I2R Innovative Imaging & Research

Reducing the Size of Thermal Infrared Imagers by Using an On-board Imaging Transfer Radiometer

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Problem

- The NASA Sustainable Land Imaging program desires a 60 m thermal imaging sensor or better
- As an instrument's spatial resolution improves the aperture increases the size of the instrument and on-board calibrator

Thermal Imager	GSD	Aperture Required (at 705 km)
Landsat TIRS	100	~110 mm
Future Thermal Imager †	60	~200 mm

† NASA-SLI-001 Land Imaging Requirements Rev B.xlsx

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Landsat-(SLI) TIRS Specification

	Band 10	Band 11
Center Wavelength [μm]	10.8	12.0
Center Wavelength Tolerance [μm]	0.2	0.2
Minimum Lower Band Edge [μm]	10.3	11.5
Maximum Upper Band Edge [μm]	11.3	12.5
Typical Temperature [K]	300	300
Typical Radiance [(W/(m^2 sr μm)]	9.64	8.94
Saturation Temperature [K]	360	360
Saturation Radiance [W/(m^2 sr μm)]	20.5	17.8
NEΔL [W/(m^2 sr μm)]	0.059	0.049
NEΔT at 240K [K]	0.80	0.71
NEΔT at 300K [K]	0.40	0.40
NEΔT at 360K [K]	0.27	0.29
Min Edge Slope - In-track [1/m] (60 m GSD or less)	0.143	0.143
Min Edge Slope - Cross-track [1/m]	0.143	0.143

Equivalent Black Body Temperature Range	Absolute Radiance Uncertainty (1-σ)
240K-260K	< 4%
260K-330K	< 2%
330K-360K	< 4%

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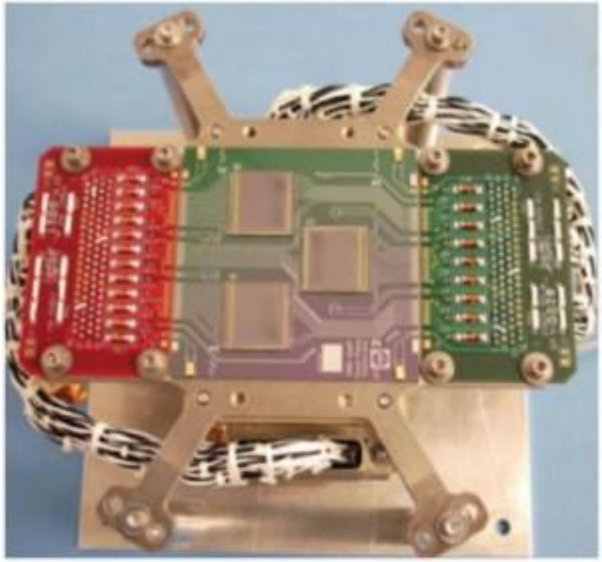
Landsat-8 Thermal Infrared Radiometer System (TIRS)

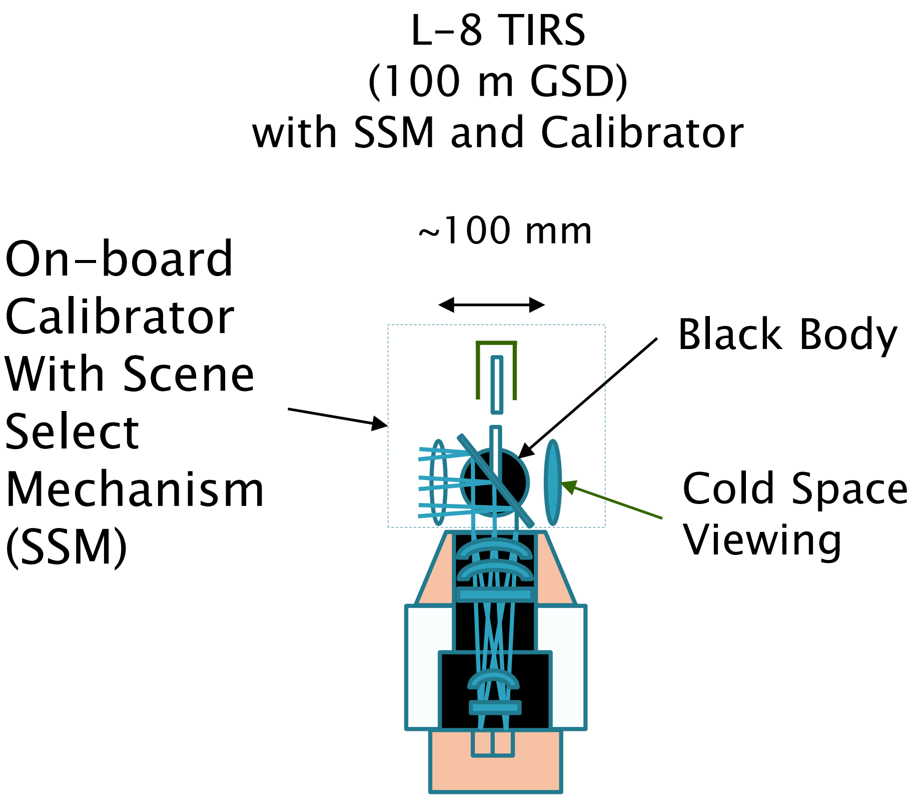
- Pushbroom sensor
- 4 element refractive telescope
- f/1.64
- Focal Length 178 mm
- Aperture 109 mm
- 3 cryogenically cooled QWIP arrays (640 detectors each)
- Operates at 43K
- Detector 25 x 25 microns
- Split band at 10.9 and 12.0 μm
- 15 deg. FOV with a 185 km swath
- Three year design life



Irons, J.R., et al., The next Landsat satellite: The Landsat Data Continuity Mission, Remote Sensing of Environment (2012), doi:10.1016/j.rse.2011.08.026

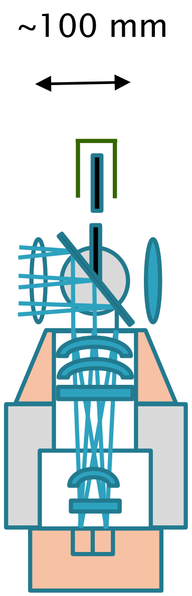
Traditional Calibration Approach

- Scene selector to select ground, on-board black body viewing, or deep space (cold look)
- Augment with vicarious and cross calibration



Landsat Thermal Imager and Calibrator Size with GSD

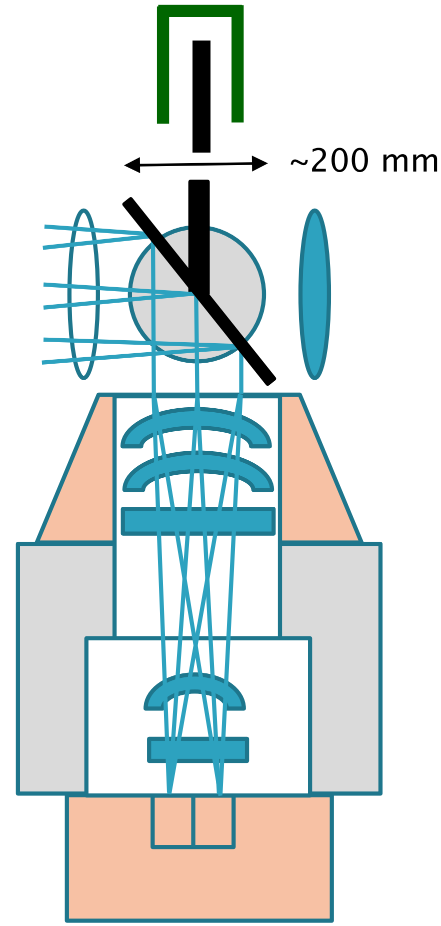
L-8 TIRS
(100 m GSD)
with SSM and Calibrator



Next generation TIRS increases in size significantly with decreasing GSD

Traditional full aperture calibration is sizable fraction of total instrument

Potential L-10 TIRS
(60 m GSD)
with SSM and Calibrator



Alternative: Compact Thermal Imaging Calibrator (CTIC)

- Perform on-board calibration with a separate small imaging radiometer that has coarser resolution than the primary thermal imager
- Incorporate a traditional temperature selectable blackbody calibrator on the separate smaller imaging radiometer
- The smaller imaging radiometer becomes a transfer radiometer providing continuous cross calibration with the following advantages
  - Coincident imaging
  - Same viewing angle
  - Same spectral response
  - Co-registered (boresighted and then resampled)

