Landsat 9 TIRS-2 Performance Results Based on Subsystem-Level Testing

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SPIE Remote Sensing
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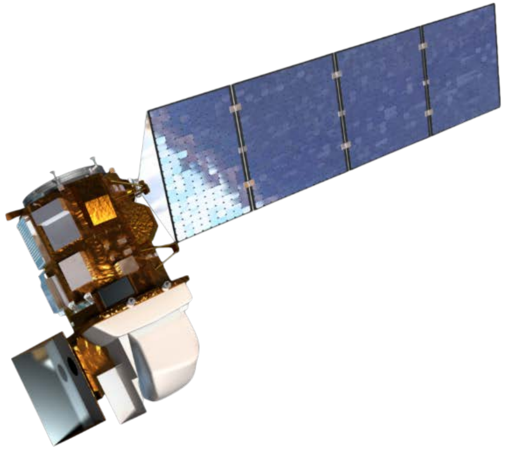
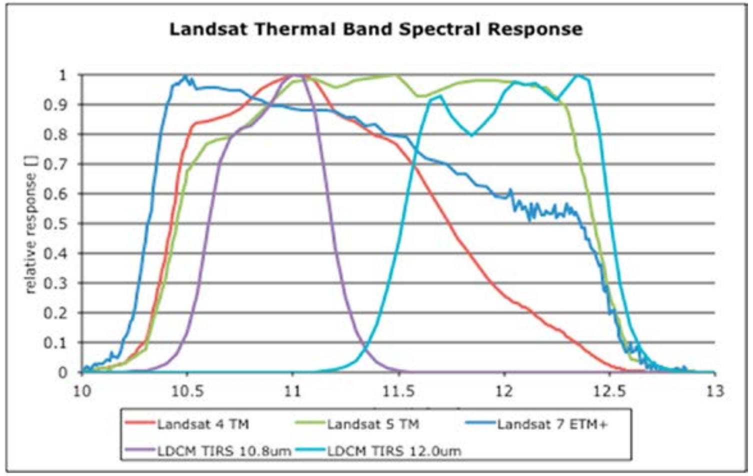
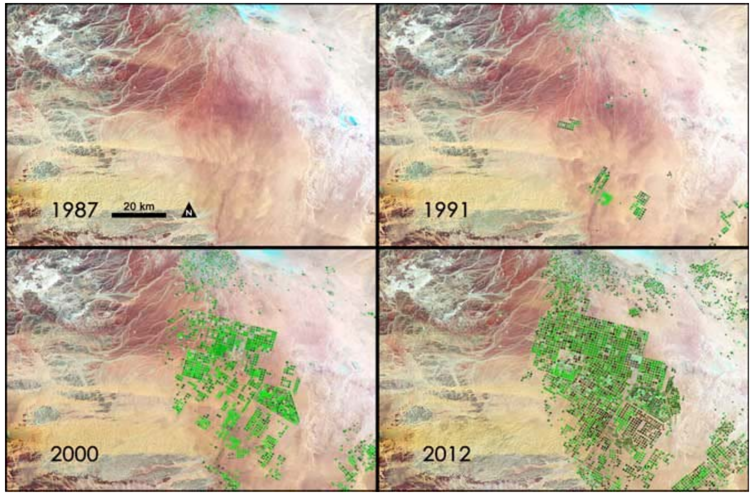


TIRS-2 Project Overview

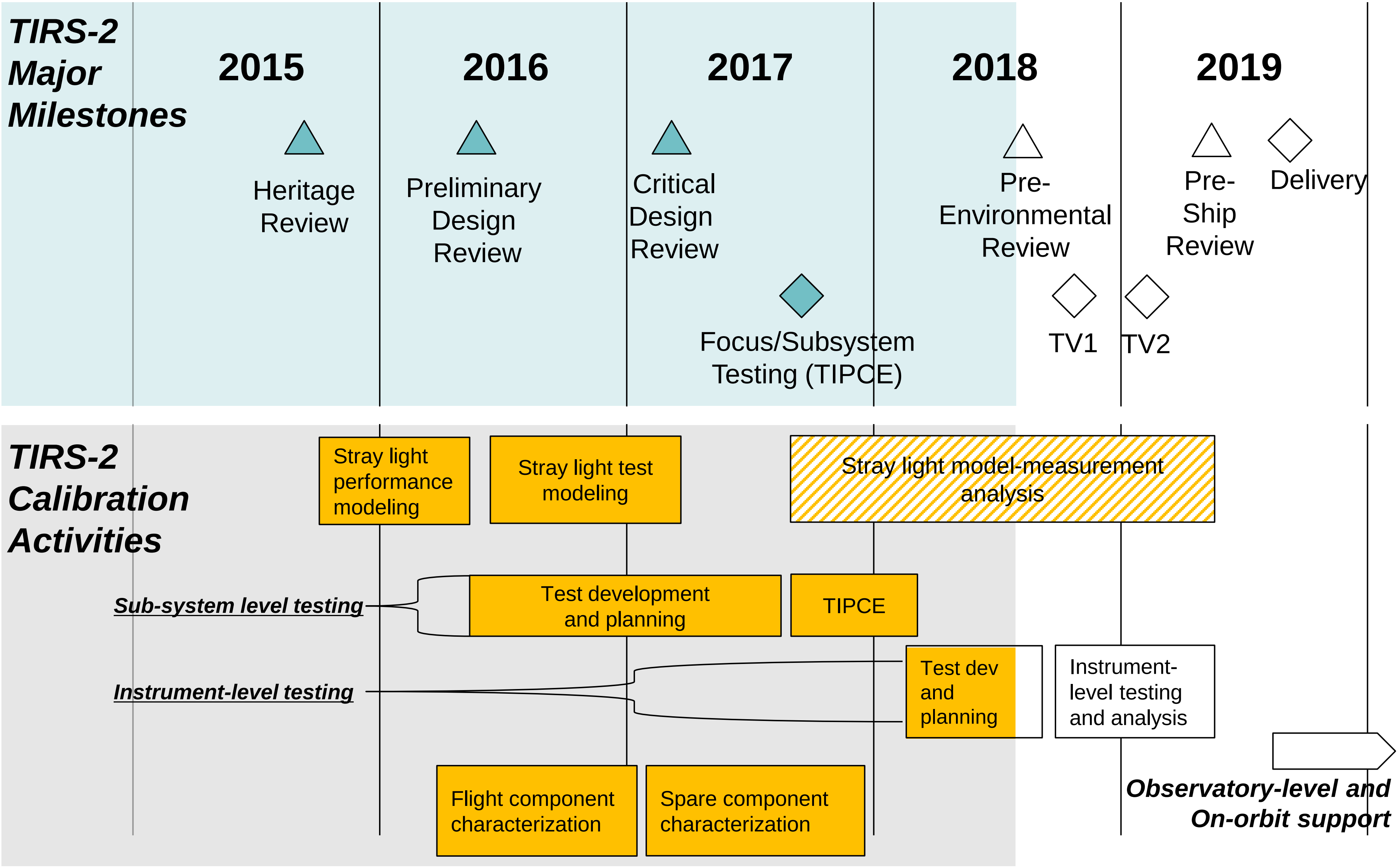
- TIRS-2 will fly on the LandSat 9
  - 16 day re-visit cycle
  - 2 bands: 10.8 μm & 12 μm
- Like TIRS on Landsat 8, TIRS-2 will produce radiometrically calibrated, geo-located thermal image data
- Risk Class C for Landsat 8 to Class B for Landsat 9
  - Increased redundancy to satisfy Class B reliability standards
  - Improved stray light performance through improved telescope baffling
  - Improved position encoder for scene select mirror to address problematic encoder on Landsat 8 TIRS
- USGS will be responsible for operations
- TIRS-2 development:
  - NASA GSFC TIRS-2 team formed in 2015
  - TIRS-2 completed Critical Design Review in Feb. 2017
  - Instrument in fabrication at NASA GSFC
  - **Initial pre-launch imaging and spectral characterization Nov. 2017 – March 2018**
  - On target for August-2019 delivery to spacecraft





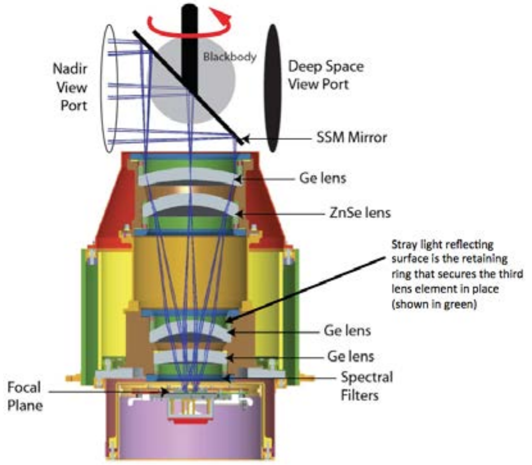
–Increase in pivot irrigation in Saudi Arabia from 1987 to 2012 as recorded by Landsat. The increase in irrigated land correlates with declining groundwater levels measured from GRACE (courtesy M. Rodell, GSFC)

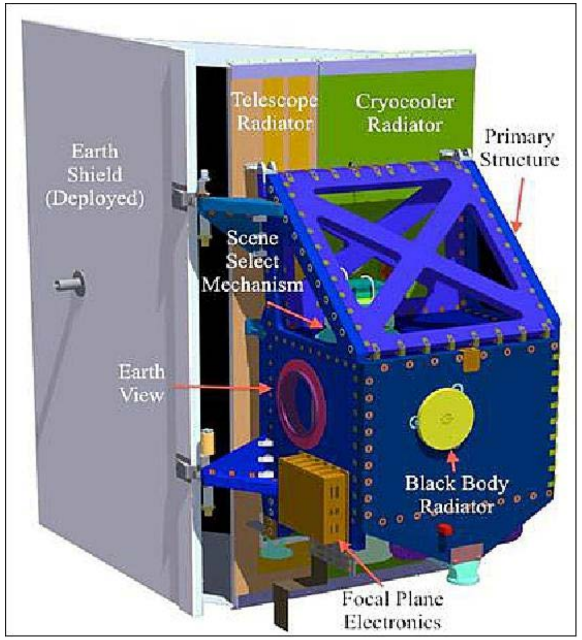
TIRS-2 Calibration Timeline



Landsat 9 TIRS-2 Requirements

Requirement	TIRS-2 Required Value	Units
NEdT (@300K)	< 0.4	Kelvin
NEdL	< 0.059, < 0.049	W/m²/sr/µm
Saturation Radiances	20.5, 17.8	W/m²/sr/µm
40 min. Radiometric Stability (1σ)	< 0.7	Percent
Inoperable Detectors	< 0.1	Percent
Swath Width	> 185	Kilometers
Ground Sample Distance	< 120	Meters
Band Registration Accuracy	< 18	Meters
TIRS-to-OLI Registration Accuracy	< 30	Meters
Spatial – Relative edge	0.0047	Meters-1
Spatial – Edge extent	245	Meters
Absolute Radiometric Accuracy	< 2	Percent
Uniformity Field-of-View	< 0.5	Percent
Uniformity Banding RMS	< 0.5	Percent
Uniformity Banding St.Dev.	< 0.5	Percent
Uniformity Streaking	< 0.5	Percent





Calibration Requirements

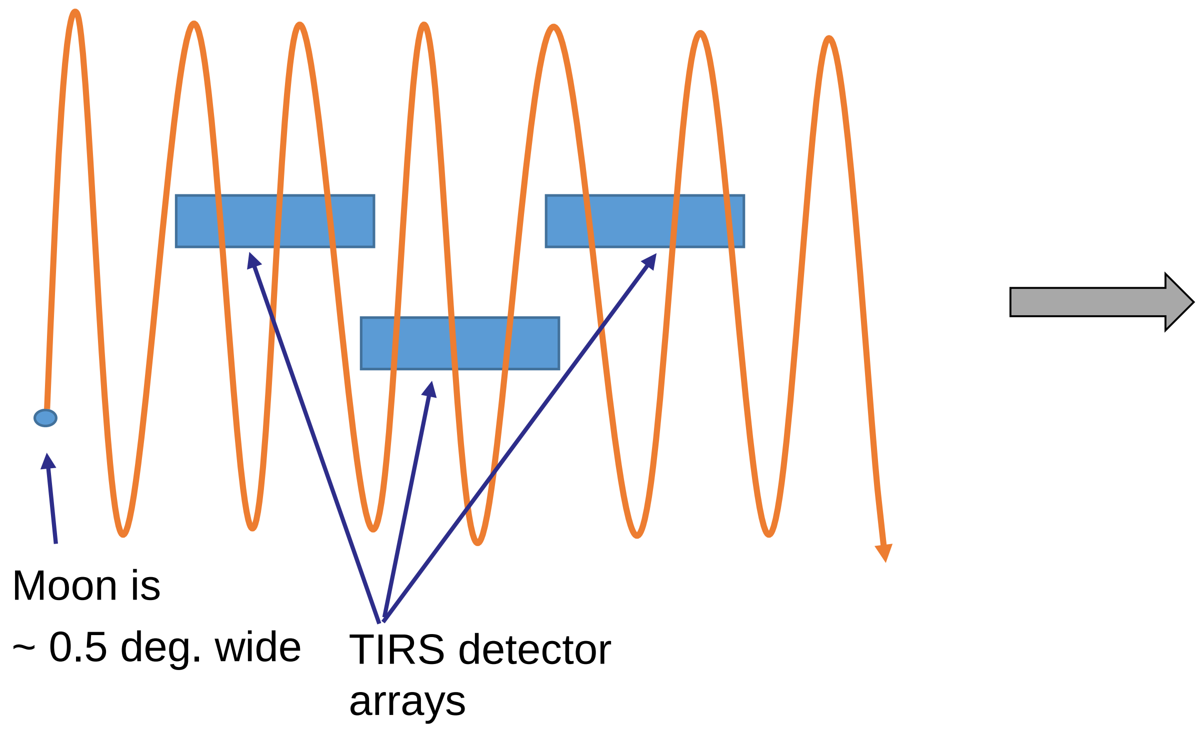
- **4** component-level requirements (4 special test)
  - Spectral characterization of optical windows, filters, lenses, detector

