennis Reuter, "Landsat 9 Thermal Infrared Sensor 2 (TIRS-2) Stray Light Mitigation and Assessment," *IEEE Transactions on Geoscience and Remote Sensing*, submitted February 2022.

Stray Light Artifact



~0.4% scattering from this source location

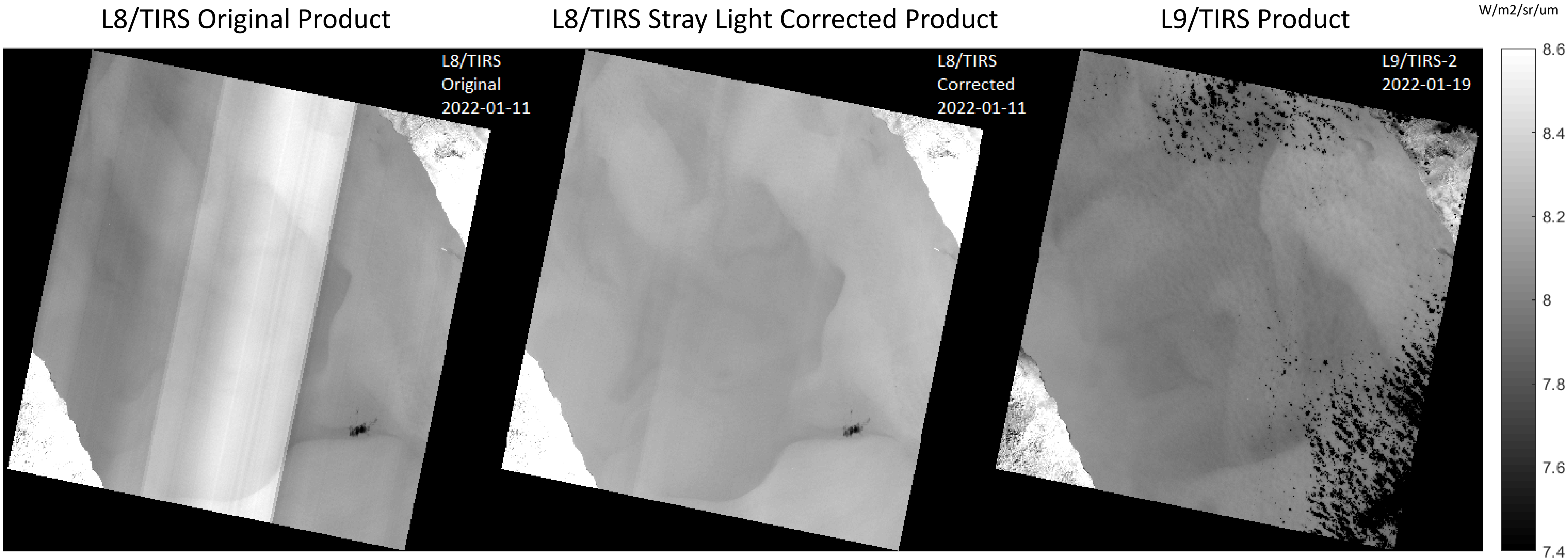
No detectable scattering

< 0.01% scattering

Matthew Montanaro, Joel McCorkel, June Tveekrem, John Stauder, Eric Mentzell, Allen Lunsford, Jason Hair, and Dennis Reuter, "Landsat 9 Thermal Infrared Sensor 2 (TIRS-2) Stray Light Mitigation and Assessment," *IEEE Transactions on Geoscience and Remote Sensing*, submitted February 2022.

Effect of Stray Light in Imagery

L8/TIRS Original Product | L8/TIRS Stray Light Corrected Product | L9/TIRS Product



On-Orbit Radiometric Performance

Monitored by internal calibrator system: variable temperature blackbody and views of deep space

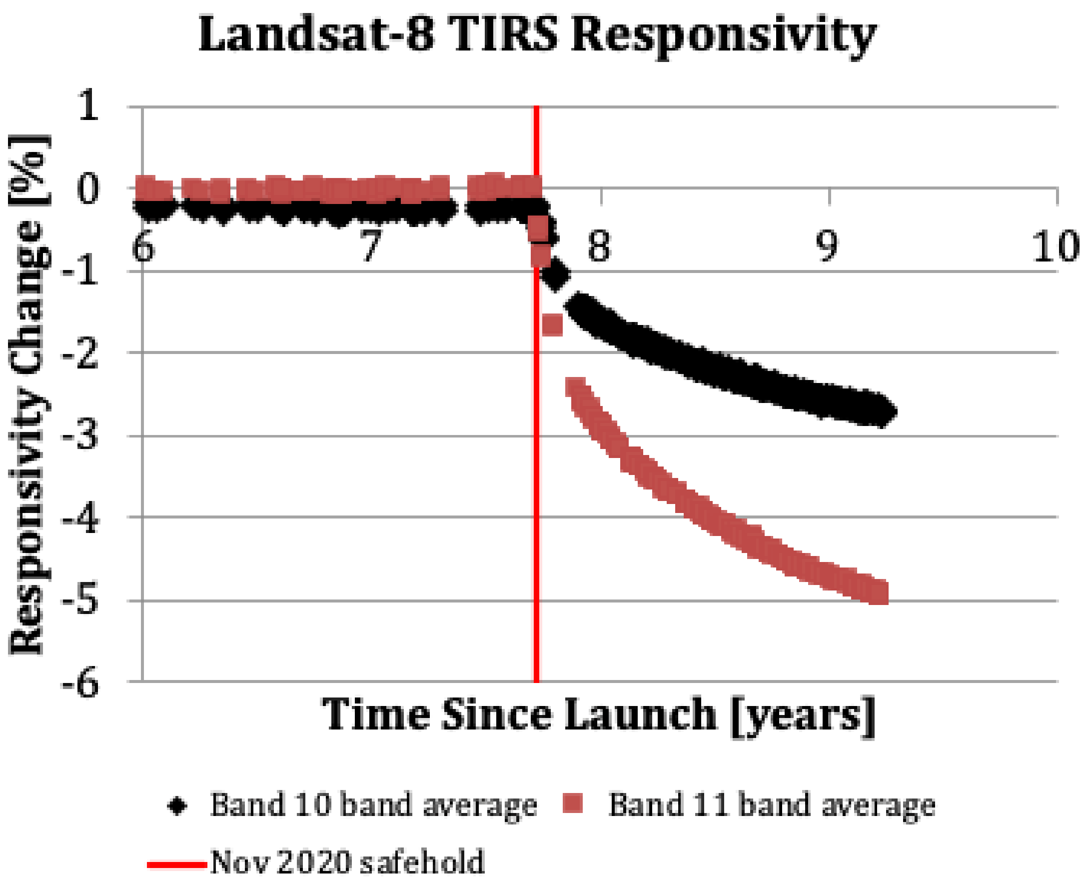
- Stability over time
  - *Dark response over 36 min : stable to better than 0.1% **
  - Blackbody response over time
- Noise performance
  - *NEΔT : <<0.1K at 300K in both instruments*
  - *Coherent noise : meets requirements, not a significant concern **
- *Uniformity across the field of view : relative gains updated quarterly to reduce striping*
- *Instrument responsivity, linearity : calibration parameters can be updated if changes are detected*