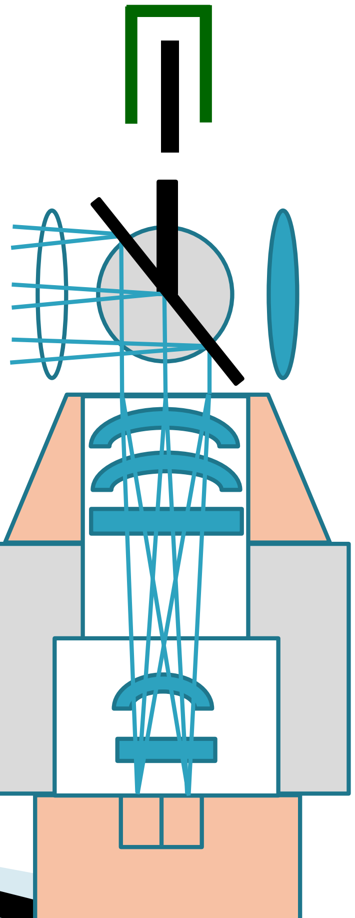
CTIC vs Traditional Cross Calibration

Parameter	Traditional Cross Calibration	Optimized CTIC
Spectral Bandpass	Error associated with spectral mismatch is usually introduced (unless a hyperspectral imager is used)	Designed to have a near identical spectral bandpass as primary instrument to reduce spectral mismatch errors
Time of Acquisition	Temporal mismatch of minutes or more between data is sensitive to changes in the atmosphere and surface	Simultaneous acquisition (within a few seconds of primary instrument)
Geometry	Usually different geometry due to physical offset of instruments	Near identical geometry minimizes angular atmosphere & surface property differences
Swath	Comparison instrument potentially smaller than primary instrument	The same or larger swaths provides complete coverage across primary sensor
Number of samples	Limited by orbital mechanics and the number of coincident collections	Continuous simultaneous data collections results in many samples per pixel per orbit

Landsat Thermal Imager and Alternative Calibrator Size Comparison

L-10 TIRS
(60 m GSD)
with SSM[†] and Calibrator

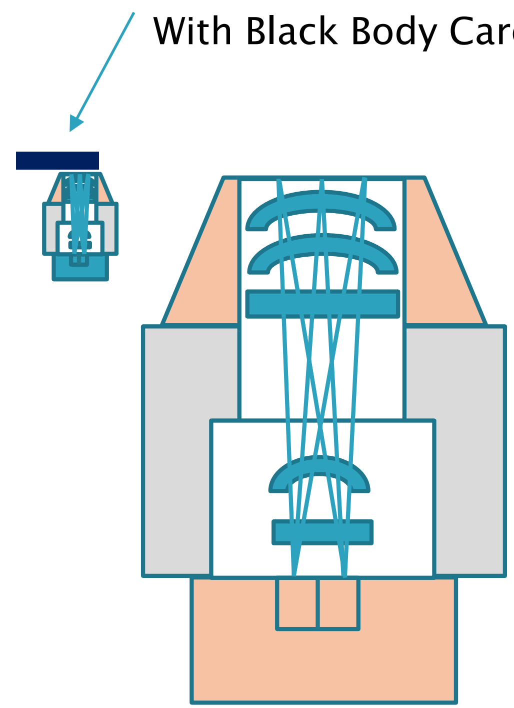
[†] SSM-Scene Select Mechanism



L-10 TIRS
(60 m GSD) without SSM
with Transfer Radiometer Calibrator

~40 % smaller total payload without SSM Solution

Transfer Radiometer
With Black Body Carousel



Transfer Radiometer Size and Sensitivity Scaling

- Aperture inversely proportional to GSD
  - For fixed F# the optical volume ~$(1/GSD^3)$
- Fine resolution and coarse resolution imagery slowly decorrelates with PSF/GSD ratio over uniform areas
  - Patch size for small uniform areas drives transfer radiometer GSD
- NEΔT depends on F#, integration time and detector technology

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Imaging Transfer Radiometer Benefits

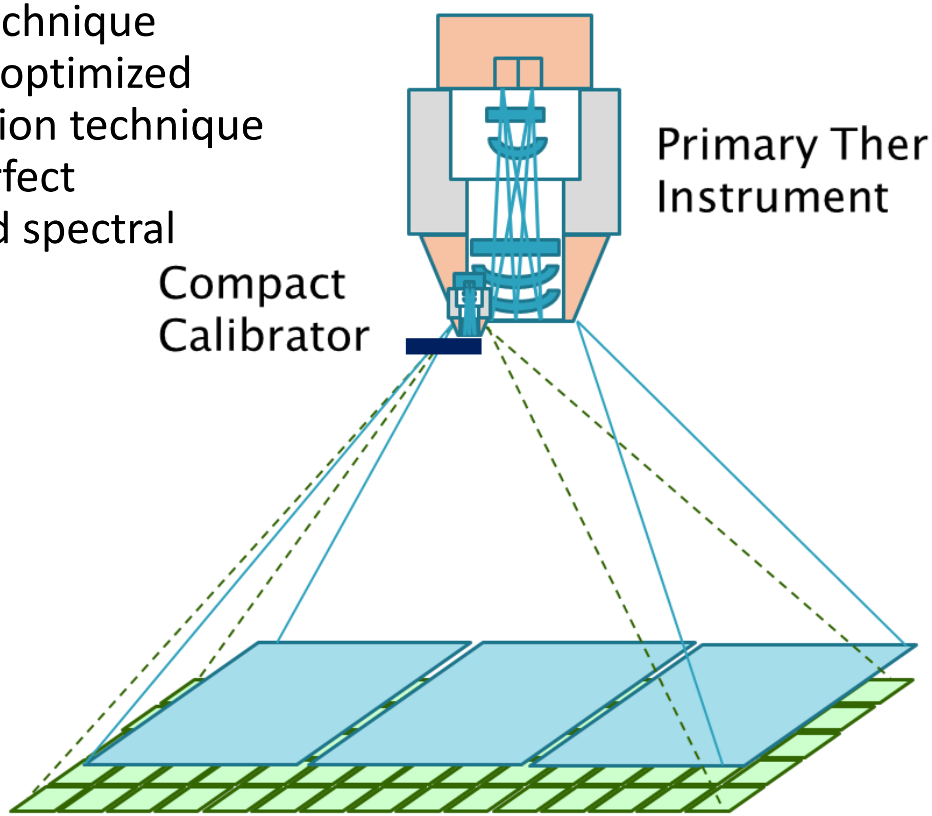
- Since the calibrator has coarser resolution the calibrator is much smaller than primary instrument
  - Improved thermal management
  - Potential for improved blackbody capability in terms of radiometry and temperature range
  - Simplified implementation
    - Less expensive uncooled detectors can be considered (e.g. thermal time constant not a driver)
  - Reduces the power, volume and mass of the calibrator by order of magnitude or more

Comparison of CTIC and the Primary SLI-TIRS Instrument

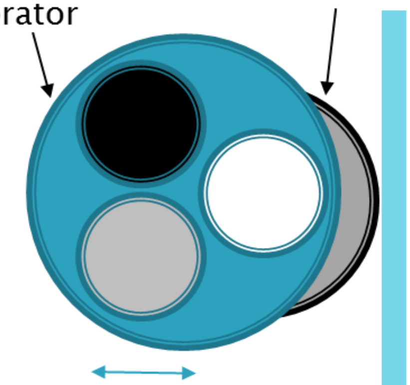
Parameter	SLI-TIRS Instrument	CTIC Value
Spectral Bands	TIRS B10 and B11	TIRS B10 and B11
GSD	<60 m	> 5x primary GSD (300 m or greater for a 60 m TIRS instrument)
Swath	185 km	185 km or greater
Optical Aperture	~200 mm (Dabney and Masek 2015)	<1/6 diameter of the primary instrument. (<~30 mm for f/1, 12 μm detectors). Expect this value can be decreased
NEDT	<0.4 K for a 300K scene	~0.4 K; Expect this values can be increased due to the number of samples
Calibration	Large complex SSM with onboard Black Body	Cavity blackbody with emissivity >0.99 with 45° mirror mounted on a simple carousel pointed toward space for cold space looks
Detector	Cooled detector (unless large progress in uncooled detector occurs)	Uncooled or cooled detector; NEDT and thermal time constants are not a large driver. (Uncooled preferred)

CTIC Concept

Calibration technique emulates an optimized cross-calibration technique with near perfect geometry and spectral response