- **6** subsystem-level requirements (2 performance, 4 special test)
  - Mated filter-detector spectral characterization
  - Scattered light measurements
  - Other measurements provide initial assessment of instrument-level Spatial and Spectral performance

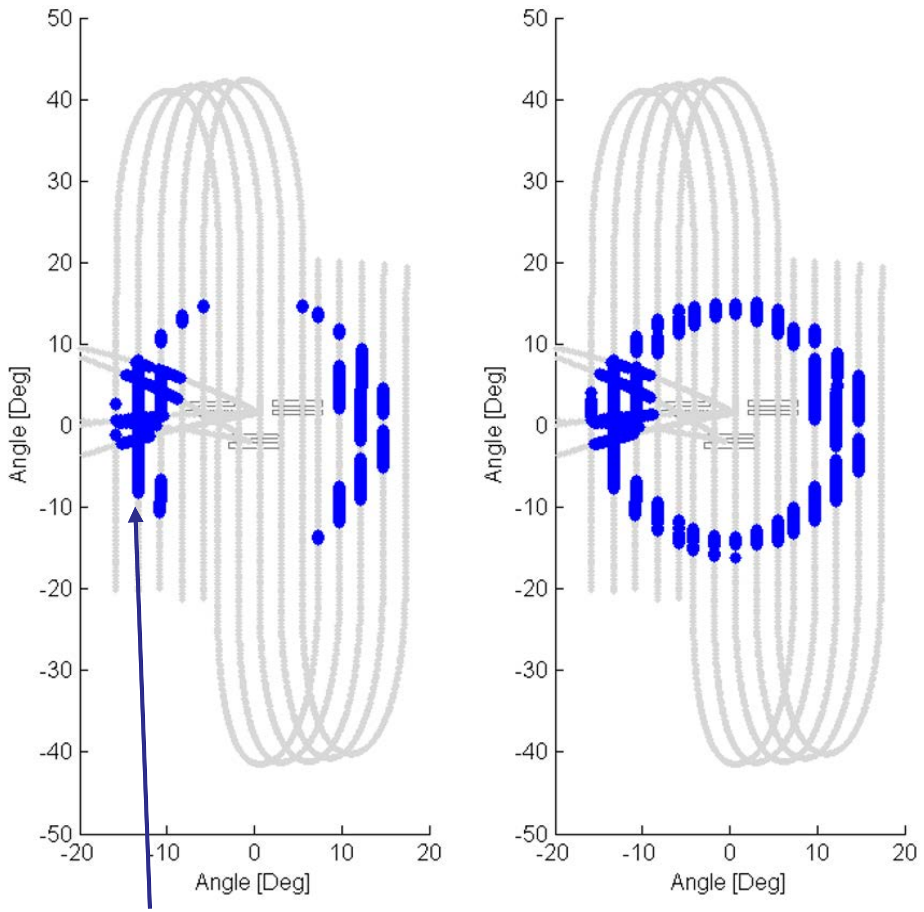
- **78** instrument-level requirements (51 performance, 27 special test)
  - Spectral (16)
  - Radiometric (42)
  - Spatial (8)
  - Scattered light (5)
  - Geometry (7)

Stray Light Issue from TIRS

- Non-uniform banding and absolute calibration error found in TIRS imagery post-launch – suspected stray light
- Characterized on-orbit using a raster-scan of the moon around the out-of-field-view



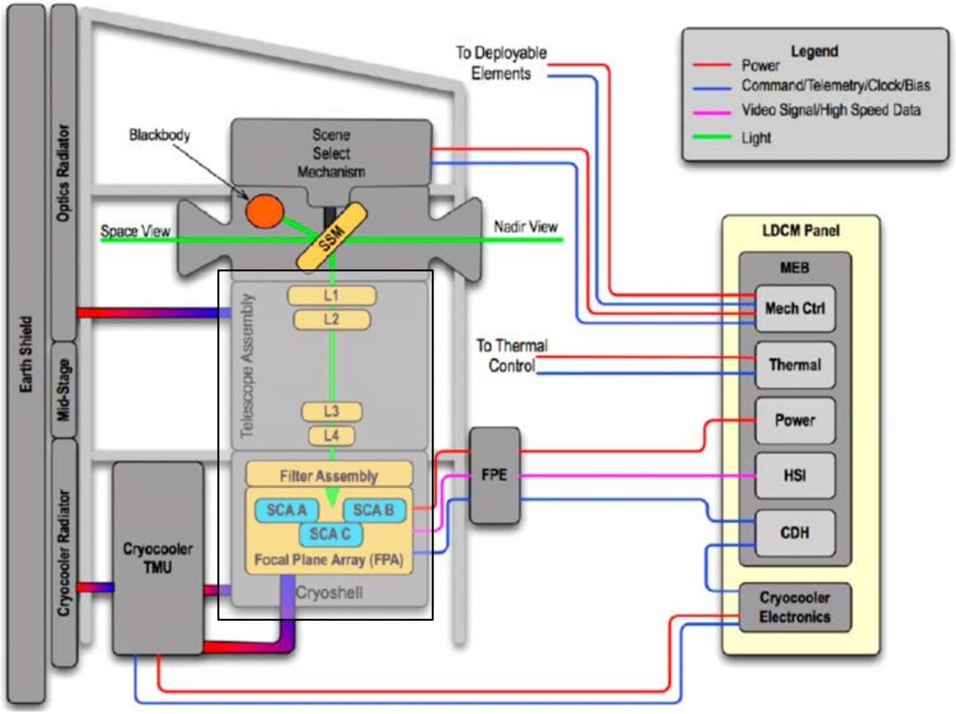
Stray light source roughly 13° from optical axis



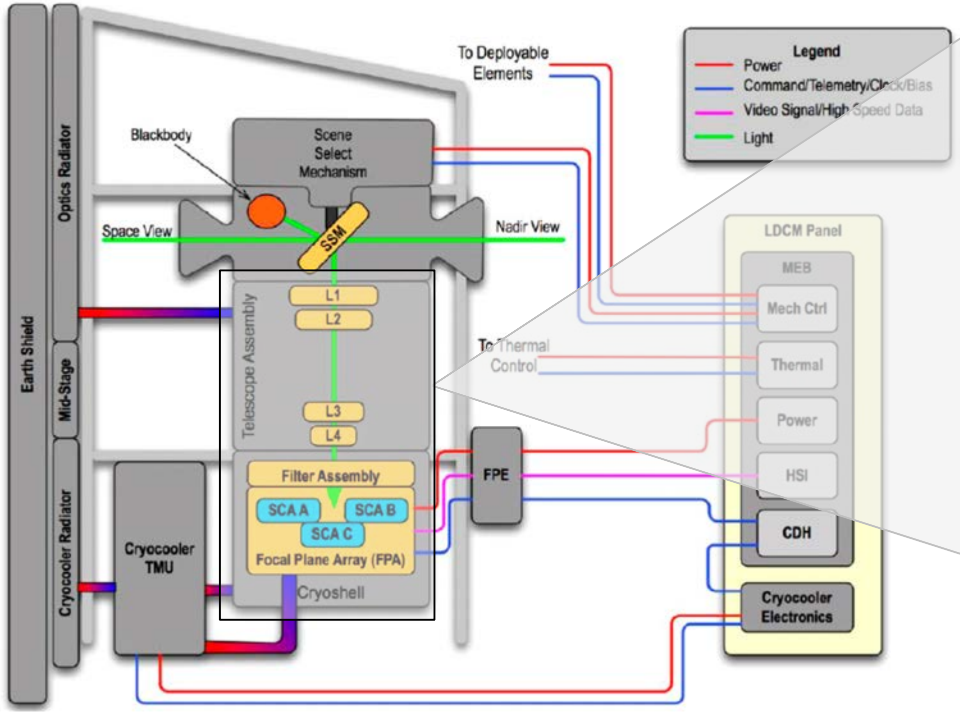
Lunar locations where a stray light signal appeared anywhere on the detectors

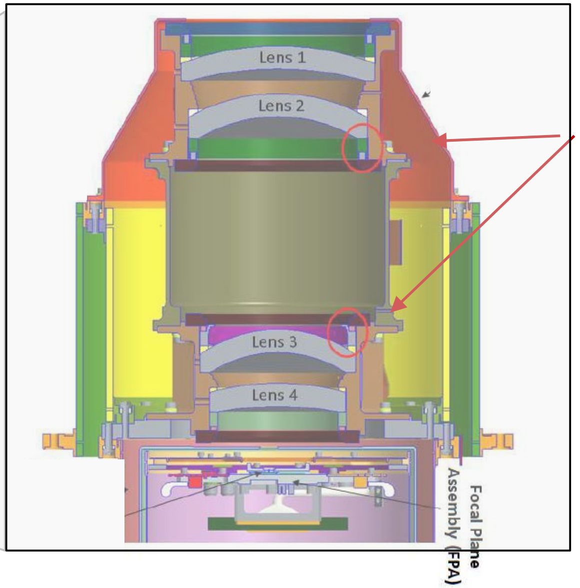
M. Montanaro. et al. *Remote Sensing*, (2014).

TIRS-2 Architecture



TIRS-2 Architecture



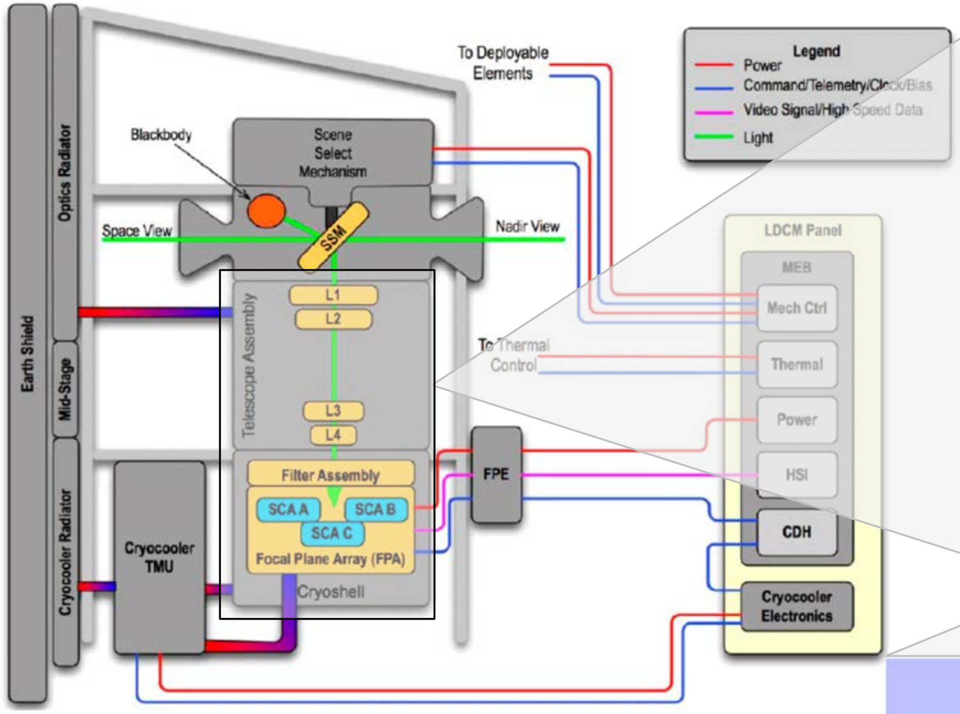


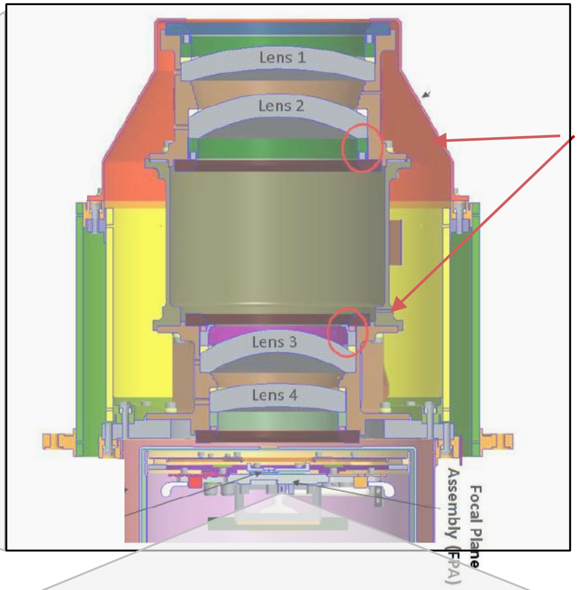
Baffles added for TIRS-2 to reduce stray light

The baffles at Lens 3 and Lens 2 locations address scattered light paths at 13° and 22° off-axis, respectively

[Reuter et al Remote Sens. 2015
Montanaro et al IGARSS 2018]