* Aaron Pearlman, Boryana Efremova, Matthew Montanaro, Allen Lunsford, Dennis Reuter, and Joel McCorkel, "Landsat 9 Thermal Infrared Sensor 2 On-Orbit Calibration and Initial Performance," *IEEE Transactions on Geoscience and Remote Sensing*, submitted March 2022.

Radiometric Stability
Landsat-8 TIRS

Responsivity stability estimates here are based on the 295K blackbody acquisitions

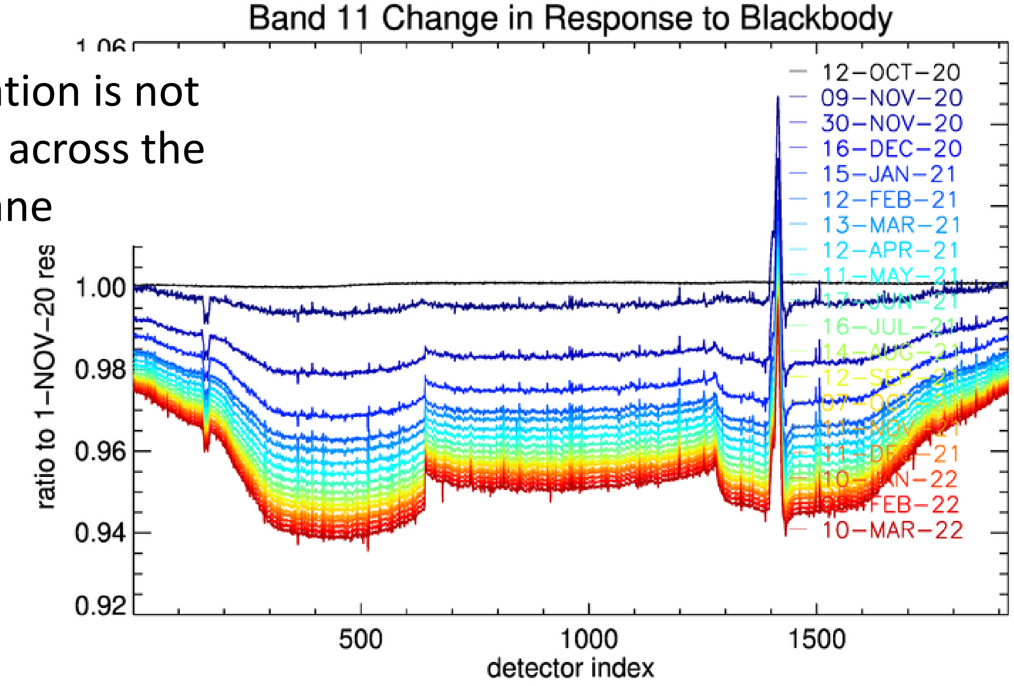
- Prior to Nov 2020, the internal calibration system indicated that TIRS was stable to better than 0.05%/year.
- A spacecraft safehold in Nov 2020 resulted in the powering down of the instruments and loss of thermal control
- After control was recovered, internal calibration data indicated the responsivity was changing
  - Initially at ~0.5%/week in B11
  - Stabilized to ~0.025%/week in B11