Thermal Imagery with Simultaneous Coarse Resolution Calibrator Imagery

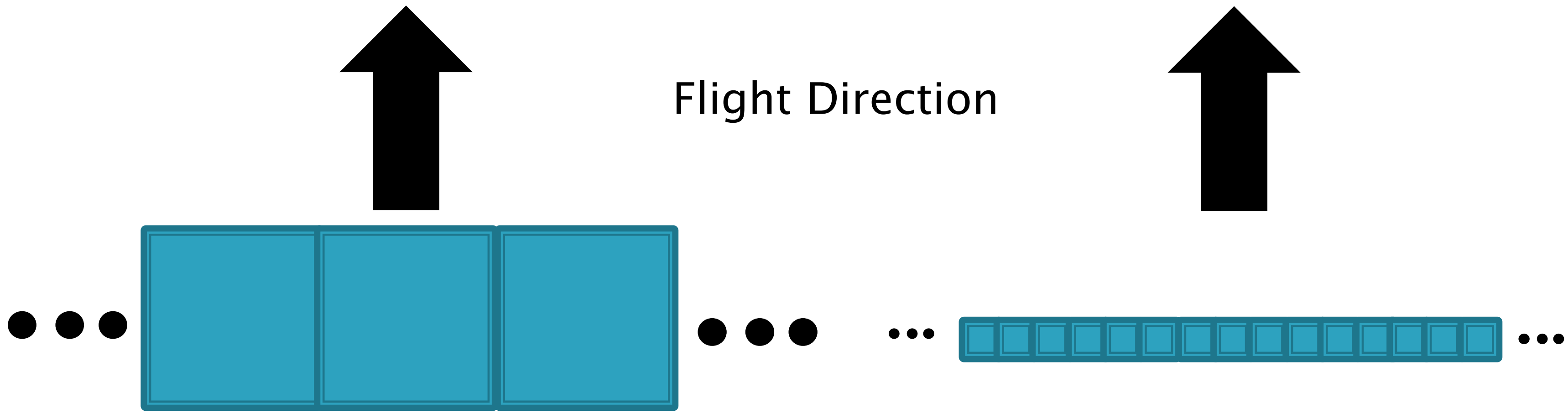


Front View

Transfer Radiometer – Primary Sensor Pixel Comparison (Pushbroom Architecture)

Transfer Radiometer
coarse resolution ~300 m pixels

Primary Sensor
fine resolution 60 m pixels



185 km Swath is ~616 pixels cross track

185 km Swath is ~3100 pixels cross track*

In this example the coarse resolution pixels are ~ 5x larger than the primary sensor pixels

- Slightly more pixels are needed if there is a requirement to have pixels <=60 m across the swath

Early Simulation (TIRS B10 Data)

- Acquired Path 28 Rows 20-33 Level 1R imagery for TIRS B10 data
- Seamed together all the rows into one continuous image for different FPA/SCA (640 pixels across) 640x23520 single

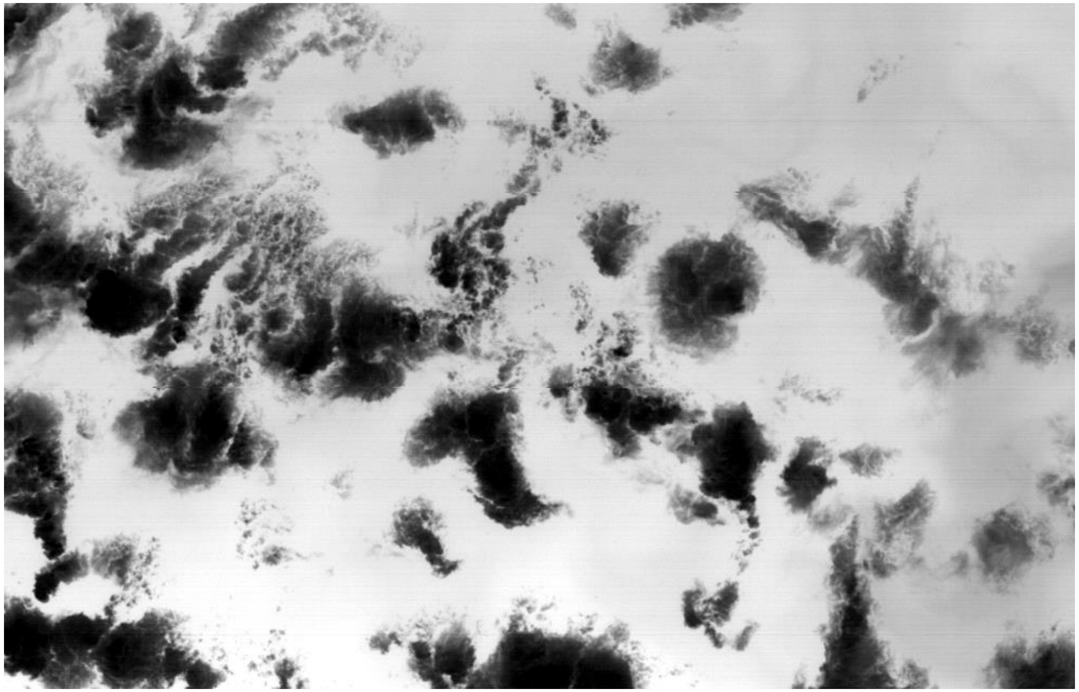
- Simulated Transfer Radiometer with sampling (misregistration) and blur associated with Transfer Radiometer 128x4704 (5x GSD)

- Interpolate (upscale) transfer radiometer data to primary sensor resolution
- Create x,y pairs Original imagery (x) vs Transfer Radiometer (y)
- Regress results and analyze statistics to create pixel-by-pixel calibration/correction

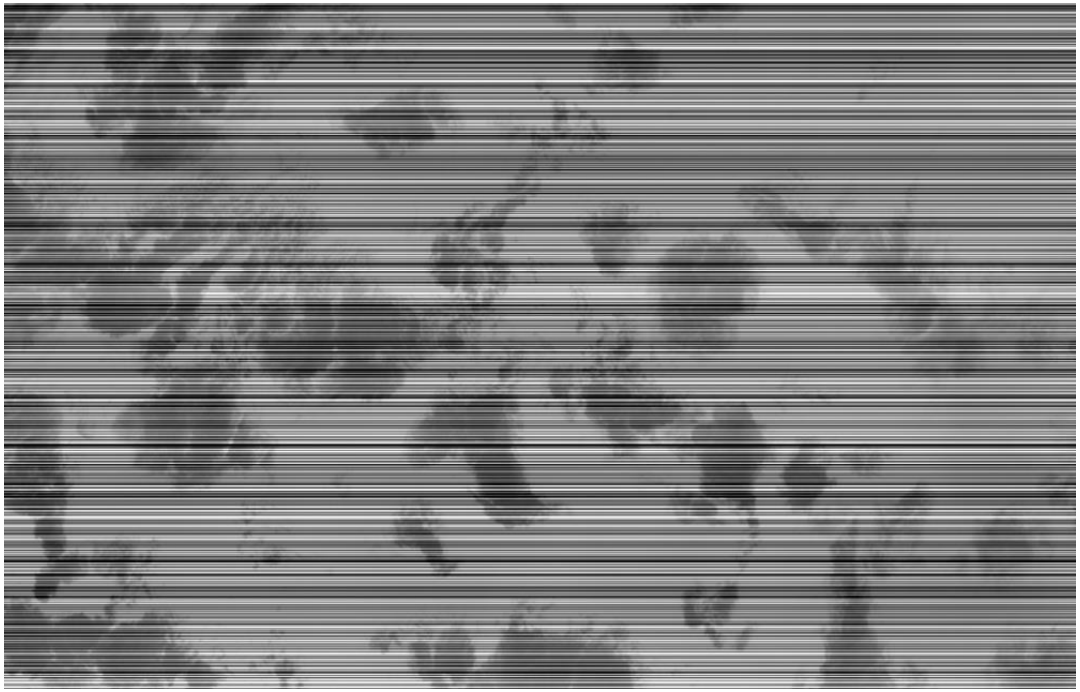
Example Simulation Parameters

- Outlier Rejection 3.0 STD of Residuals
- Transfer Radiometer (TR) Noise 0.06 W/(m2 sr micron) (~Same SLI Requirement)
- TR GSD Scaling 5x
- In-track averaging 5 pixels for primary instrument and upscaled Transfer radiometer for each x,y pair