TIRS-2 Architecture





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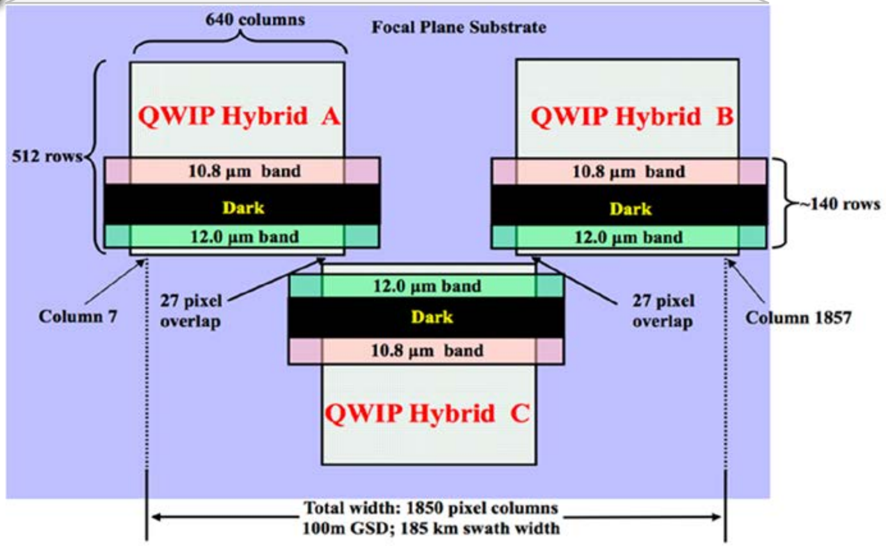
FPA made up of three separate quantum well infrared photodetector arrays each filter covering ~30 pixel rows and 1850 total pixel columns (185 km swath width)



Focal Plane Assembly (FPA)

[Reuter et al Remote Sens. 2015
Montanaro et al IGARSS 2018]

TIRS-2 Characterization

Initial subsystem-level performance tests are “almost” at instrument-level:

Has integrated telescope/focal plane arrays/focal plane electronics, no scene select mirror

	Subsystem-Level Testing (TIPCE)	Instrument Level Testing
Focus	X	Confirm
Geometry		X
Spatial Shape	Preliminary	X
Spectral Shape	Preliminary	X
Scatter	X	Subset
Radiometry		X
Bright Target Recovery		X
Special Tests		X
Orbit-In-The-Life (OITL)		X

→ Focus test: Determine focus position of FPA/telescope, determine proper shims, & verify

→ Scatter survey test: Only opportunity to measure far-field scattering (due to config of test article and CGSE in the chamber)

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This Talk

Calibration Ground Support Equipment

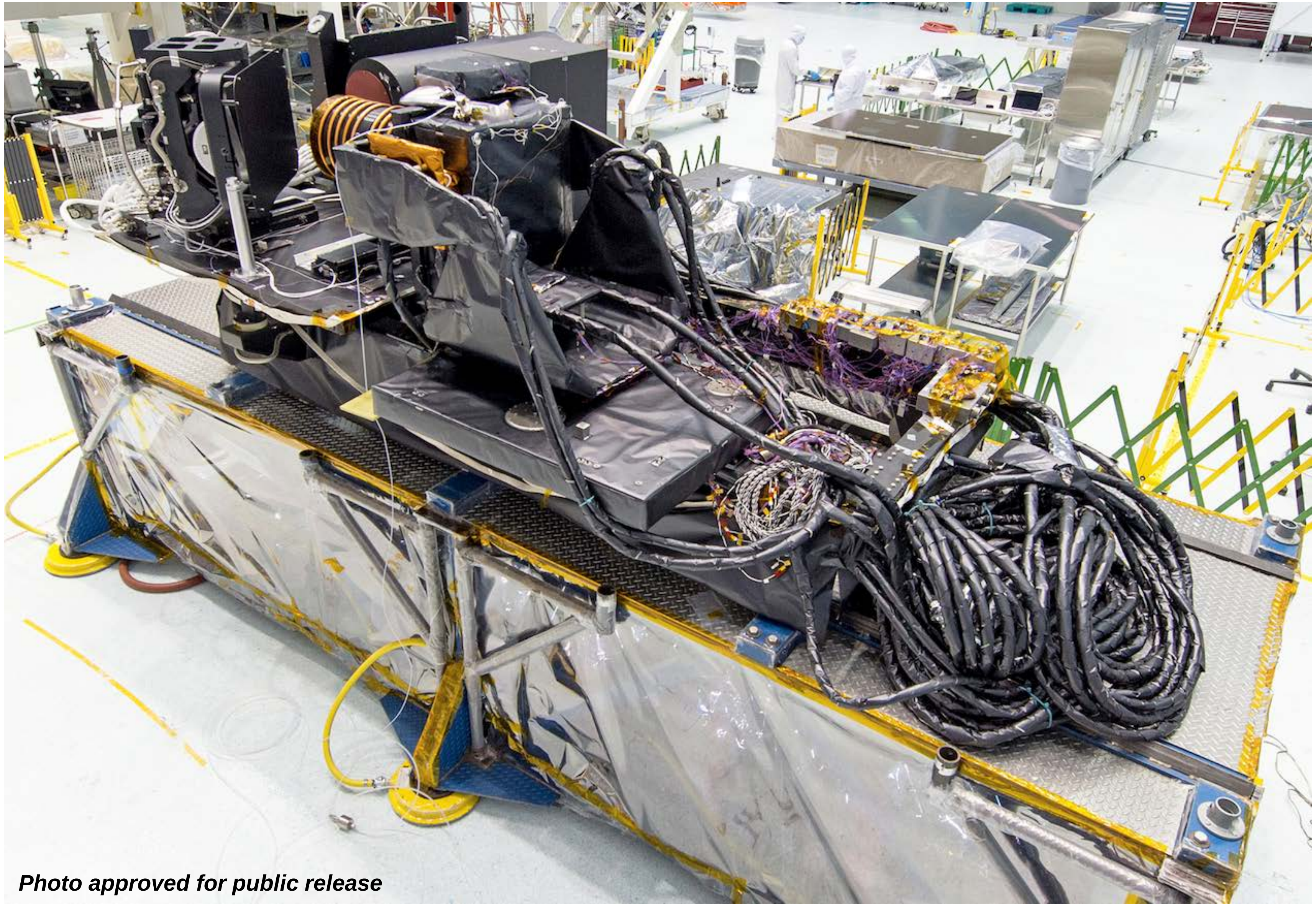


Photo approved for public release

TIRS-2 photos

Prior to Subsystem-level test, January 2018

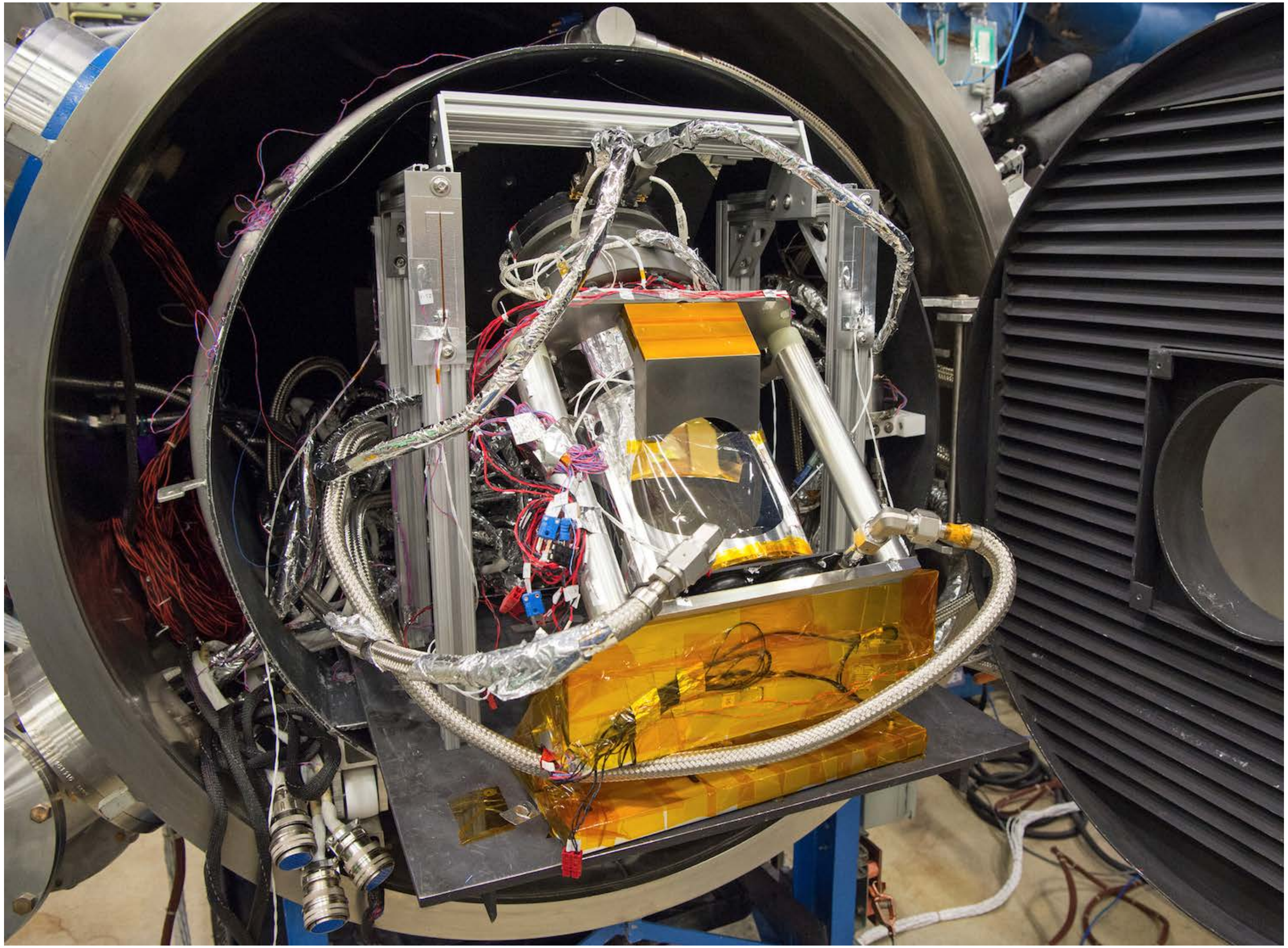
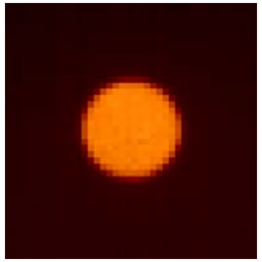