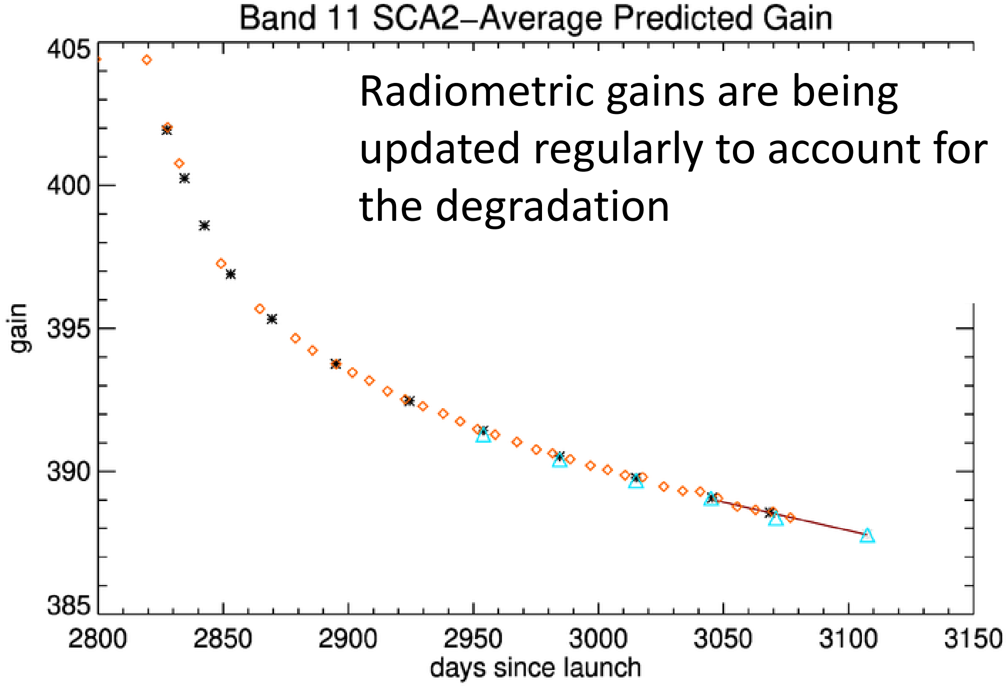


L8 TIRS Calibration Adjustment

Degradation in responsivity is likely due to a slow build-up of a contaminant

Degradation is not uniform across the focal plane





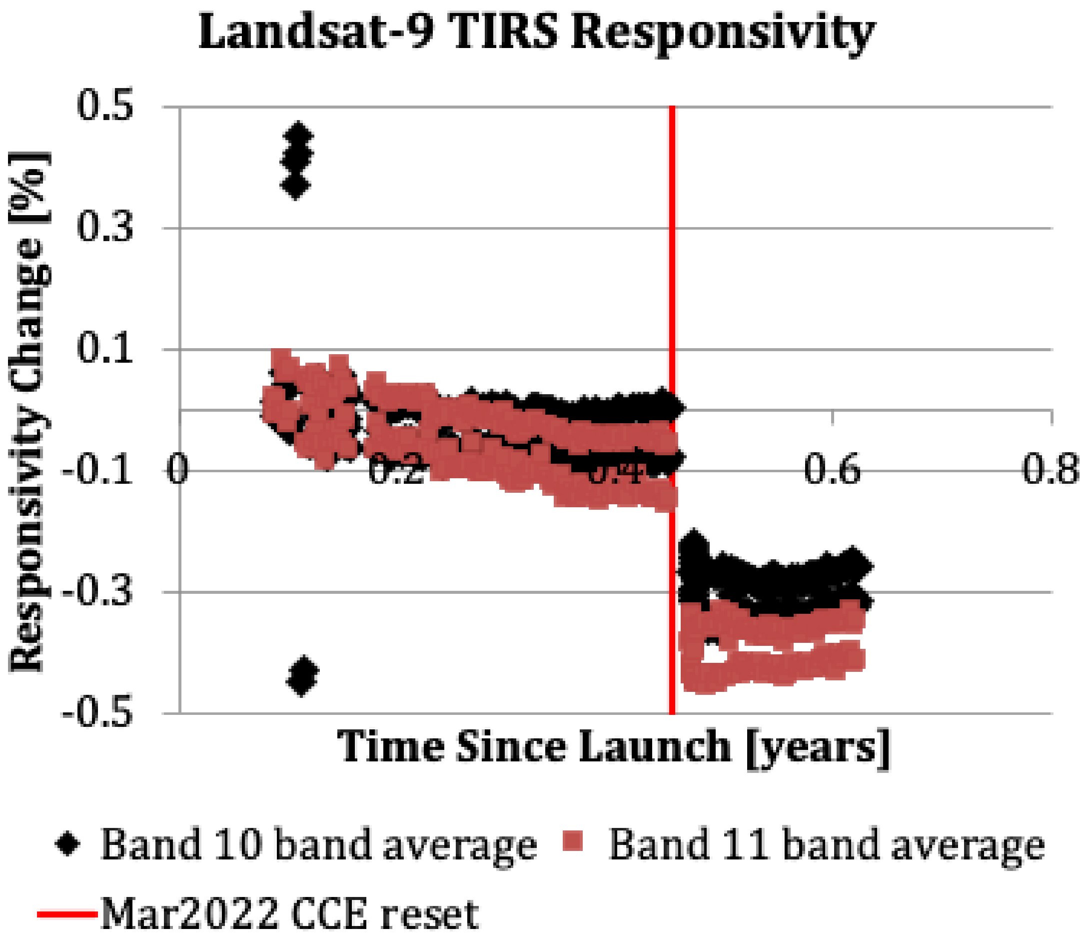
Radiometric gains are being updated regularly to account for the degradation

This degradation in TIRS responsivity is transparent to users of Level-1 and Level-2 data products