Original TIRS Image Path 28 Row 20

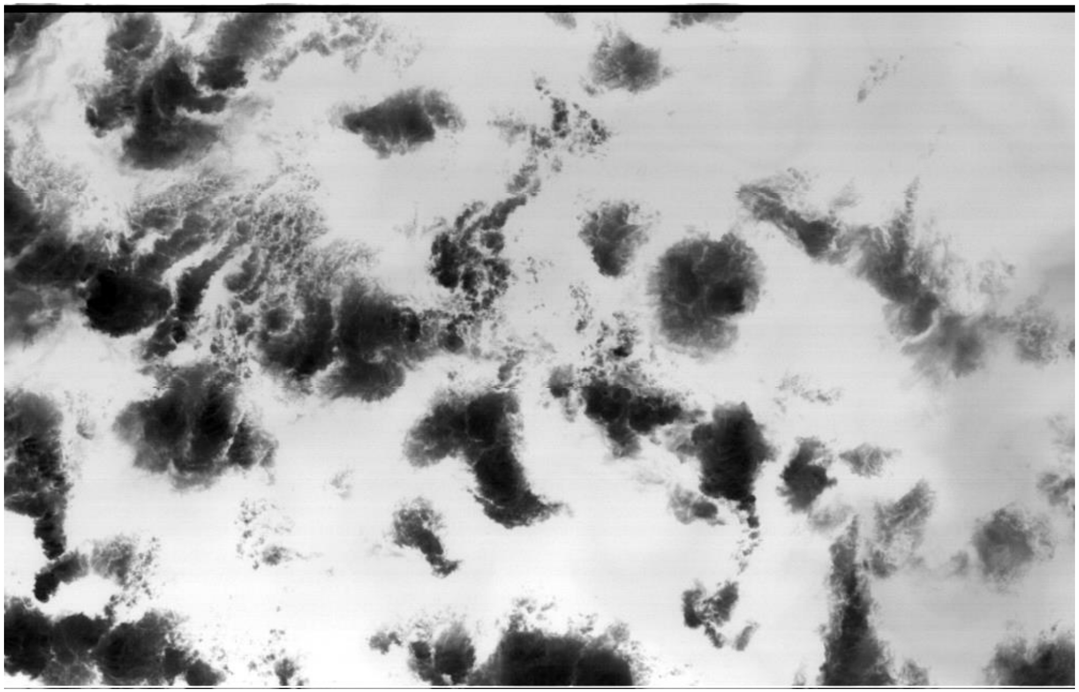


Simulated Raw Image

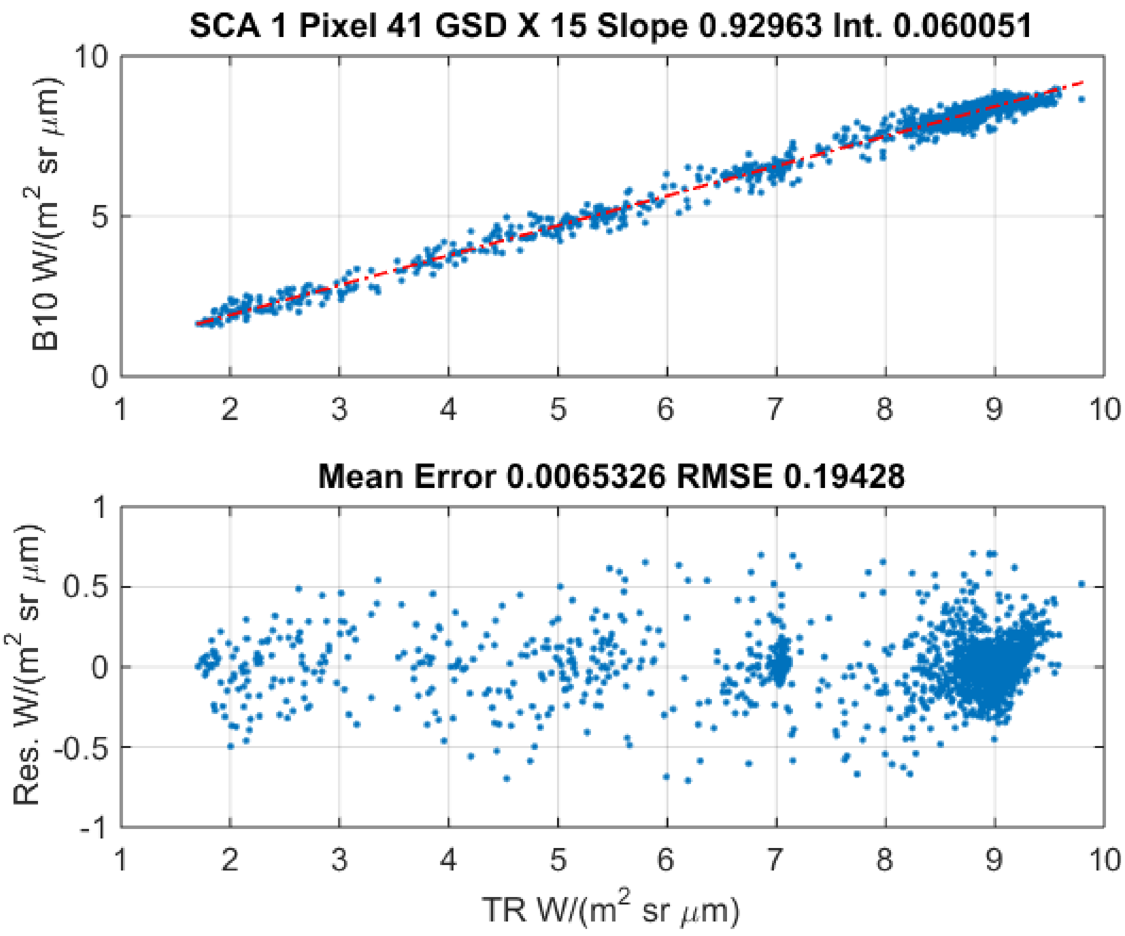


Introduced large gain and offset for each pixel

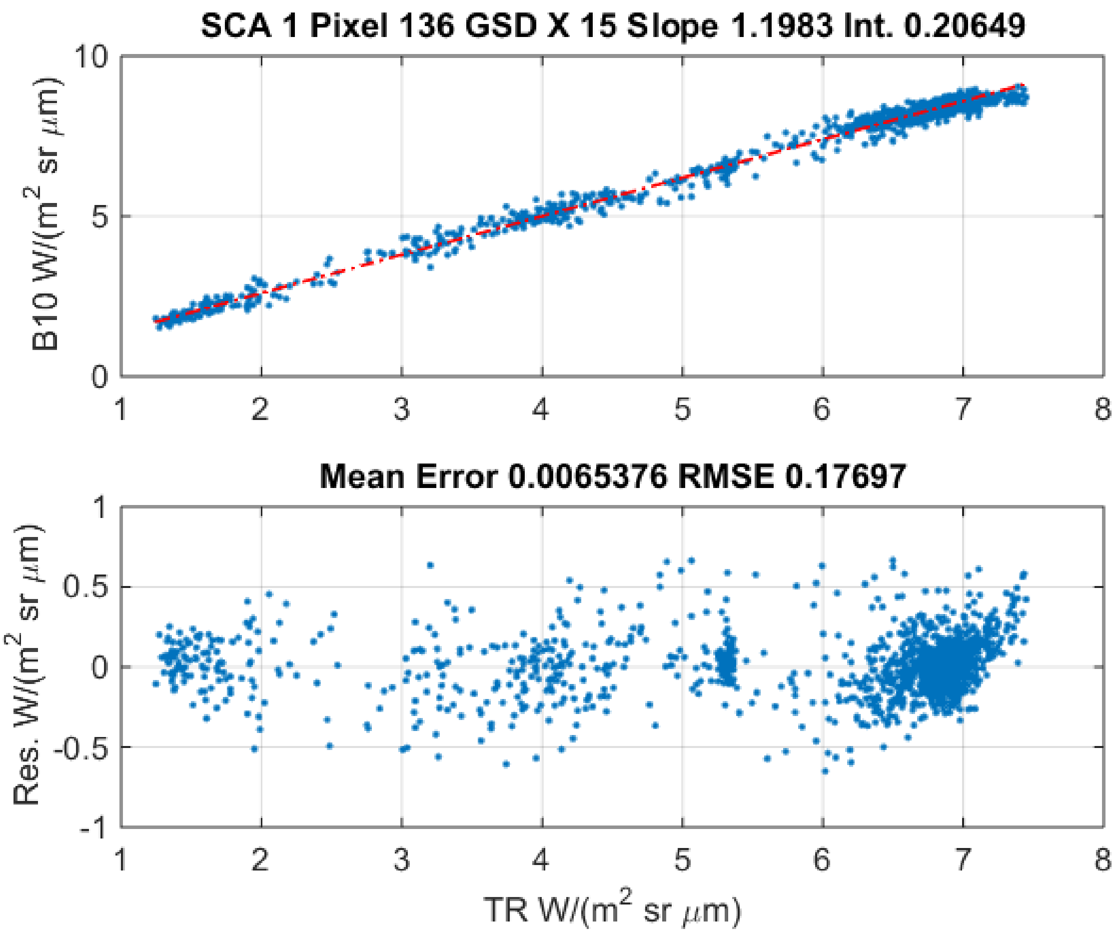
Transfer Radiometer Corrected Image