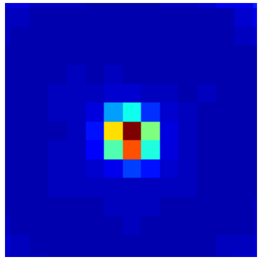
Photo approved for public release

TIPCE Configuration

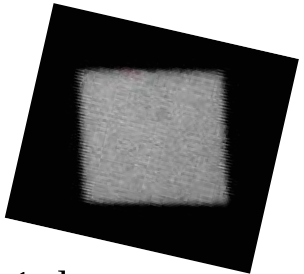
Focus, Scatter, & Spatial



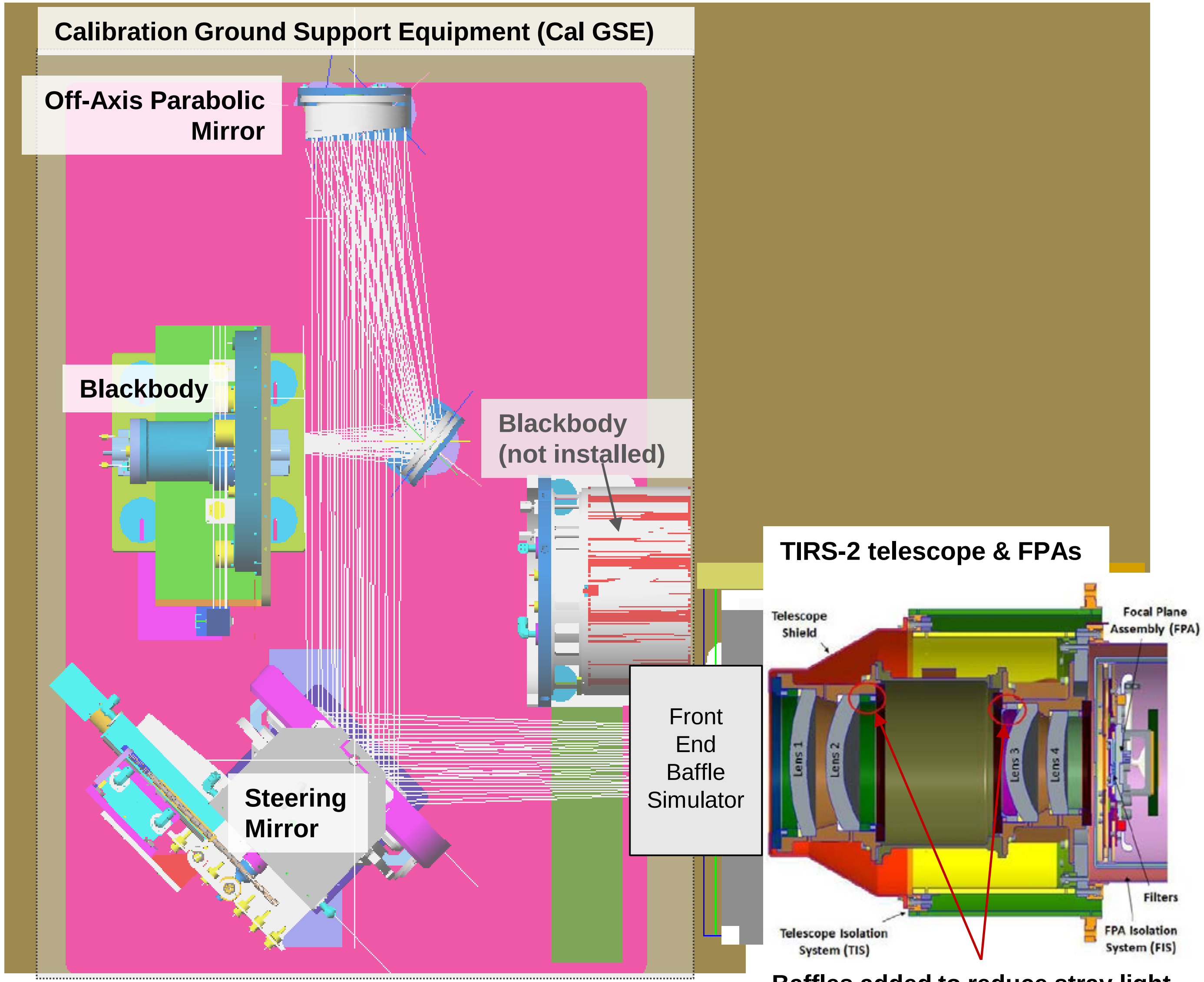
16-pixel circular target



1- and 2-pixel circular targets

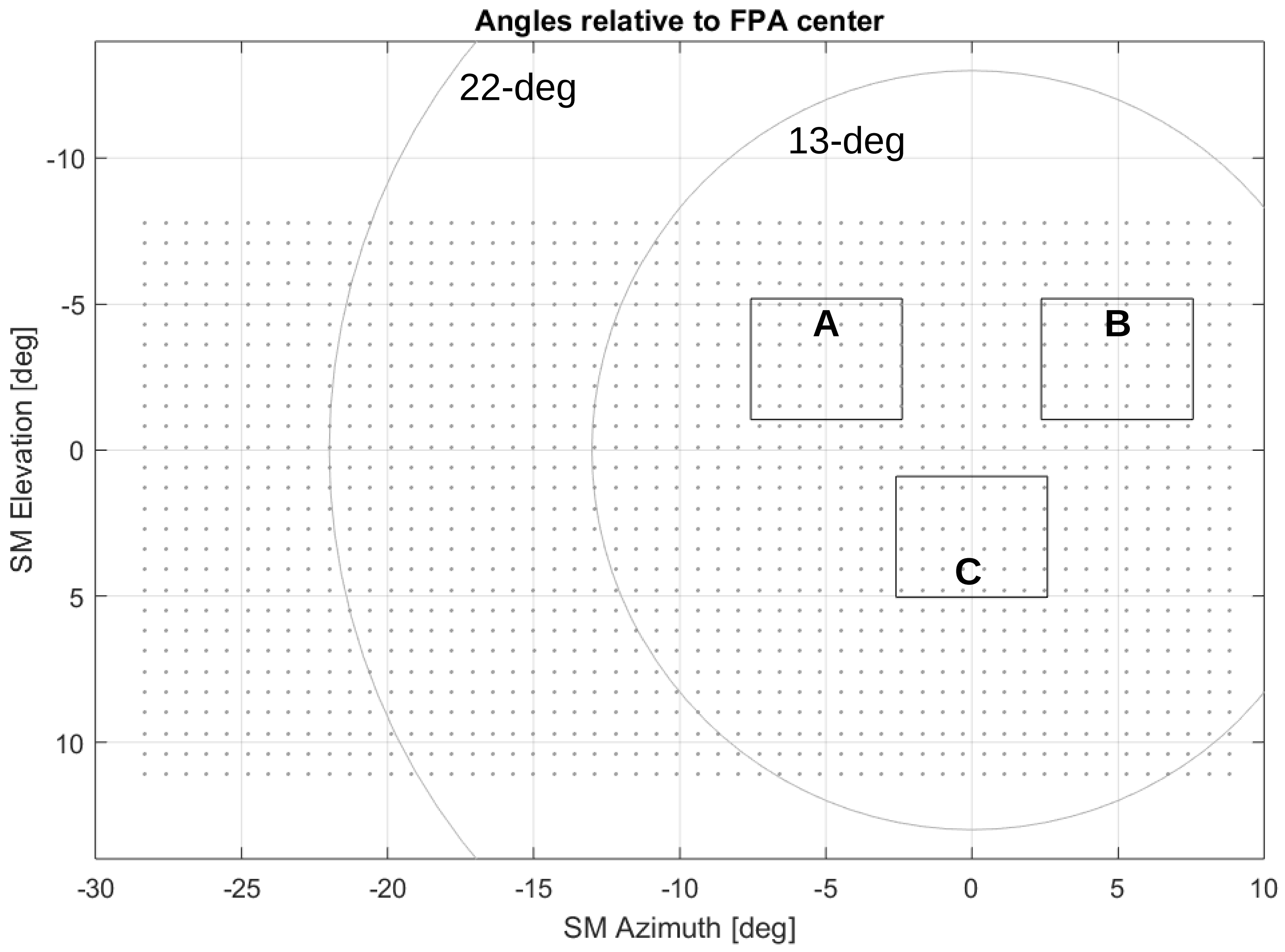


1-degree target



Baffles added to reduce stray light

Scatter Survey Test Methodology

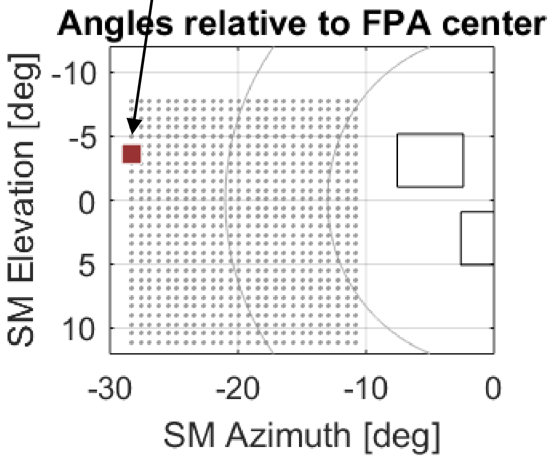


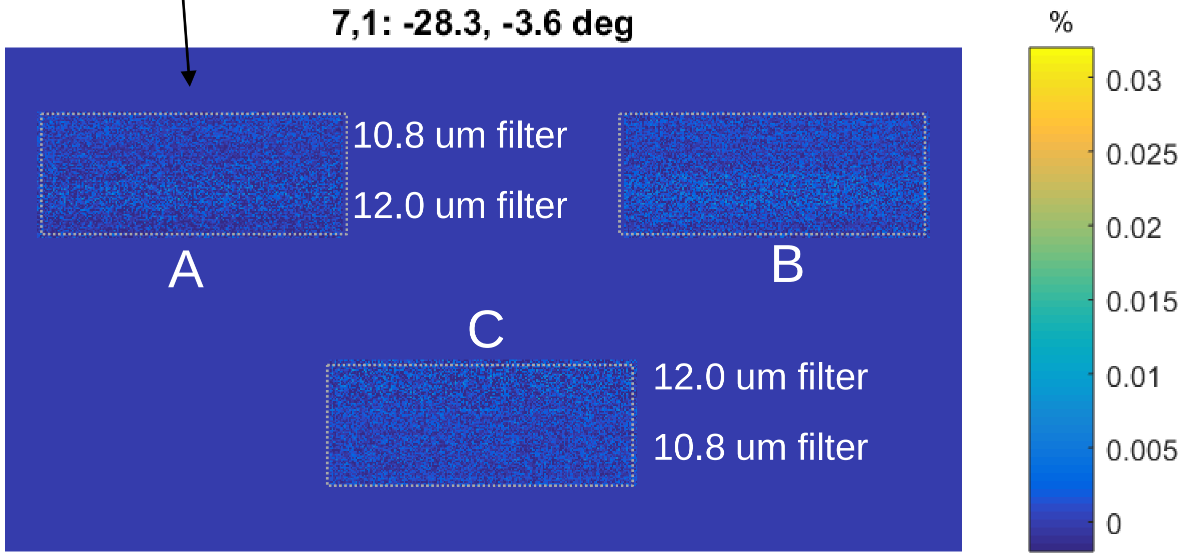
- Optical modeling reveals residual scattering at 13-deg and at 22-deg with the baffles.
- Wanted to scan the azimuthal extent of the 22-deg feature in TIPCE.
- Each dot represents the center of the 0.7-deg blackbody square target

Scatter Results: Target @ -28 deg

Blackbody square target is here

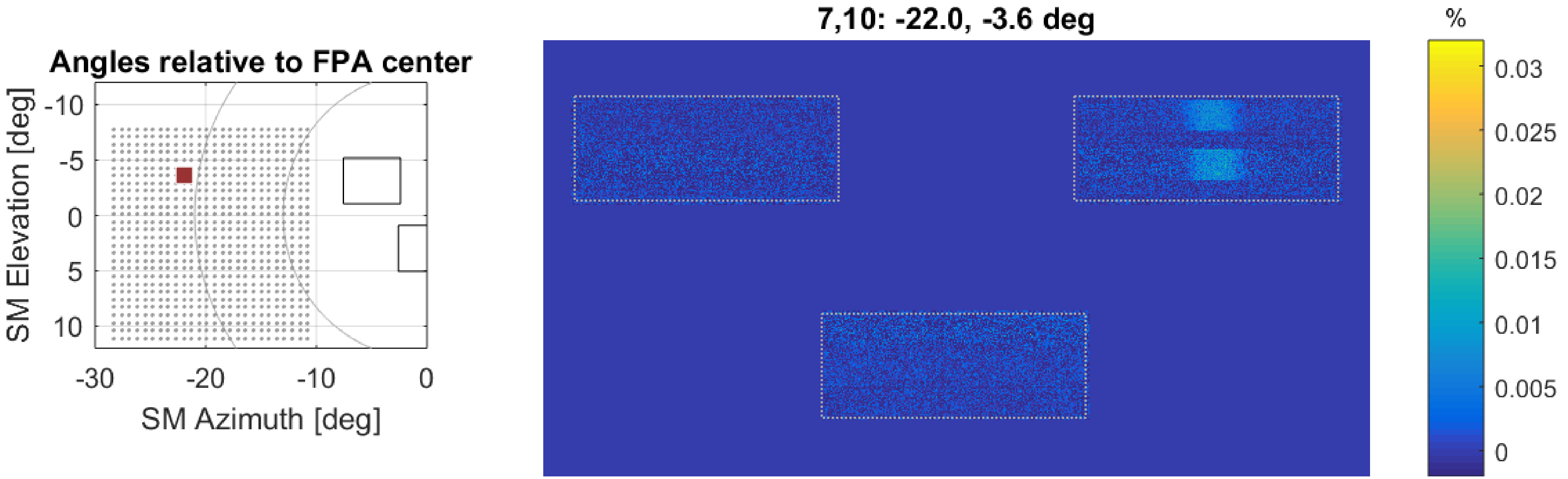
Frame of signal corresponding to the grid location

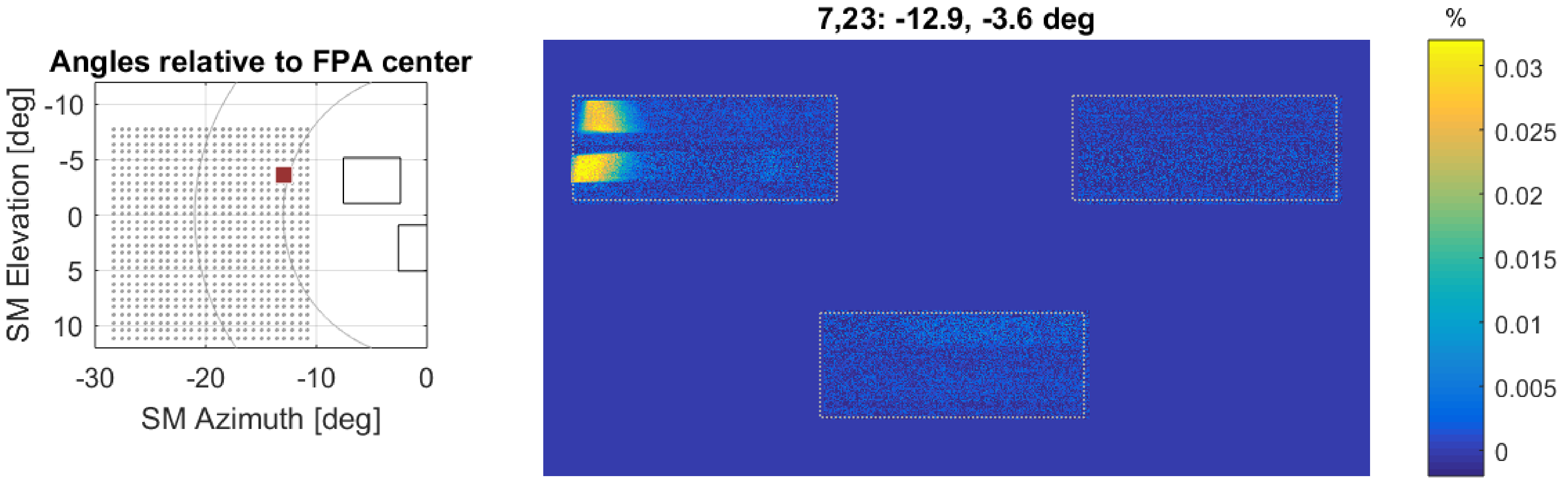




Units are percent of the signal when the target is directly illuminated on the detectors