Radiometric Stability
Landsat-9 TIRS

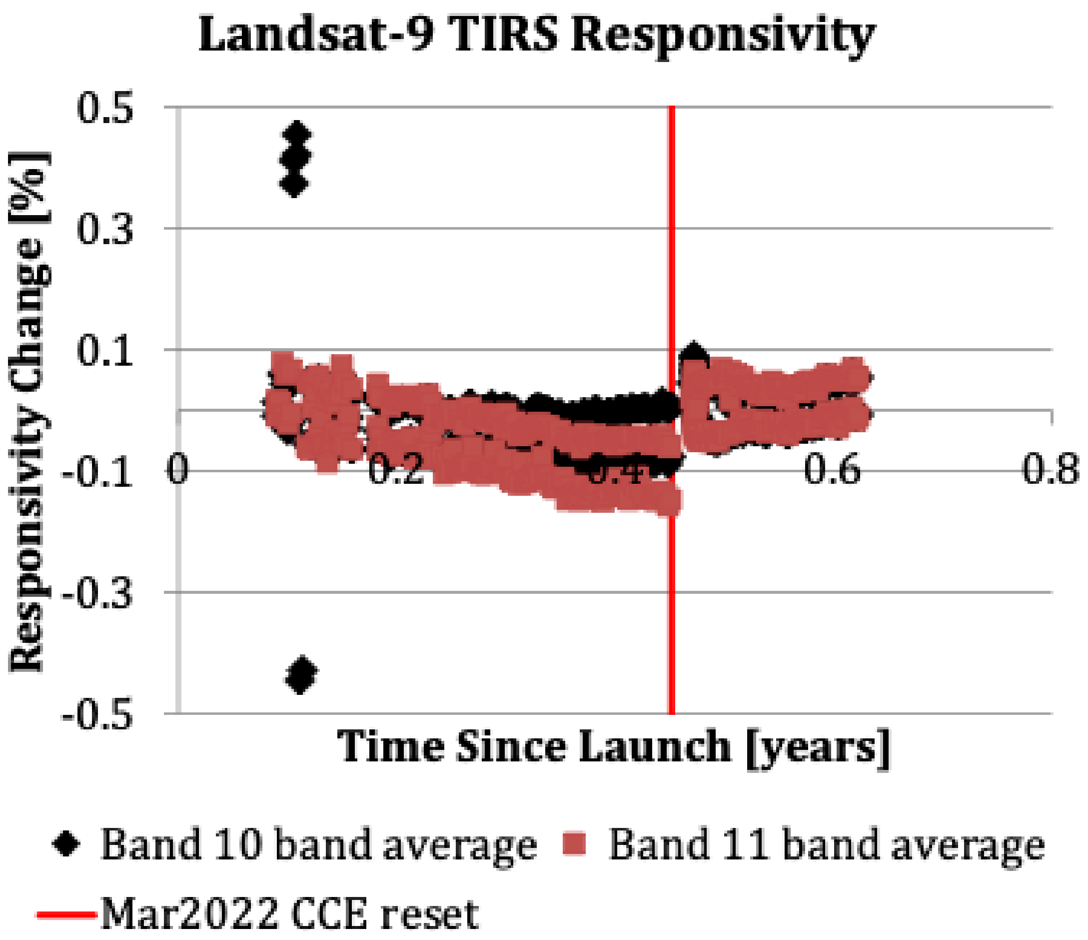
Responsivity stability estimates here are based on the 295K blackbody acquisitions

- Prior to Mar 2022, the internal calibration system indicated that TIRS was stable to better than 0.05%.
- A TIRS Croycooler Electronics reset in March 2022 resulted in the powering down of the instrument and loss of thermal control
- After control was recovered, internal calibration data indicated the responsivity changed by ~0.2%



Radiometric Stability
Landsat-9 TIRS

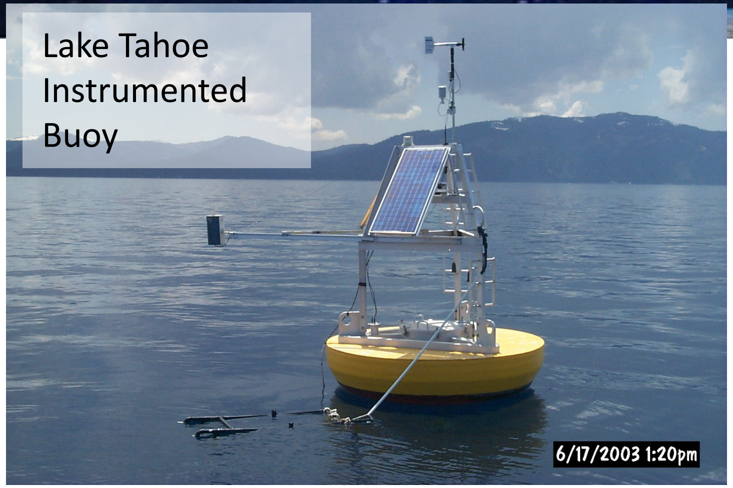
- On-board calibration sequence was performed to establish the new radiometric gains
  - Blackbody temperature sweep
- Radiometric gains were updated to account for the change
  - Instrument is stable to better than 0.1%
- **This change in TIRS responsivity is transparent to users of Level-1 and Level-2 data products**