Sample Regression Between Transfer Radiometer and Simulated Primary Instrument



Sample Regression Between Transfer Radiometer and Simulated Primary Instrument



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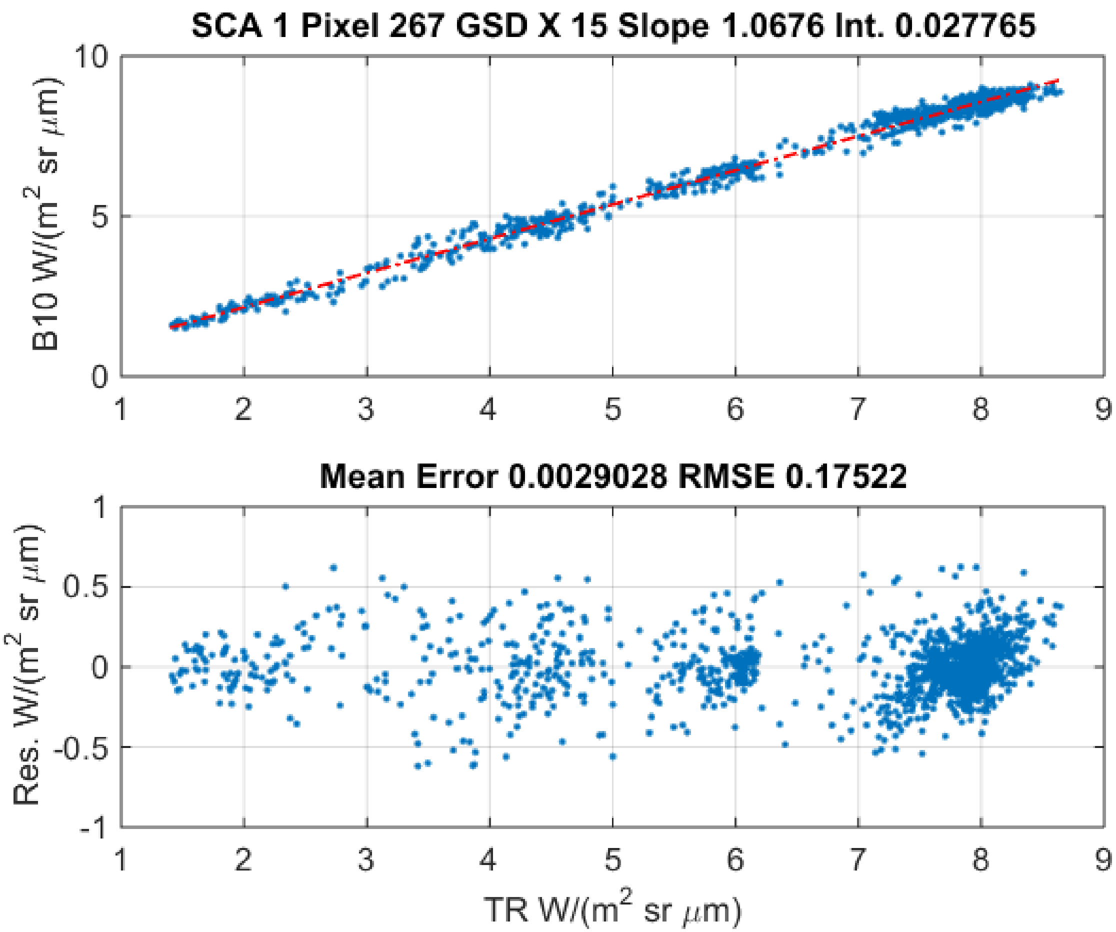
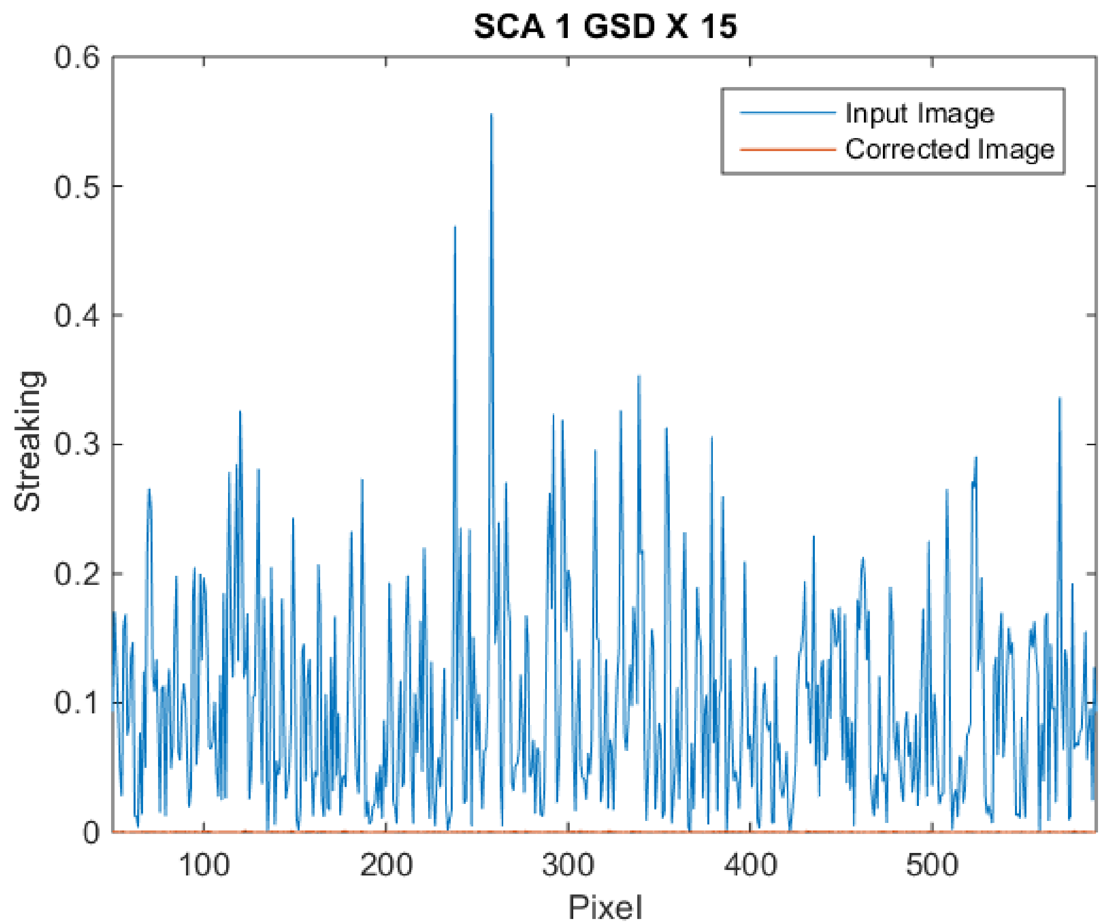
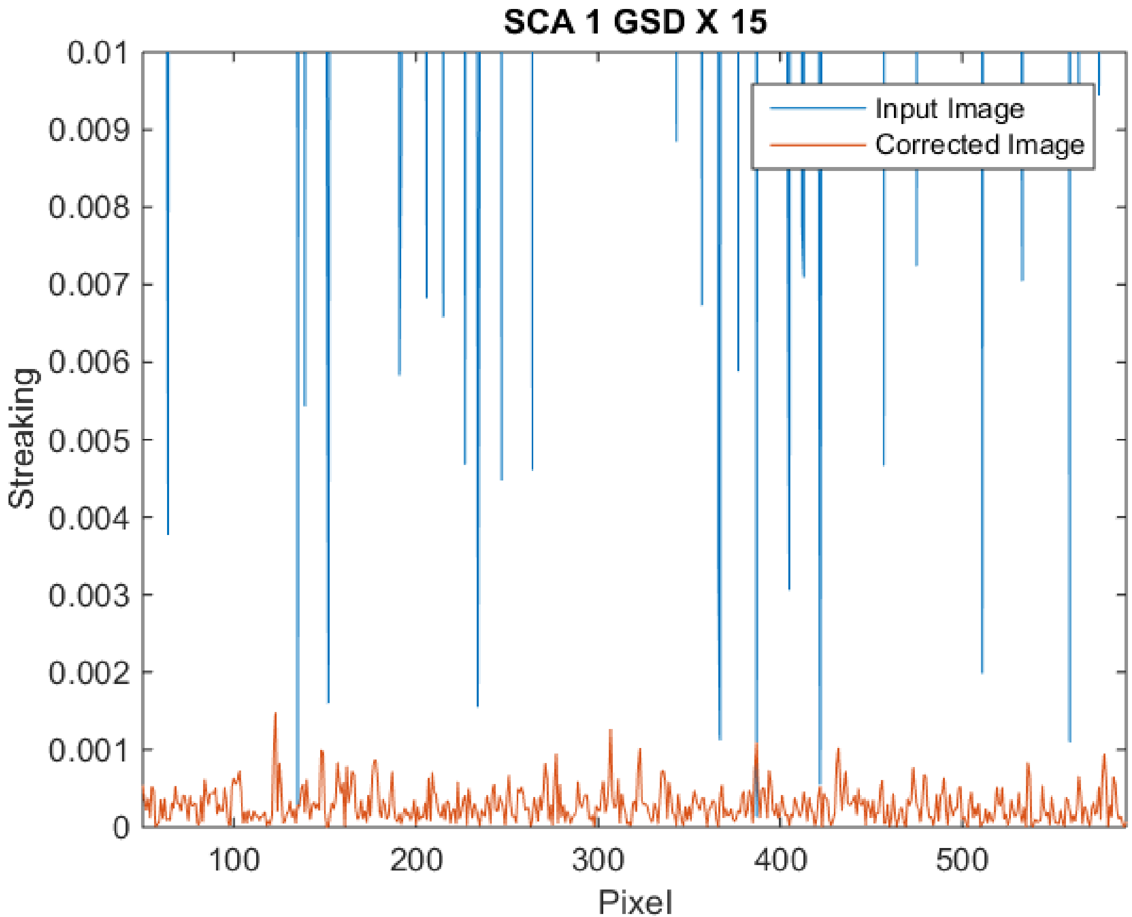