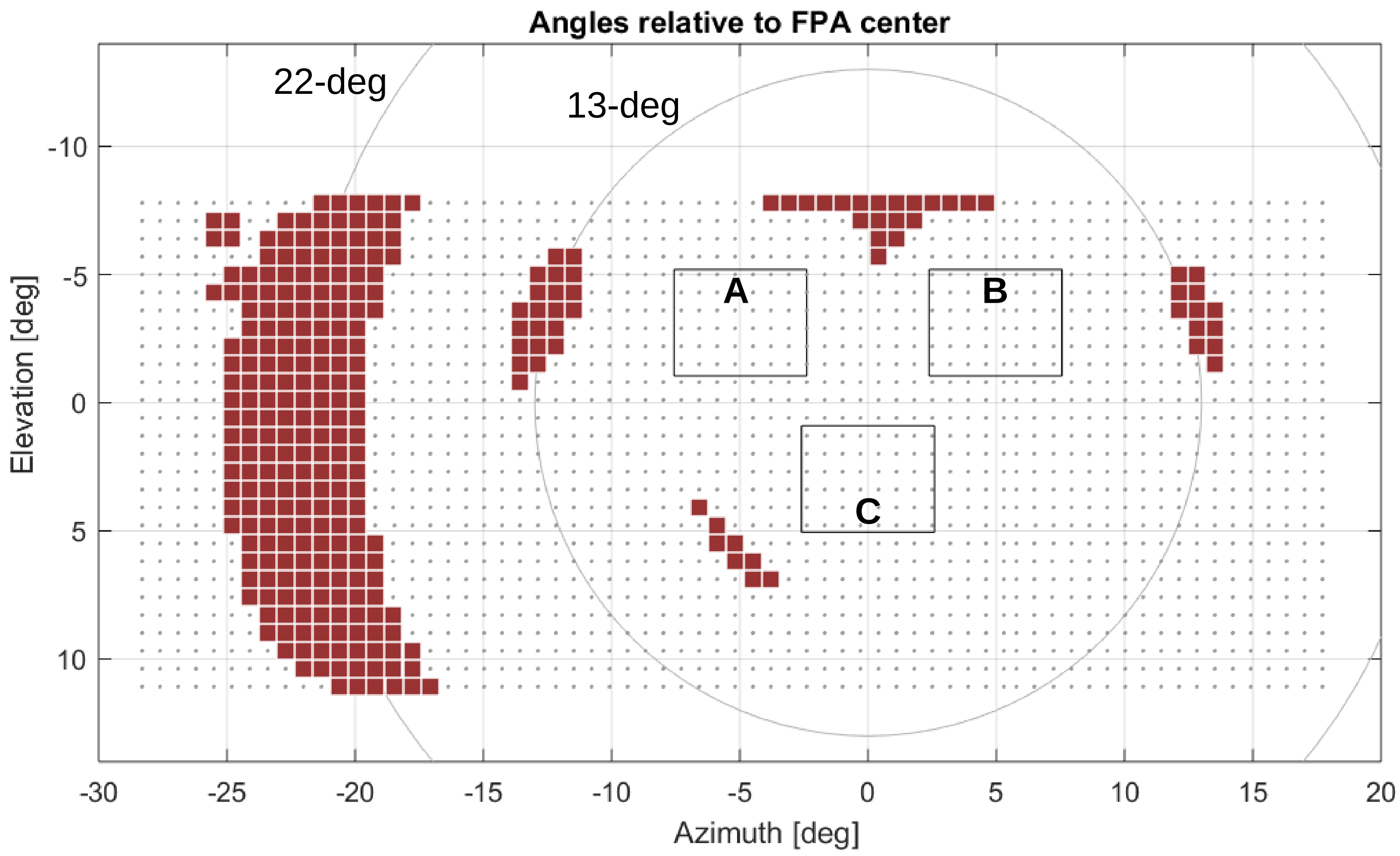
Scatter Results:
Target @ -22 deg and @ -13 deg



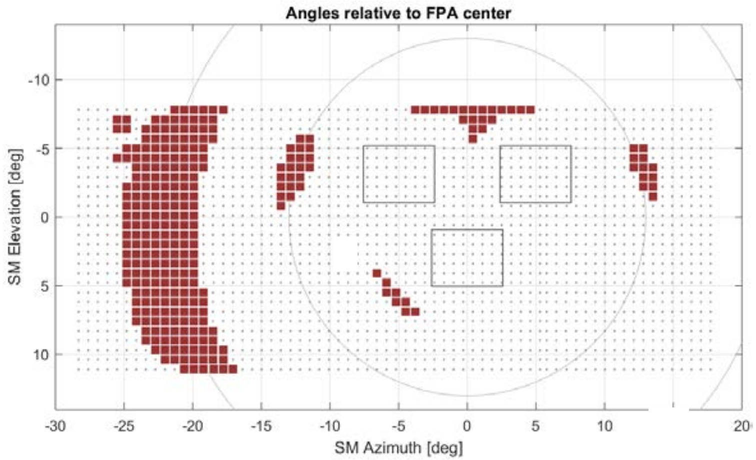


Scatter Results: Total Scattering

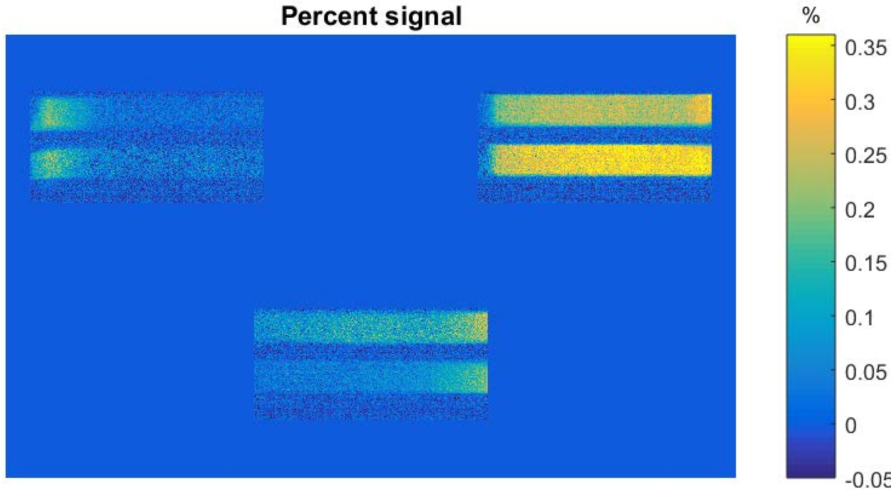
- Combine scattering data from TIPCE2 and TIPCE3. Red boxes where source was when signal observed on any detector.



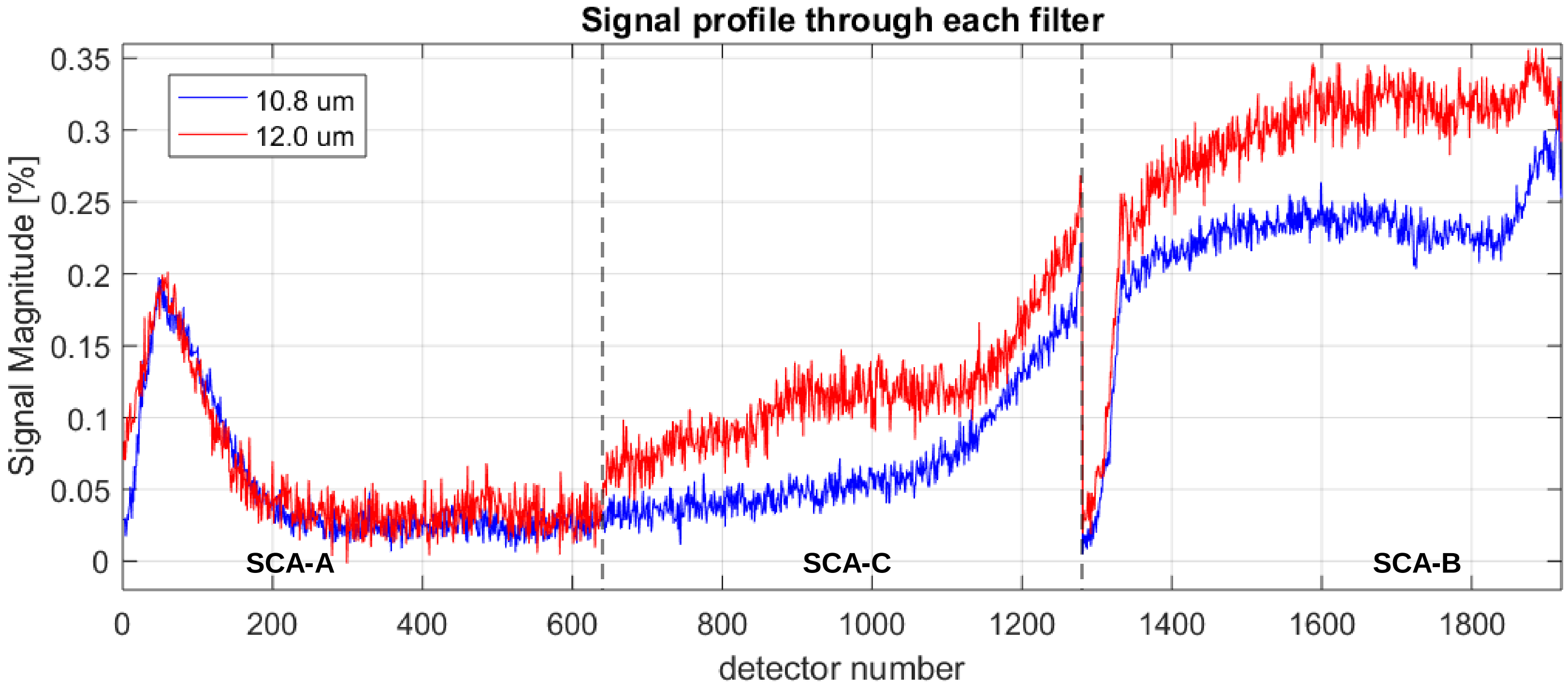
Scatter Results: TIPCE Scattering Sum



Sum All Measured Locations

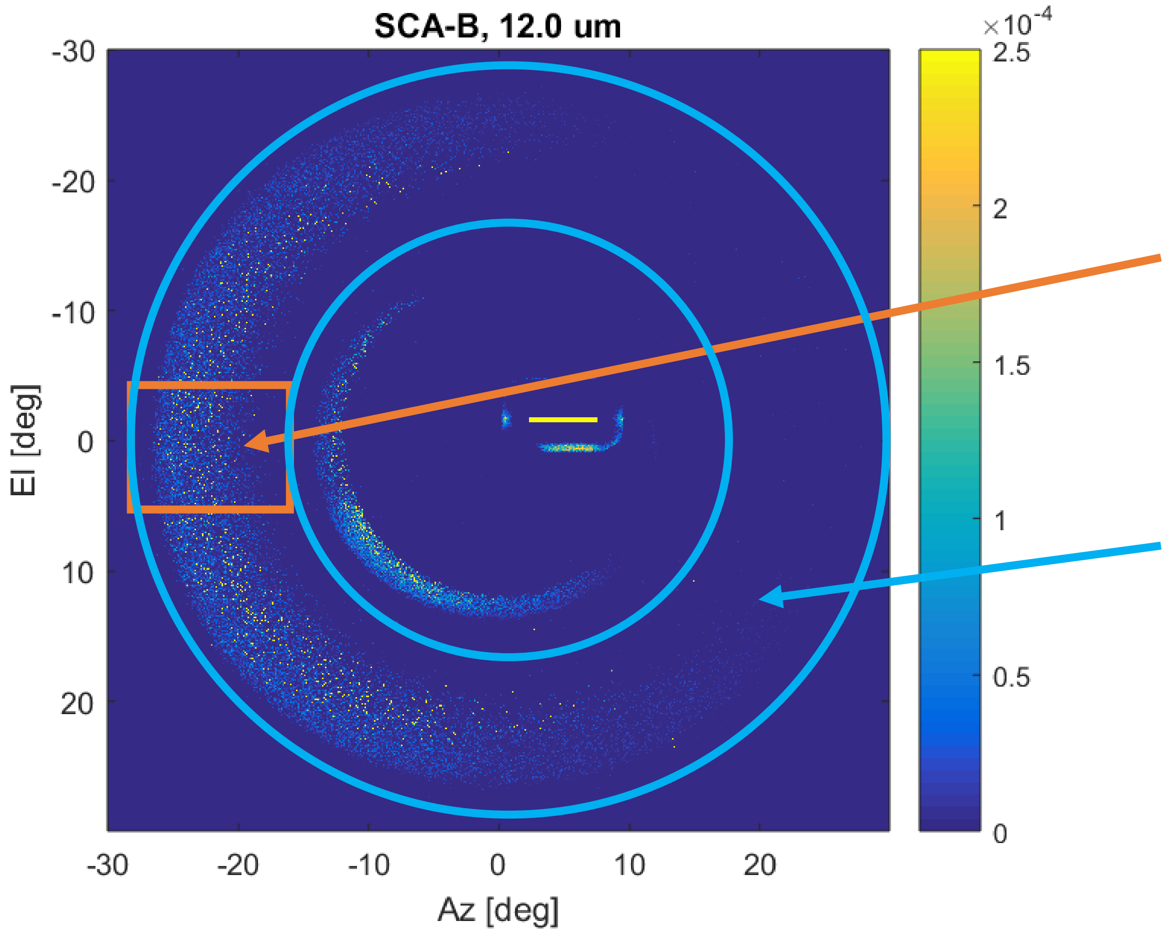


Profile through center of each filter



Scatter Results: TIPCE3 Scatter vs. Optical Model

Optical model from June Tveekrem for SCA-B, 12 um band



- TIPCE angles do not encompass entire out-of-field but can use TIPCE results to scale optical model to same units.
- Use sum of TIPCE signal here and sum of model signal here to derive scale factor
- Scale entire optical model using scale factor and sum up signal for each SCA/band.