Vicarious Calibration Methodology

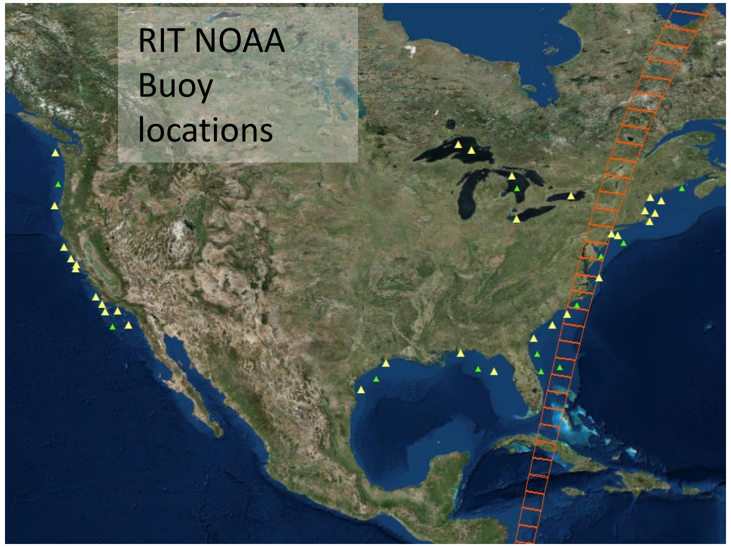
Jet Propulsion Lab (JPL) operates network of instrumented buoys on Lake Tahoe and Salton Sea

- temperature ranges 4-35C
- night and day coverage



Rochester Institute of Technology mines network of NOAA coastal buoys around the US

- temperature ranges 3-30C
- day coverage only



Vicarious Calibration Methodology

Surface measurements are propagated through the atmosphere and converted to sensor-reaching radiance

$$L_{TOA} = \varepsilon L_T \tau + L_u + L_d(1 - \varepsilon)\tau$$

where

L_T is the surface-leaving radiance

τ, L_u, L_d are atmospheric parameters determined by running radiance propagation code

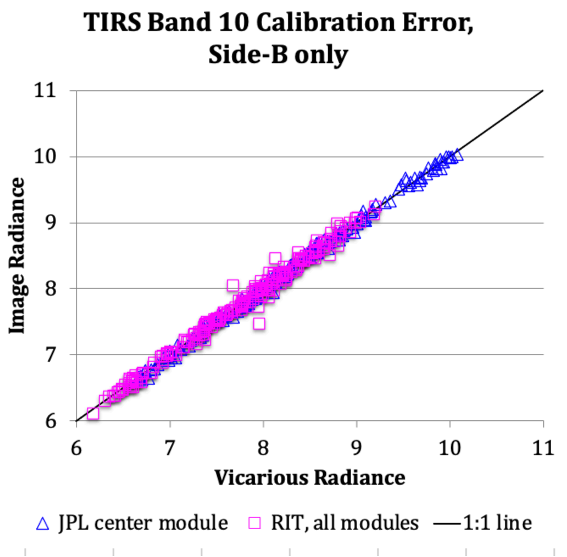
ε is emissivity of water

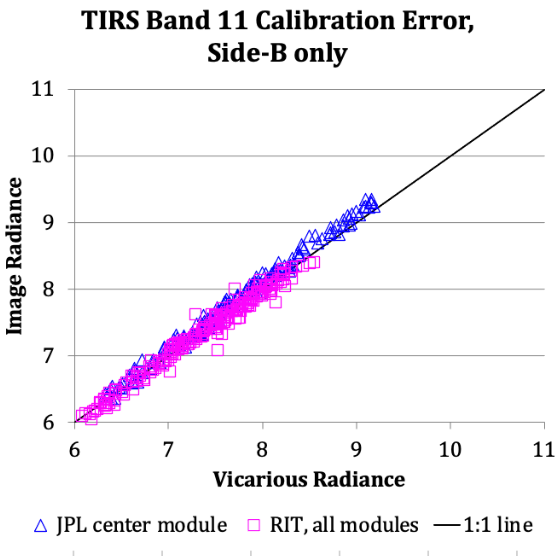
Sensor reaching radiance (L_{TOA}) can be compared directly to the the TIRS radiance.

Current results

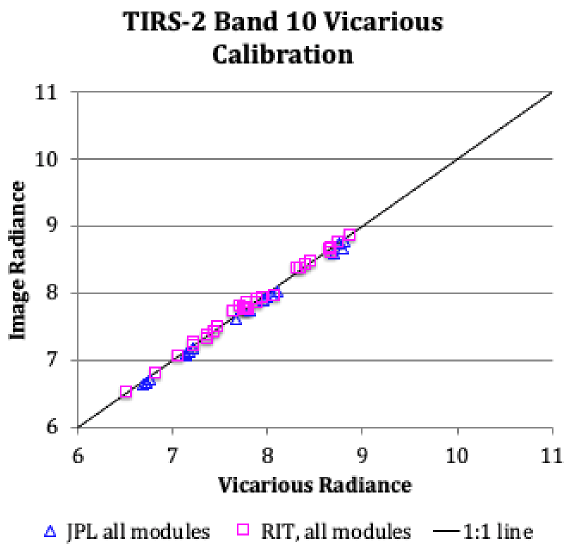
- Landsat-8 TIRS absolute calibration was updated with Collection-2
- Landsat-9 TIRS absolute calibration is based on the prelaunch calibration, with an adjustment made for the shift after the CCE reset (March 2022)