Streaking Correction with CTIC

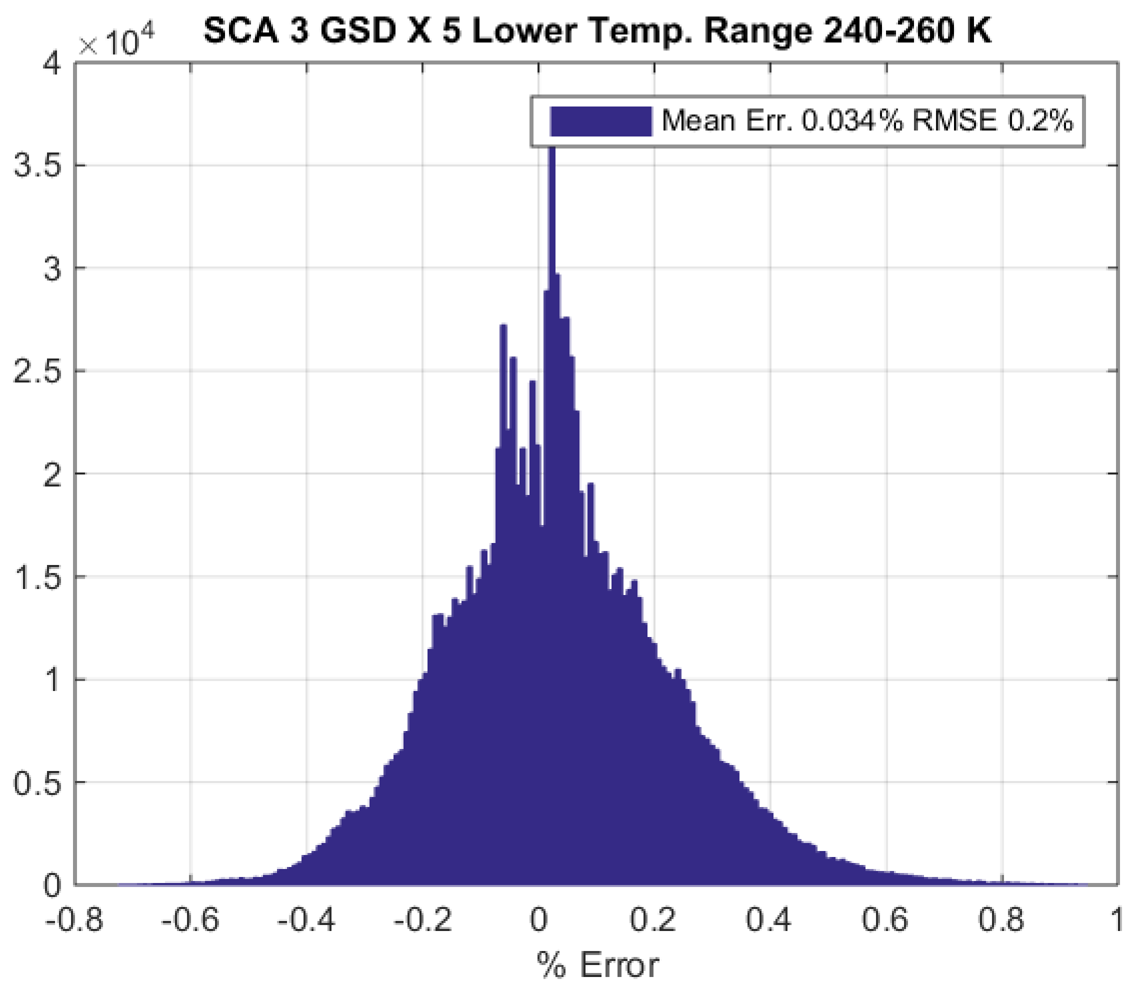


Streaking Correction with CTIC

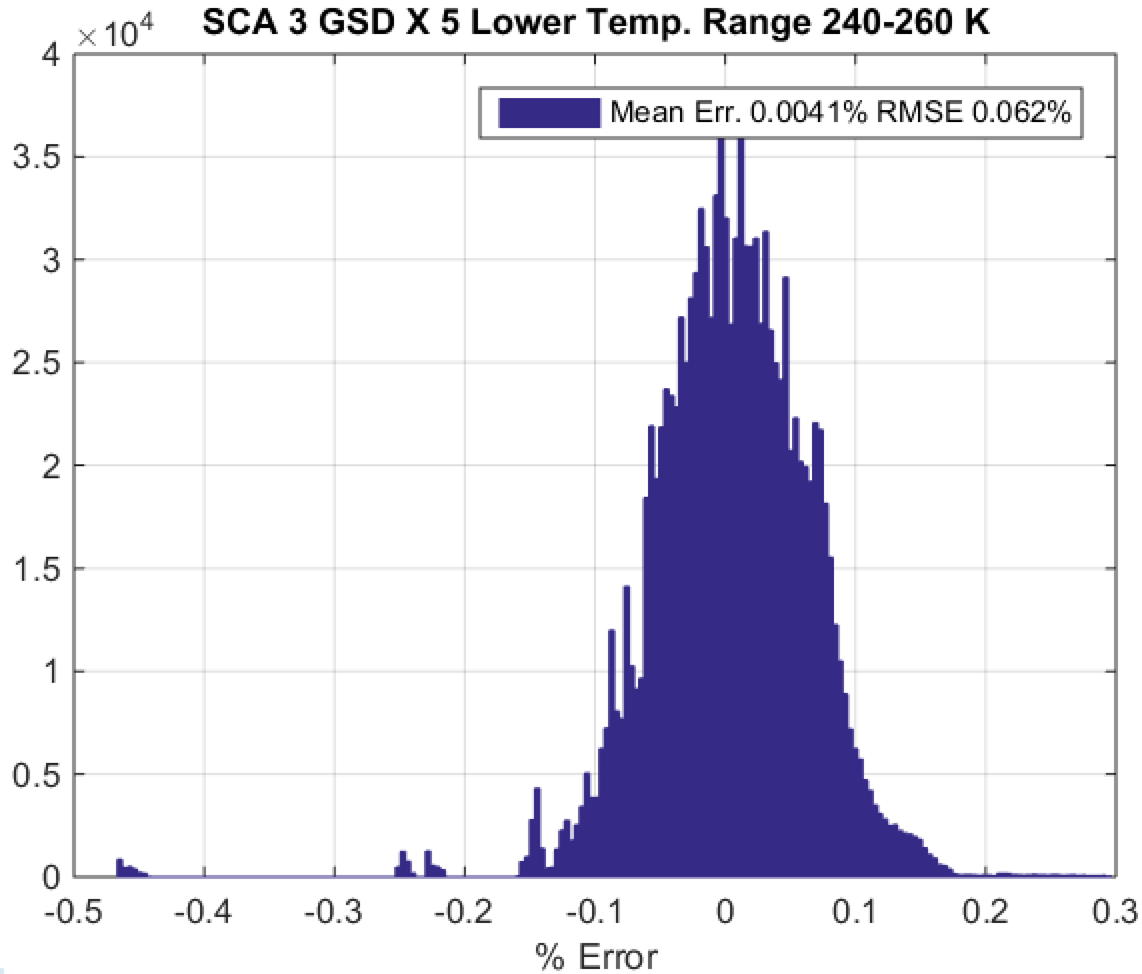


Better than 0.5% requirement

Example Difference Between Original and Corrected



Example Difference Between Original and Corrected (Cold Look)



Preliminary Overall Uncertainty Budget

CTIC Transfer Radiometry Uncertainty (Regression Residuals) Expected<0.5%

CTIC/Primary Instrument Spectral Response Differences (Regression Residuals) Expected<0.5%

CTIC Absolute Radiometry Uncertainty Expected<1.0%

Expected overall error under 2% for all cases

Possible Concept of Operations

- Assume transfer radiometer is stable for at least a single orbit and near continuously acquiring imagery during primary sensor acquisitions
  - Transfer radiometer internal calibration occurs twice an orbit (or a few quick black body looks can be used to achieve stability)
  - Possible cold sky looks
- If 400 scenes a day are taken, each orbit collects ~28 scenes
  - Then each SCA column has ~ 17,000 (~616*28) independent samples for 5xGSD implementation to derive a calibration correction per orbit