Scatter Results: Total Scatter Sum

Sum using optical model :

	10.8 um	12.0 um
SCA-A	0.69 %	1.11 %
SCA-B	0.76 %	1.01 %
SCA-C	0.24 %	0.21 %

TIRS-2 estimated to have an about order of magnitude lower stray light impact than TIRS-1

SCA-A, 12.0 um, 1.11%

Out-of-field Temperature is:

In-field Temperature is:	200	240	260	270	280	290	300	320	330
240	-2.06	-1.36	-0.83	-0.52	-0.18	0.19	0.59	1.48	1.97
260	-1.40	-0.92	-0.56	-0.35	-0.12	0.13	0.40	1.00	1.33
270	-1.18	-0.77	-0.47	-0.30	-0.10	0.11	0.34	0.84	1.12
280	-1.00	-0.66	-0.40	-0.25	-0.09	0.09	0.29	0.72	0.96
290	-0.86	-0.57	-0.35	-0.22	-0.08	0.08	0.25	0.62	0.82
300	-0.75	-0.49	-0.30	-0.19	-0.07	0.07	0.21	0.54	0.72
310	-0.66	-0.43	-0.26	-0.17	-0.06	0.06	0.19	0.47	0.63
320	-0.58	-0.38	-0.23	-0.15	-0.05	0.05	0.17	0.42	0.55
330	-0.52	-0.34	-0.21	-0.13	-0.05	0.05	0.15	0.37	0.49
360	-0.38	-0.25	-0.15	-0.10	-0.03	0.03	0.11	0.27	0.36

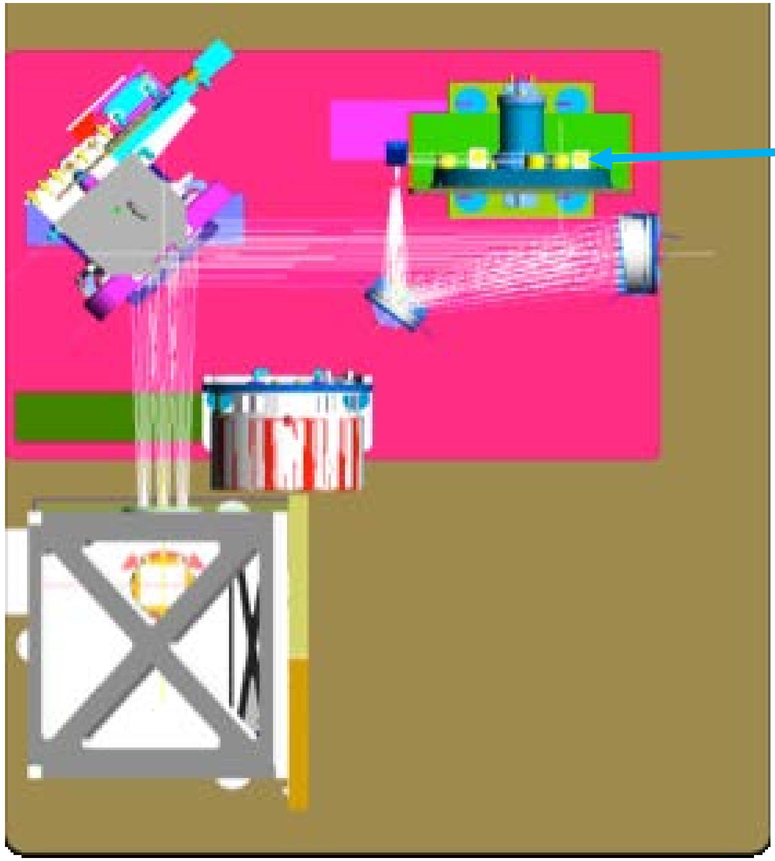
Preliminary look at science impact

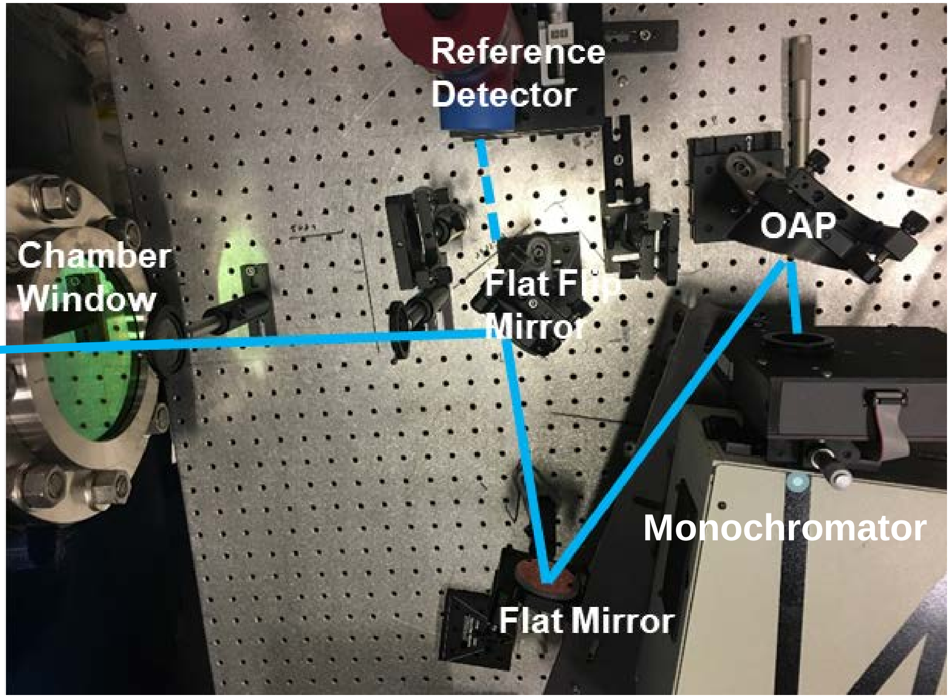
Numbers in table are the percent radiance that the condition is high or low when an out-of-field radiance of 285 K is assumed and removed from the calibration.

Spectral Response Test Methodology

- Data collect with TIRS from the monochromator bracketed by collects with the MCT reference detector

- Cal GSE in “monochromator mode” where collimated beam from the setup outside the chamber is focused and then re-collimated





Background subtracted TIRS counts

reference path transmittance

$$dn_{corr}(\lambda, pix) = \frac{dn_{TIRS}(\lambda, pix) \times \tau_{ref\ path}}{\tau_{TIRS\ path} \times V_{ref}}$$

TIRS path transmittance

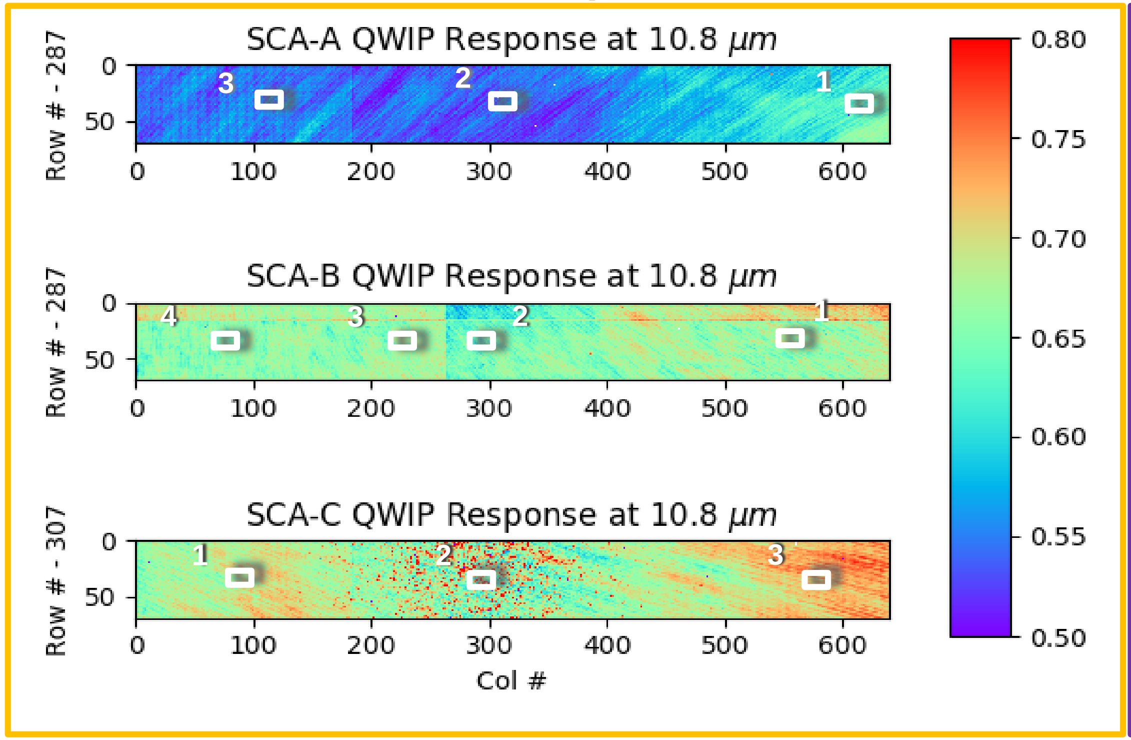
TIRS reference detector signal

$$RSR_{TIRS}(\lambda, pix) = \frac{dn_{corr}(\lambda, pix)}{max_{\lambda}(dn_{corr}(\lambda, pix))}$$

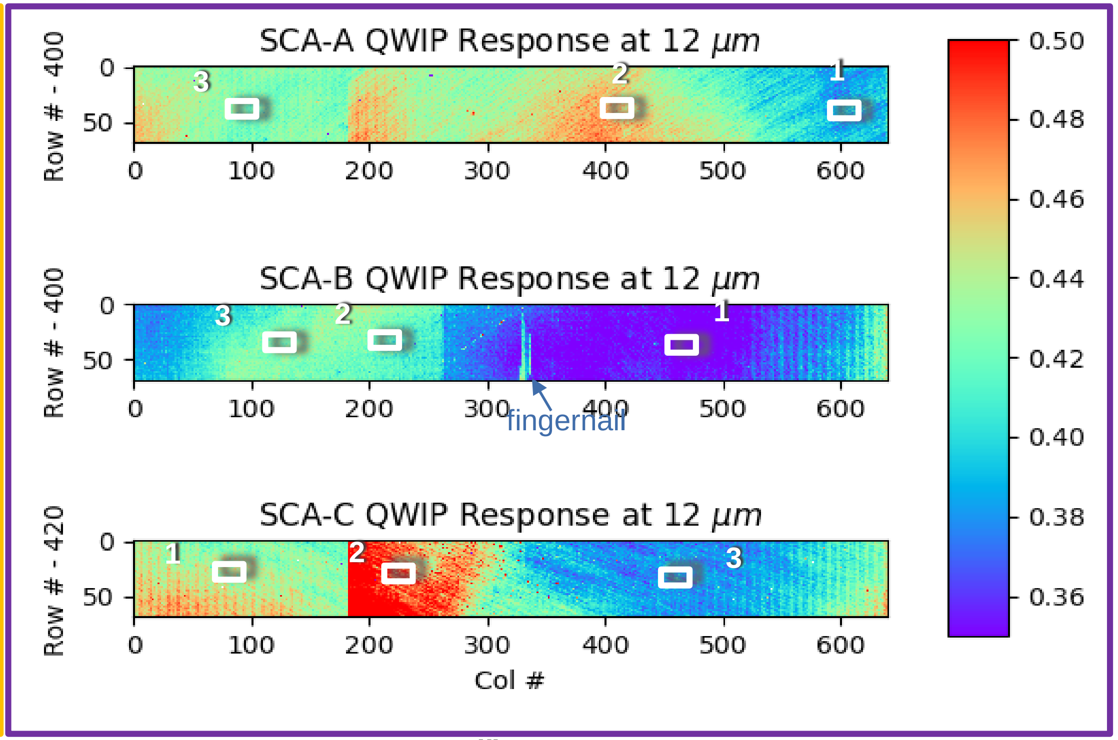
Spectral Response Test Methodology

- Data was collected for three or four locations on each SCA.
- The monochromator slits were 2 mm (~150 nm).
- TIRS data is collected using the monochromator shutter to provide background measurement. MCT data is collected between channels/SCAs.
- Optimization of the linear stage is run before each collect.
- Optimized for integration time