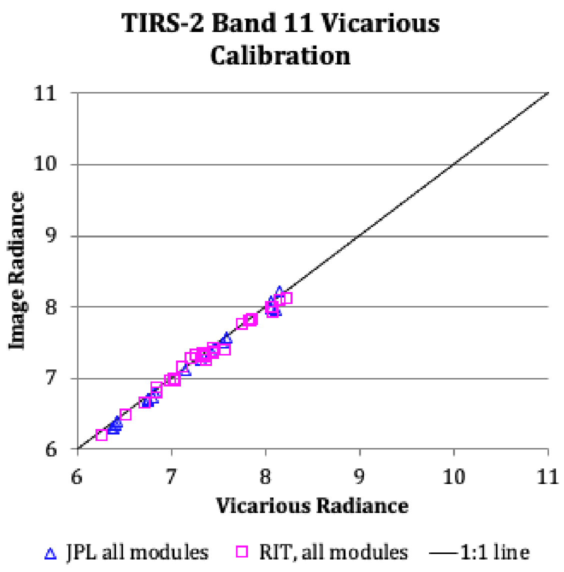
Landsat-8





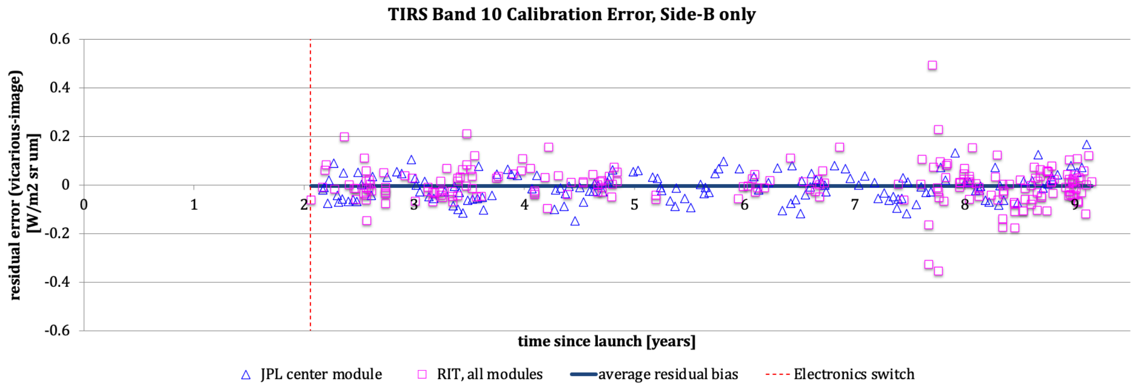
Landsat-9

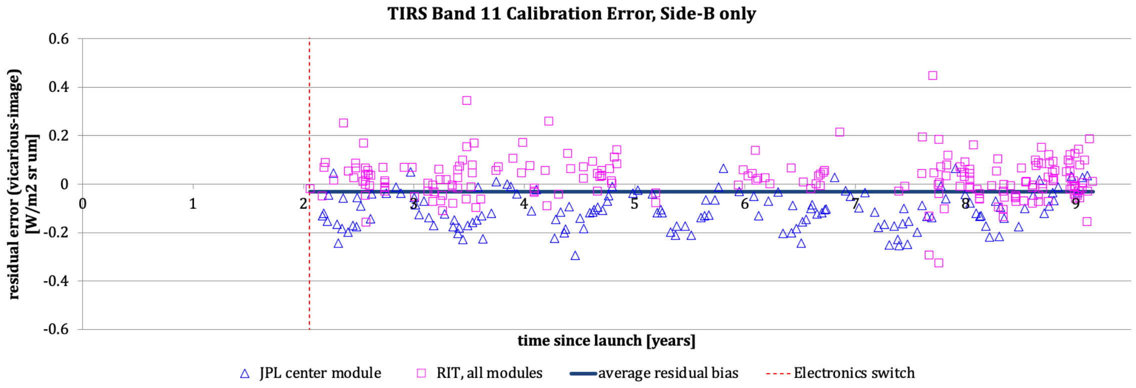




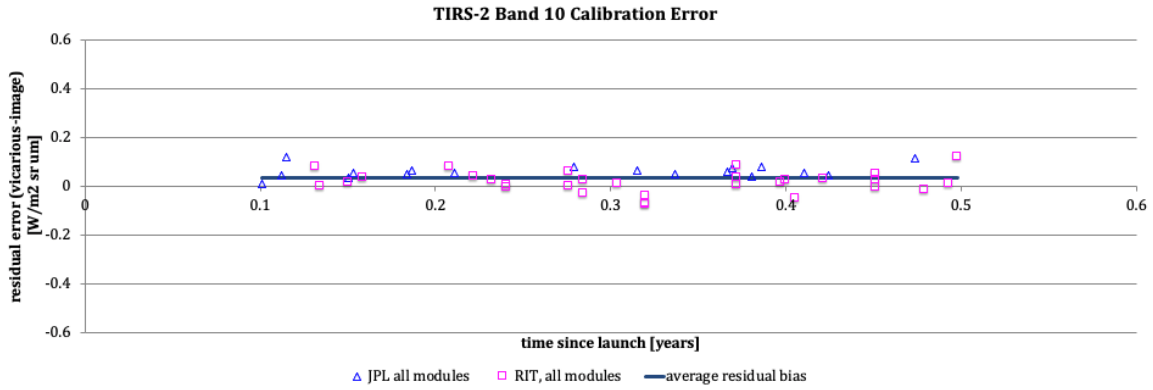
Current results
residual error over time