Early Simulation Summary

- The comparison between the two sets of pixels show that they are highly correlated and the slope is close to unity and offset is small
- Early results indicate that pixel-by-pixel absolute calibration appears possible
  - Flat Fielding also promising
- Expect improvements with more Landsat rows
  - Current analysis only with about the 50% of the rows acquired in a path
- More analysis with additional path rows needed to determine how robust and universal the results are
- Although not shown, small geolocation misregistration between the transfer radiometer and high resolution instrument do not seem to affect the results significantly

Uncooled Microbolometer Implementation

- Initial analysis indicates microbolometers could be a candidate detector technology for a low cost implementation
  - Low power
  - Reliable no mechanical cooler
  - Relatively simple
- MTF and RER is not as critical for a coarser resolution instrument as compared to primary instrument
- Recent developments with 12 micron detectors could provide a compact solution
  - NEΔT 40-50 mK with f/1 optics
  - Initial assumption NEΔT transfer radiometer goals are L8 (averaging could relax requirement)

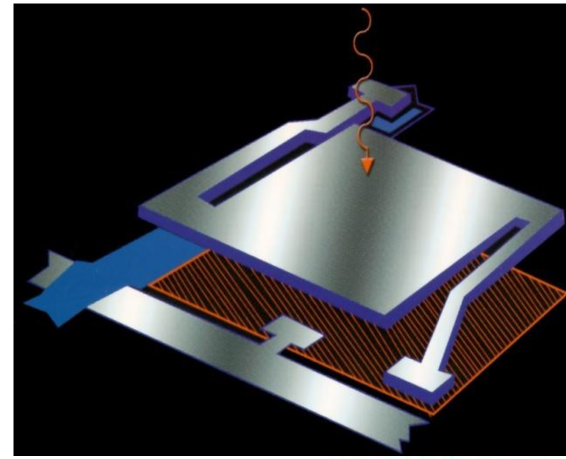
Uncooled Silicon Microbolometer FPA Characteristics

Typical Focal Plane Sizes

320x240 pixels(~25-50 µm pitch)
640x480 pixels (~25 µm pitch)
1024x1024 pixels (~17 µm pitch)
1x512 pixels (~40 µm pitch)

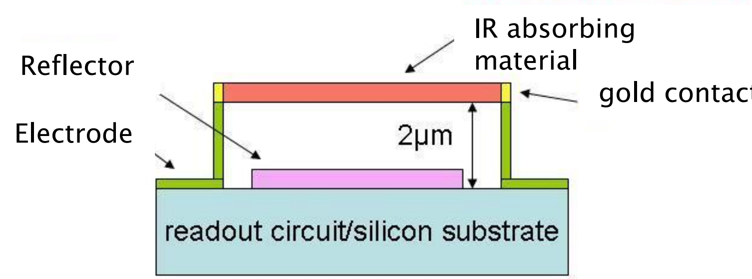
Recent

320x240 up to 1980x1280 pixels (~12 µm pitch)



Frame Rates

30 - 60 Hz standard but 100 Hz systems have be
demonstrated



Thermal Time Constants ~4-18 ms

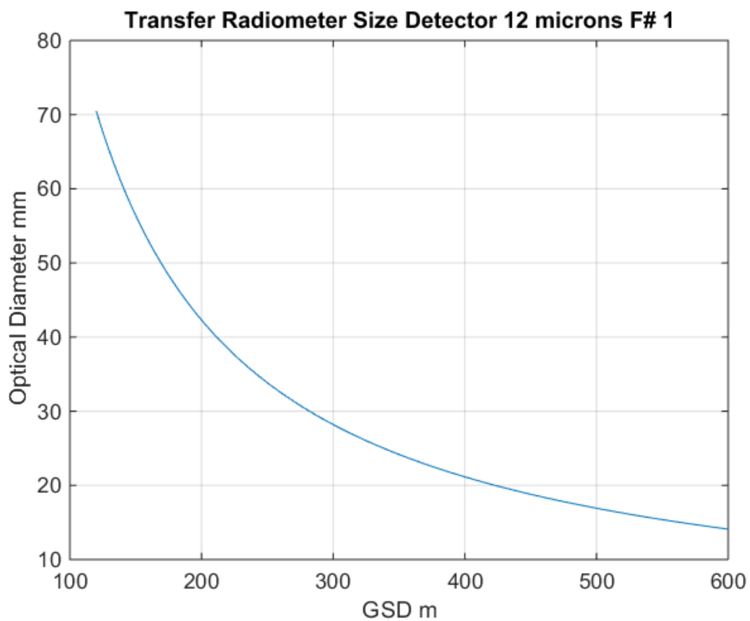
NE∆T (conservative value)

40 mK or better for 60 Hz, f/1 optics and
7 ms time constant (300K Background)

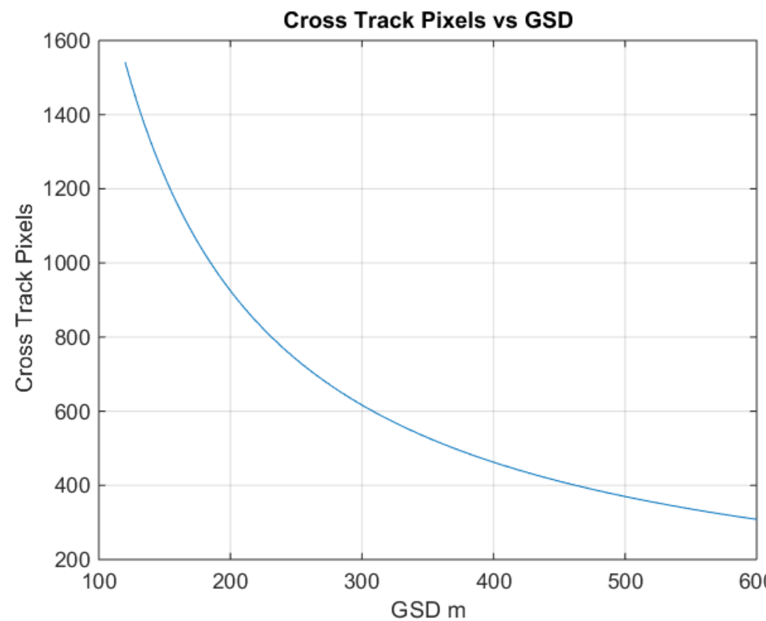
Example microbolometer: absorption coated silicon nitride isolated bridge with broadband response *(8-14 µm)*

Optical Diameter and Cross Track Pixels 12 micron Detector

Landsat 705 Km Orbit



A 300 m GSD Transfer Radiometer would require an aperture ~30 mm or less

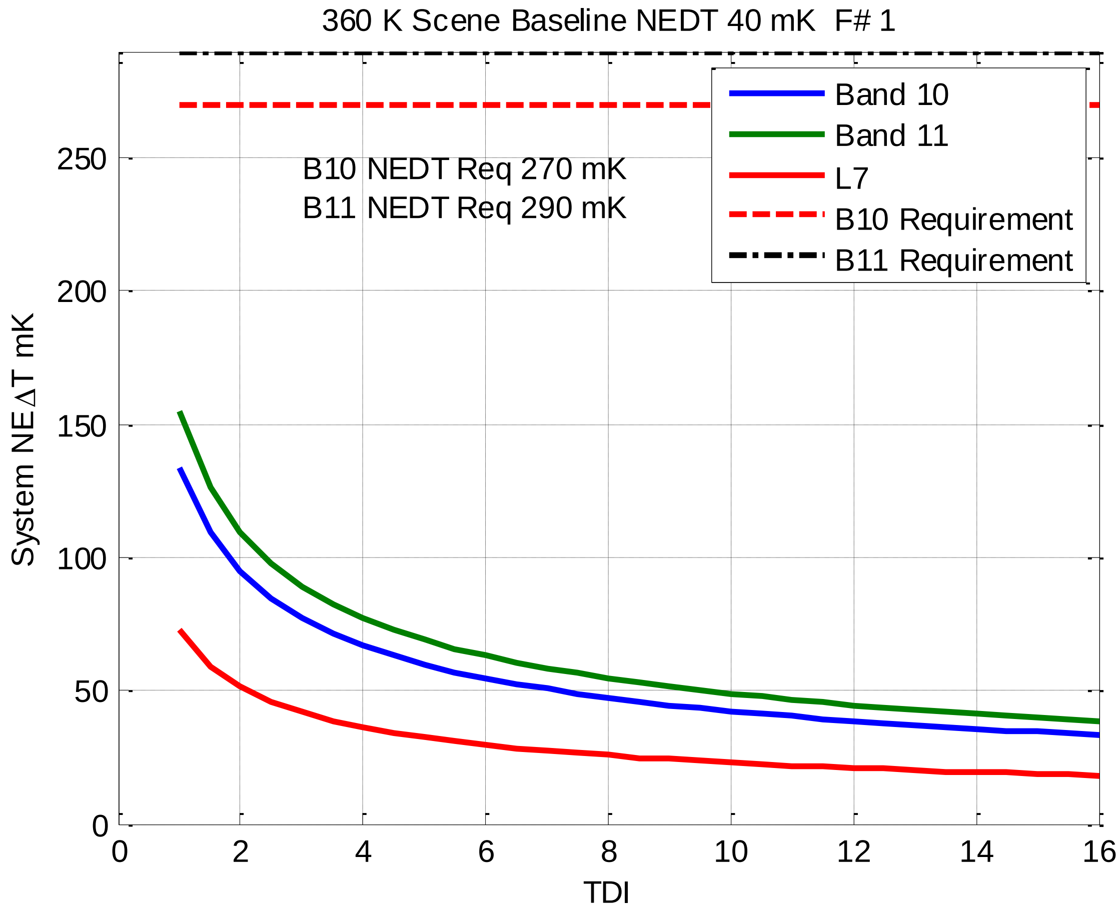


A 300 m GSD Transfer Radiometer requires approximately 616 pixels for 185 km swath (Compatible with 640 pixel across FPA)