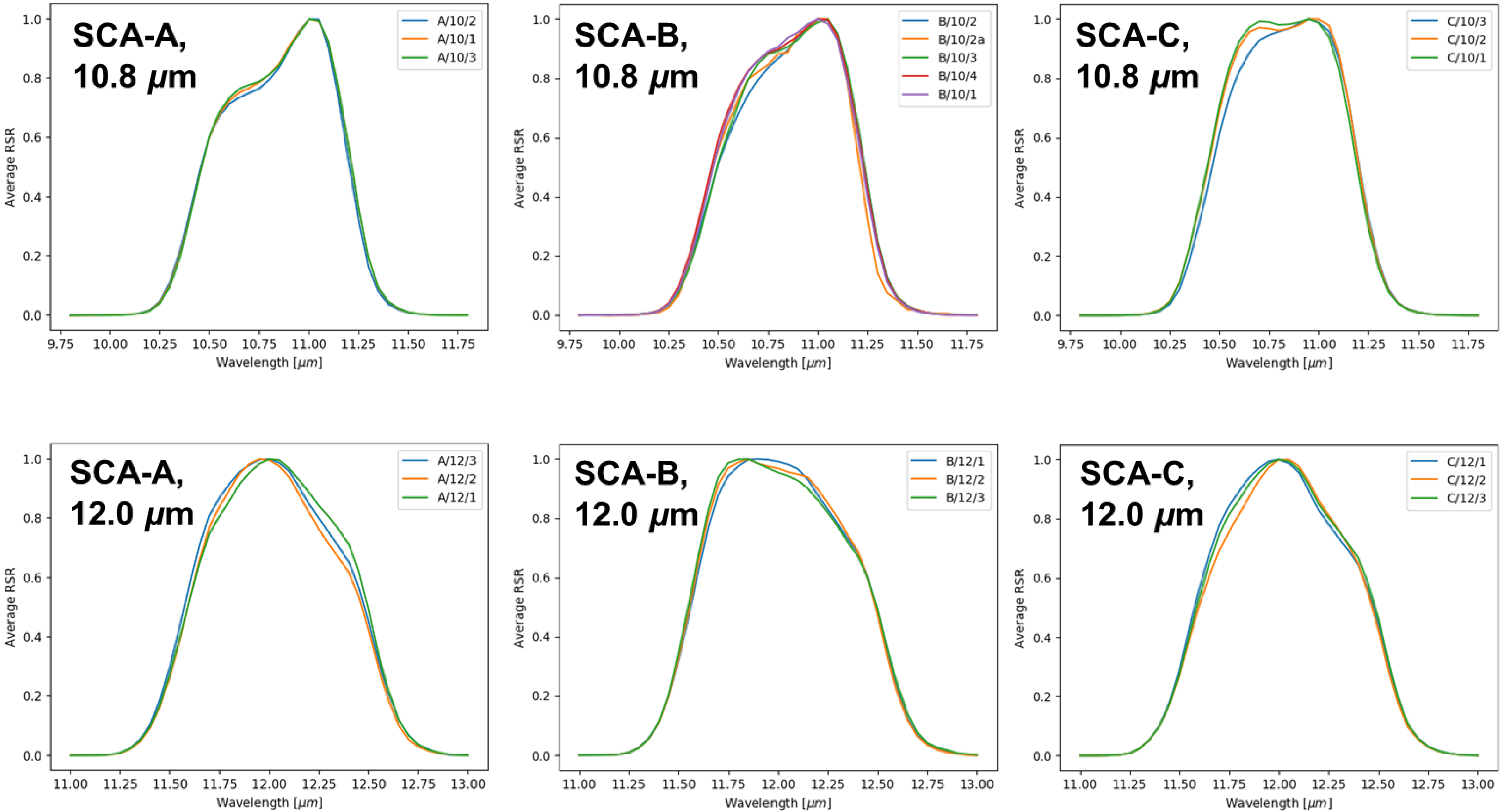
10.8 μm



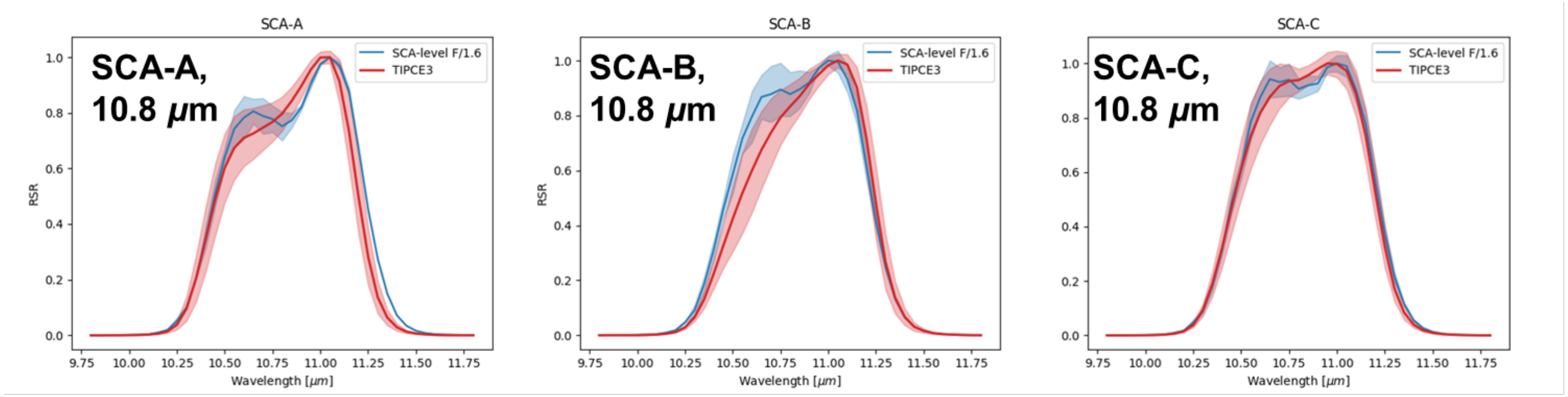
12.0 μm

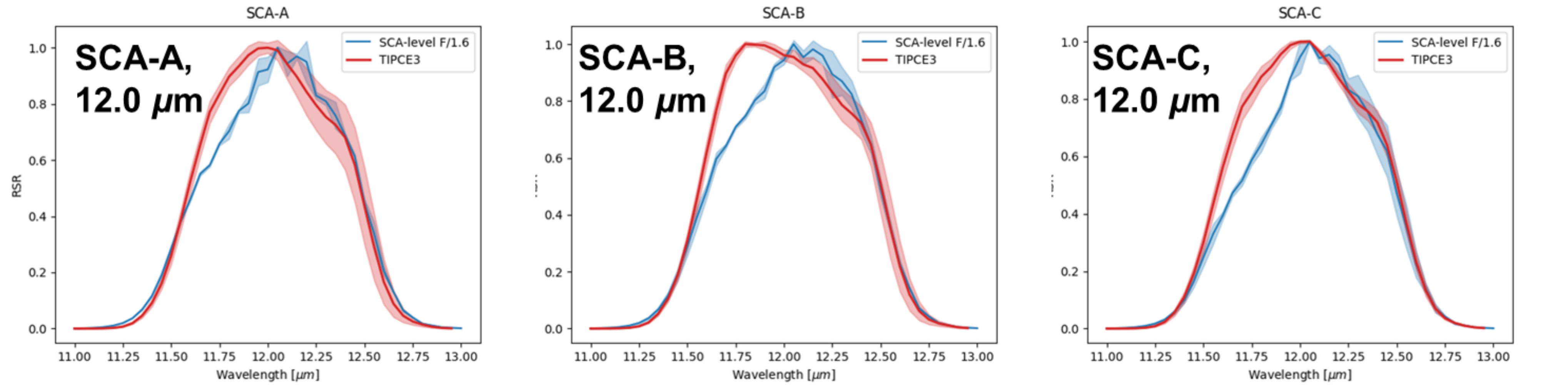


Spectral Response Results



Spectral Response Results: Comparison to Component-Level





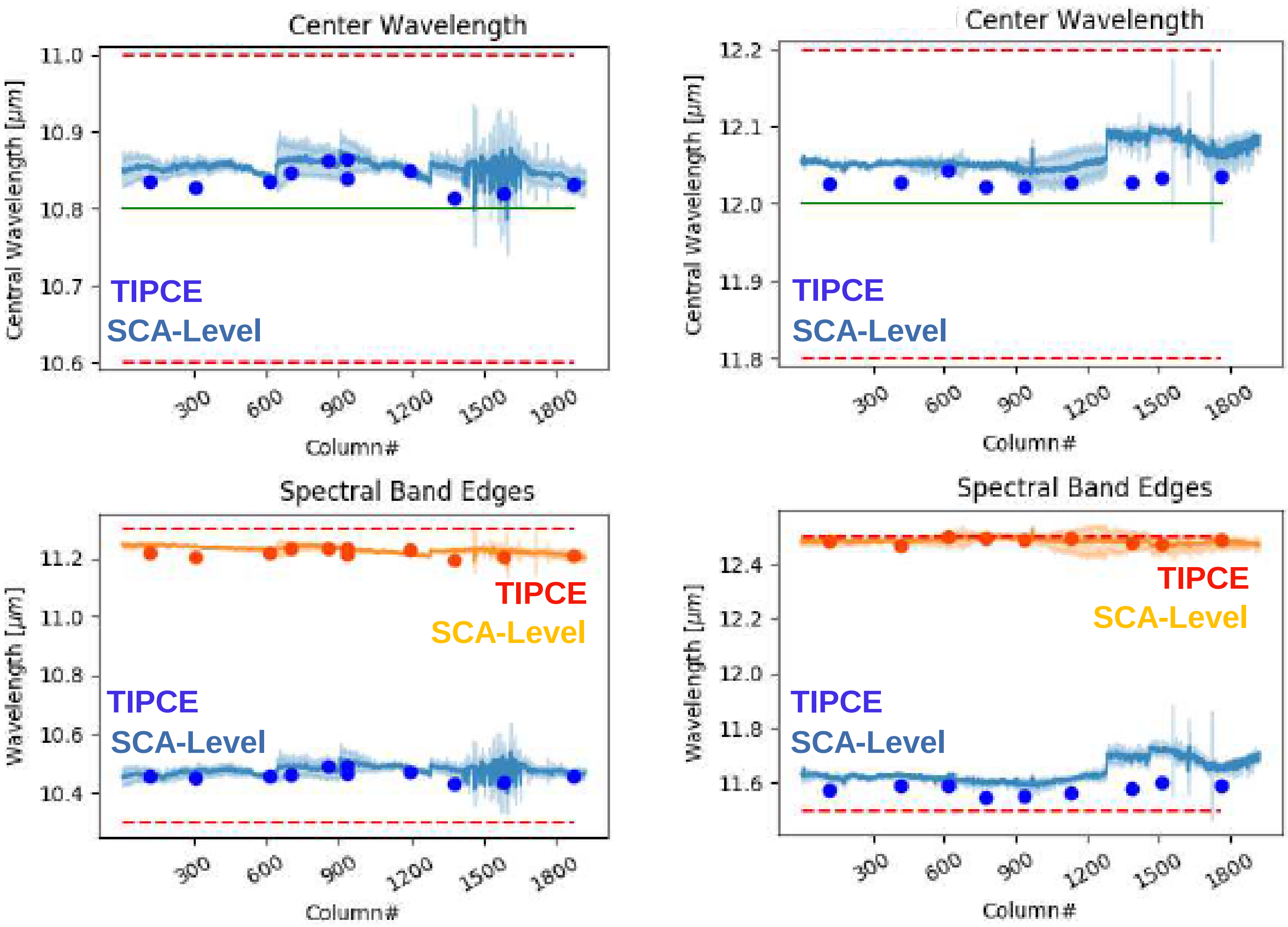
SCA-level (F/1.6)
TIPCE

The shading represents the standard deviation over the per pixel RSRs averaged at each location.

Spectral Response Results: Center Wavelength & Band Edges

- Good agreement in center wavelength and band edges between TIPCE spectral response and F/1.6-adjusted component-level spectral response (SCA-level)
- Strong indication that requirements will be met