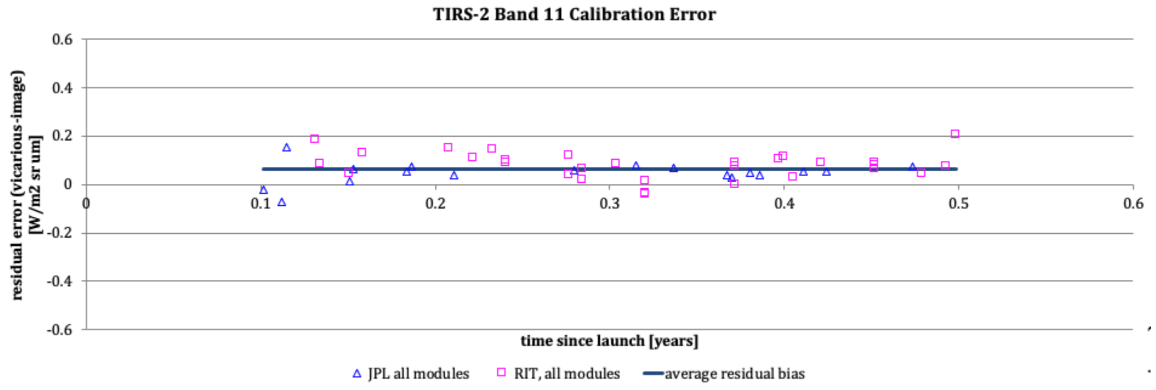
Landsat-8





Landsat-9





Current results
Vicarious Calibration Summary

Landsat-8

Daytime Side-B	N	Residual Error [K @ 300K]	RMSE [K]
B10	356	0.02	0.5
B11	356	0.25	0.9

Landsat-9

Daytime	N	Residual Error [K @ 300K]	RMSE [K]
B10	35	0.16	0.3
B11	35	0.61	0.5

Landsat-7 ETM+

Daytime	N	Residual Error [K @ 300K]	RMSE [K]
B6	1236	0.00	0.4

Summary and Conclusions

- Landsat-9 TIRS Radiometric instrument performance is excellent, exceeding requirements
  - Landsat 9 TIRS-2 has negligible amount of stray light (On-orbit tests match prelaunch stray light expectations)
  - Stable within a power-on cycle; on-board calibrator indicates stability to better than 0.1%
  - Low noise
  - Early suggestion of small calibration error, but vicarious calibration results suggest data can be calibrated to within 0.5K in both bands
- Landsat-8 TIRS Radiometric instrument performance meets requirements after post-processing
  - Responsivity is degrading but updates to the calibration parameters are tracking the change
  - Low noise
  - After Collection-2 update, calibrated to within 0.5K for Band 10 and 0.9K for Band 11
- Early Landsat-9 results will be available soon
  - Matthew Montanaro, Joel McCorkel, June Tveekrem, John Stauder, Eric Mentzell, Allen Lunsford, Jason Hair, and Dennis Reuter, "Landsat 9 Thermal Infrared Sensor 2 (TIRS-2) Stray Light Mitigation and Assessment," *IEEE Transactions on Geoscience and Remote Sensing*, submitted February 2022.
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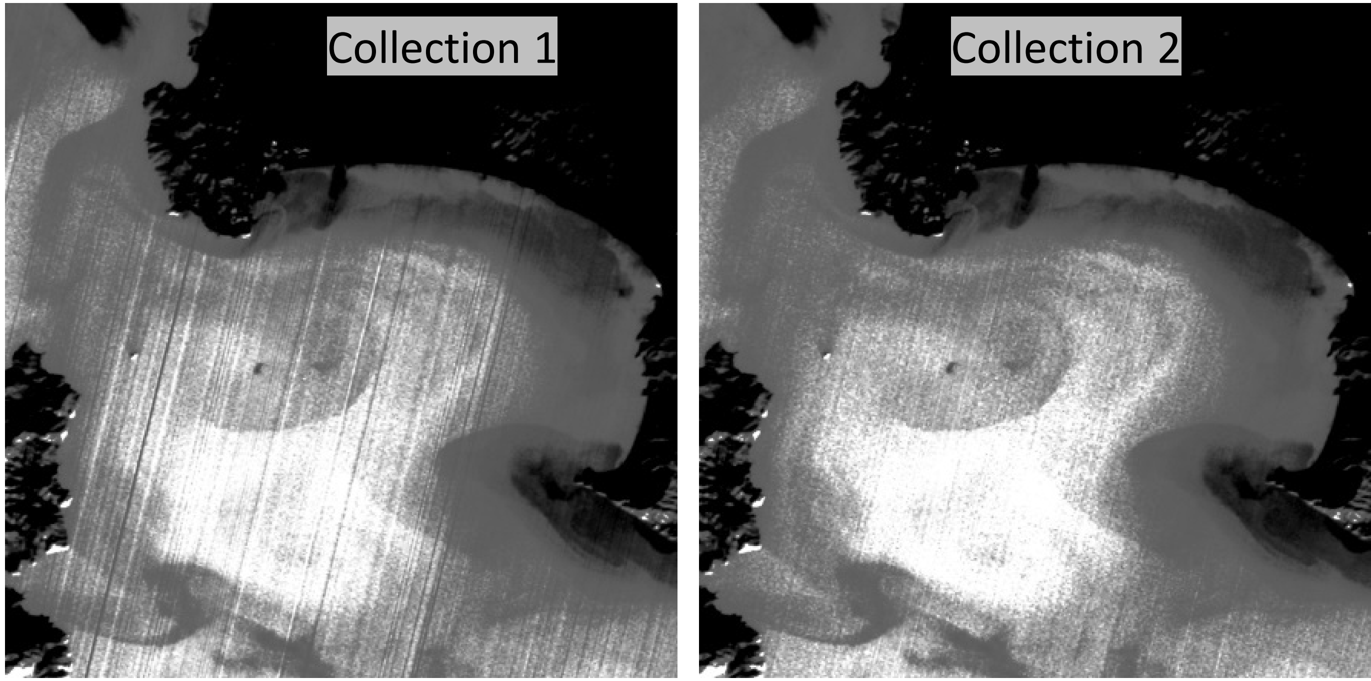
Uniformity