Microbolometer NEΔT Scaling

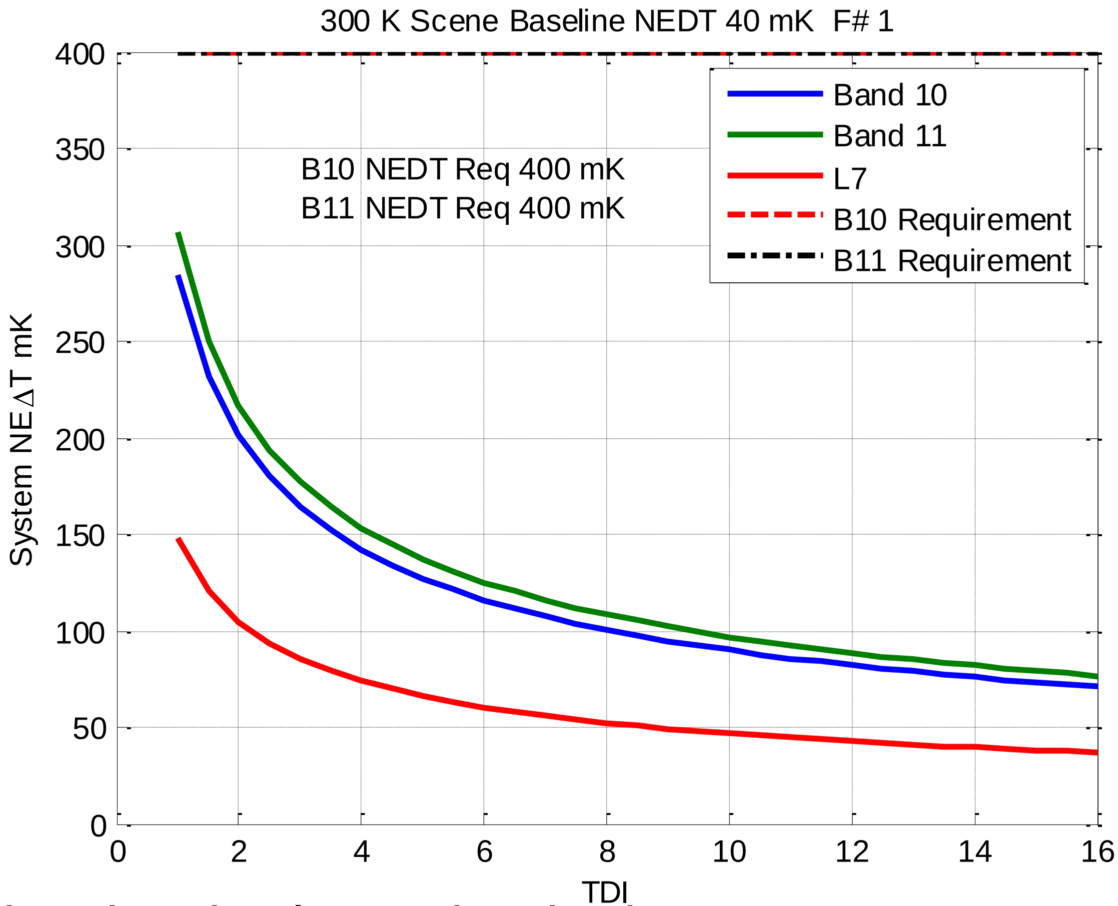
- NEΔT scales with:
  - Power on detector
    - Power scales as (f-number)$^{-2}$
  - Spectral bandwidth (approximately)
  - Filter transmission
  - (TDI)$^{-0.5}$
- Increasing the time constant improves NEΔT sensitivity but generally impacts other system parameters (e.g. Point Spread Function)

NE∆T Scaling with TDI & Band Pass f/1 360 K Scene



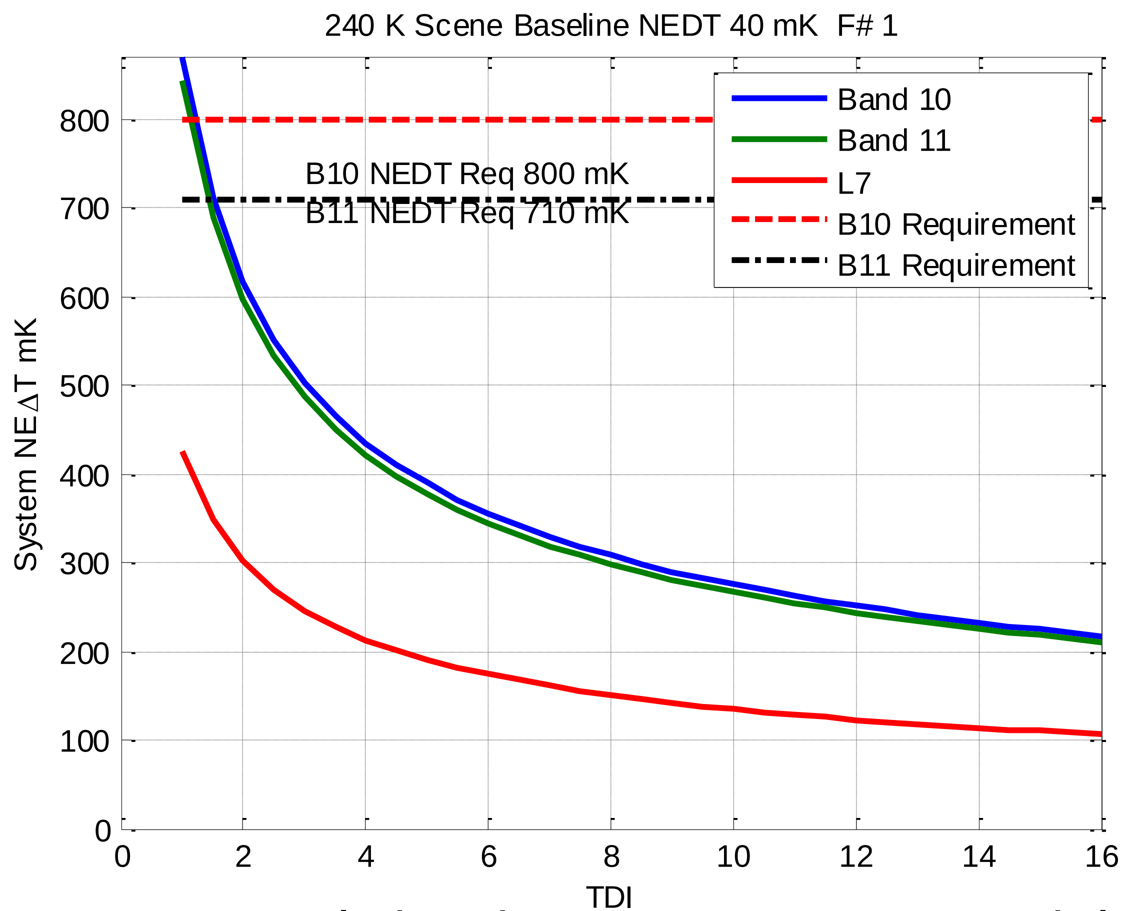
Single band and split window both meet requirement with large margin

NE∆T Scaling with TDI & Band Pass f/1 300 K Scene



Single band and split window both meet requirement with large margin

NE∆T Scaling with TDI & Band Pass f/1 240 K Scene



Single band meets requirement with large margin
Split window needs some amount of TDI for margin

Potential Next Steps

- Explore the use of more data to drive error down
- Understand outliers and simulate mis-registration of clouds
- Explore coarser CTIC GSD
  - Current 5x GSD results in about a 30 mm aperture
- Further examine the potential of microbolometers for CTIC implementation

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Acknowledgments

- USGS EROS for providing Level 1R TIRS data and help in understanding how to use it