- With almost 2000 detectors in each band, per-detector normalization is a challenge
- Landsat-8 TIRS relative gains were found to change slowly over time and the drift was not being corrected for
- Starting in 2020, with the introduction of Collection-2, the relative gains are updated on a quarterly basis for Landsat-8 TIRS
- Same process is used for Landsat-9 TIRS

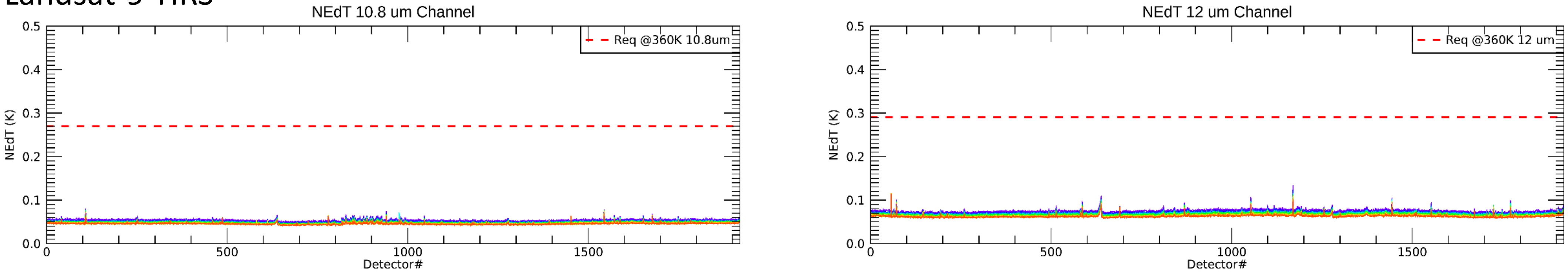
TIRS - Relative Gain Improvement



Noise performance: NEDT

Noise Equivalent Delta-Temperature is monitored using the on-board blackbody

Landsat-9 TIRS



Landsat-8 and Landsat-9 noise performance is very similar. Table shows the average of the median(NEDT) over the last six months.

Median(NEDT) at 300K	Landsat-8 [K]	Landsat-9 [K]
B10	0.048	0.048
B11	0.054	0.066

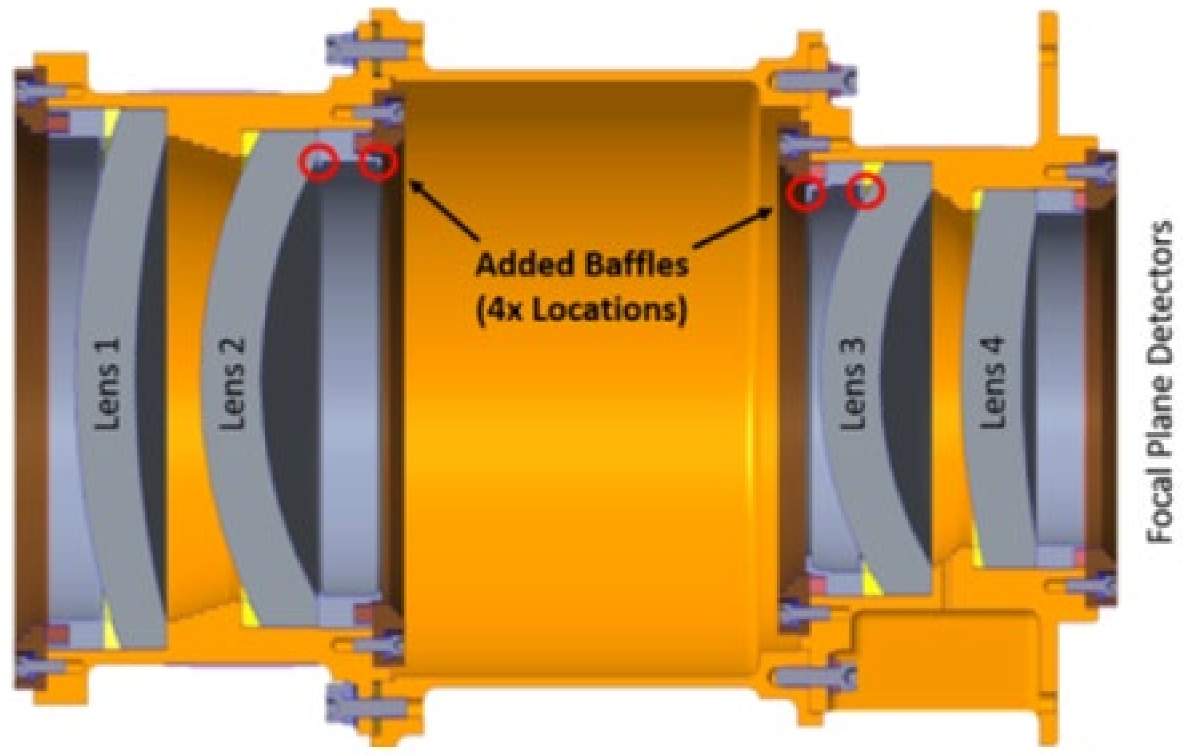


Fig. 1. Cross-section of the TIRS-2 telescope assembly indicating the locations of the added baffles to reduce the effect of scattering over the baseline design.

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On-orbit responsivity

- Temperature Sweep data
  - On-orbit process to cycle the blackbody between 260 and 340K over two days.
  - Derive per-detector calibration parameters from the resulting TIRS data
    - Linearity correction, relative gain and absolute gain
  - Performed semi-annually for regular performance assessment
  - Also performed when necessary, as in after instrument resets