10.8 μm | 12.0 μm

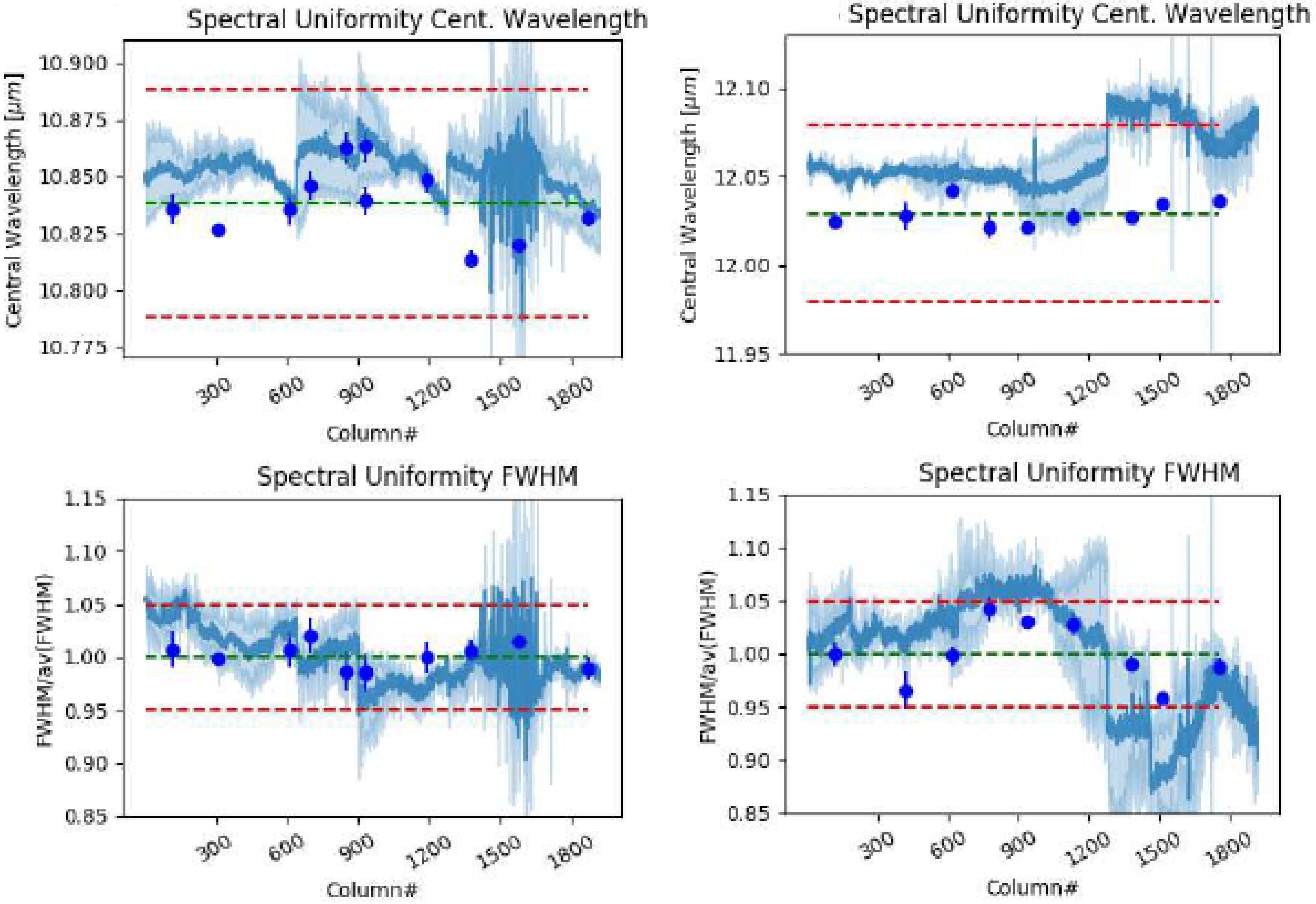


Spectral Response Results: Uniformity

TIPCE
SCA-Level

- Good agreement in spectral uniformity between TIPCE spectral response and F/1.6-adjusted component-level spectral response (SCA-Level)
- Strong indication that requirements will be met

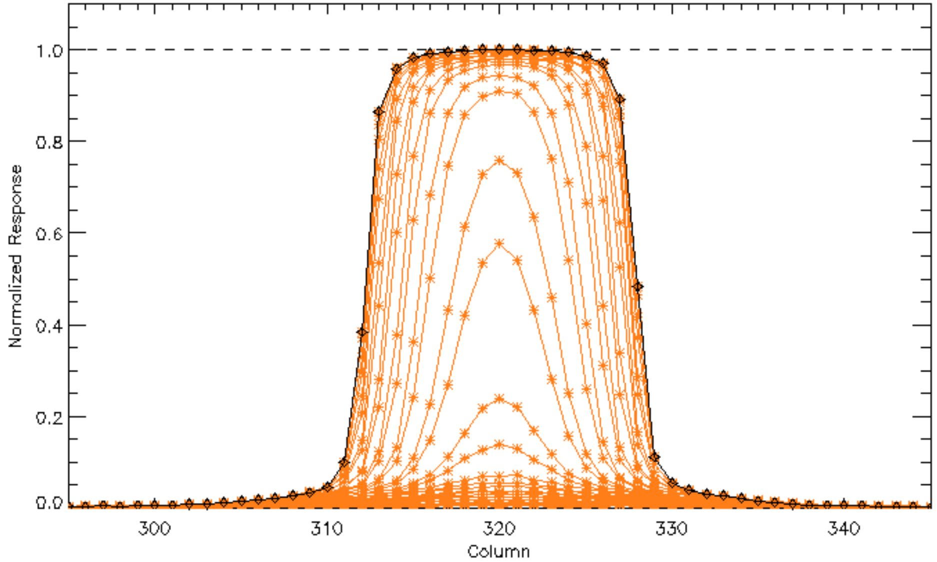
10.8 μm | 12.0 μm

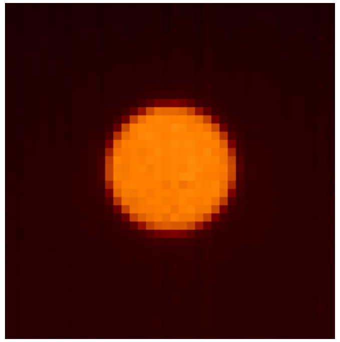


Spatial Response Test Methodology

- Processing follows the same methodology as used for TIRS
  - Using ‘hockey puck’ target collect frames as target is moved in incremental sub-pixel (1/5) steps across-track and along-track over 3 pixels in each direction.
  - 16 pixel diameter circle target (“Hockey Puck”)
  - Large square for flat field
  - Blank for background correction
  - Repeat at different locations on FPA

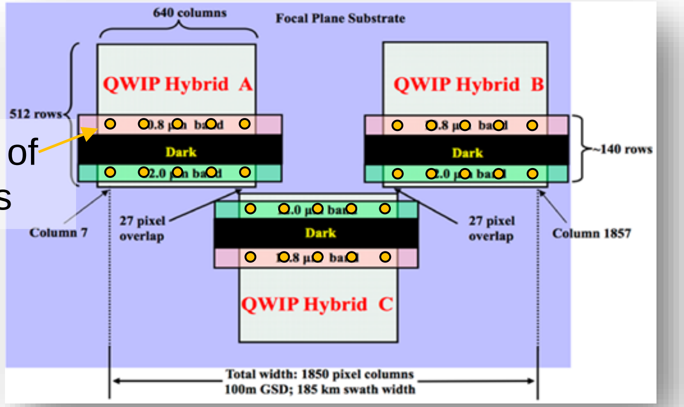
Horizontal cross section through center of puck normalized to maximum value





Raw image of ‘hockey puck’

Locations of collections

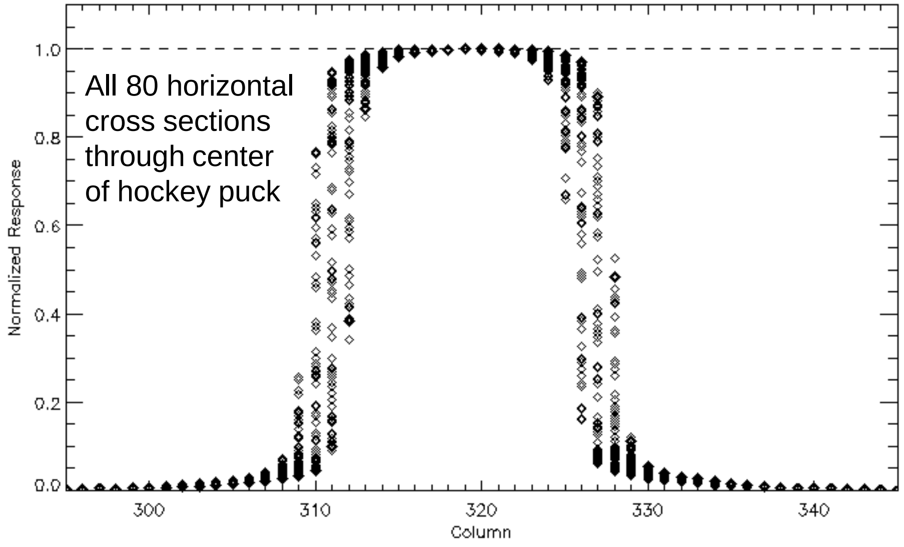


Each circular image frame has a background-correction and flat field applied at pixel level

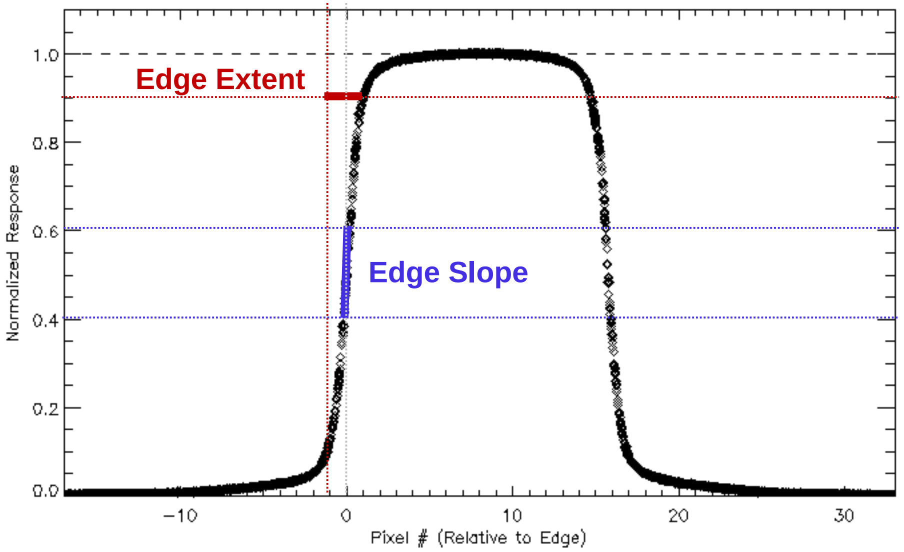
$$dn(i,j) = (DN_P(i,j) - DN_{BKG}(i,j)) / (DN_{FF}(i,j) - DN_{BKG}(i,j))$$

[Wenny et al. Remote Sens. (2015)]

Spatial Response Test Methodology



All 80 cross sections shifted to common reference point



Each frame fit with Fermi function to derive edge midpoint:

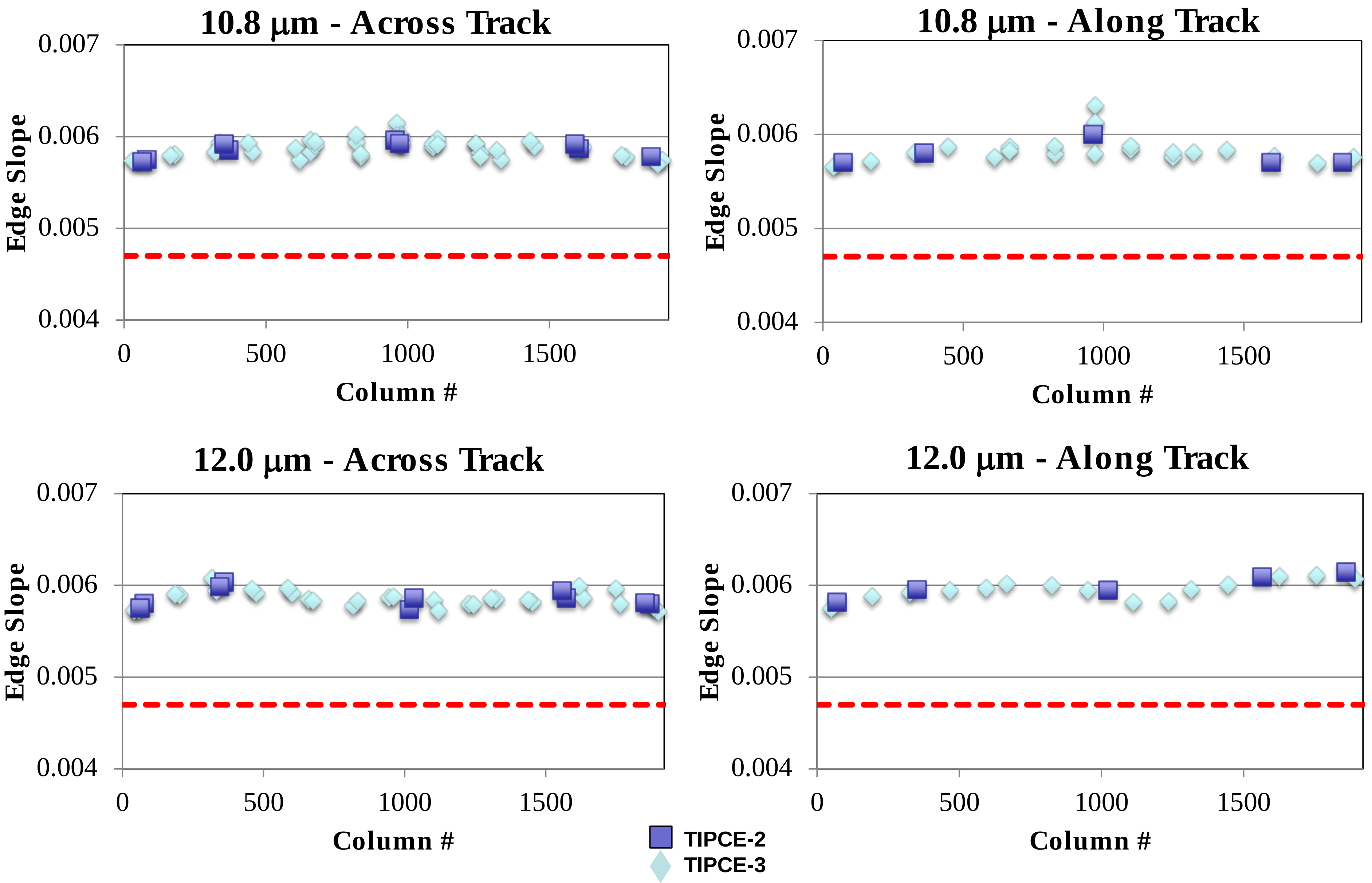
$$f(x) = \frac{a}{\left(e^{(x-b)/c}\right)+1} + d$$

Each cross section shifted to match up mid-points resulting in a well populated edge

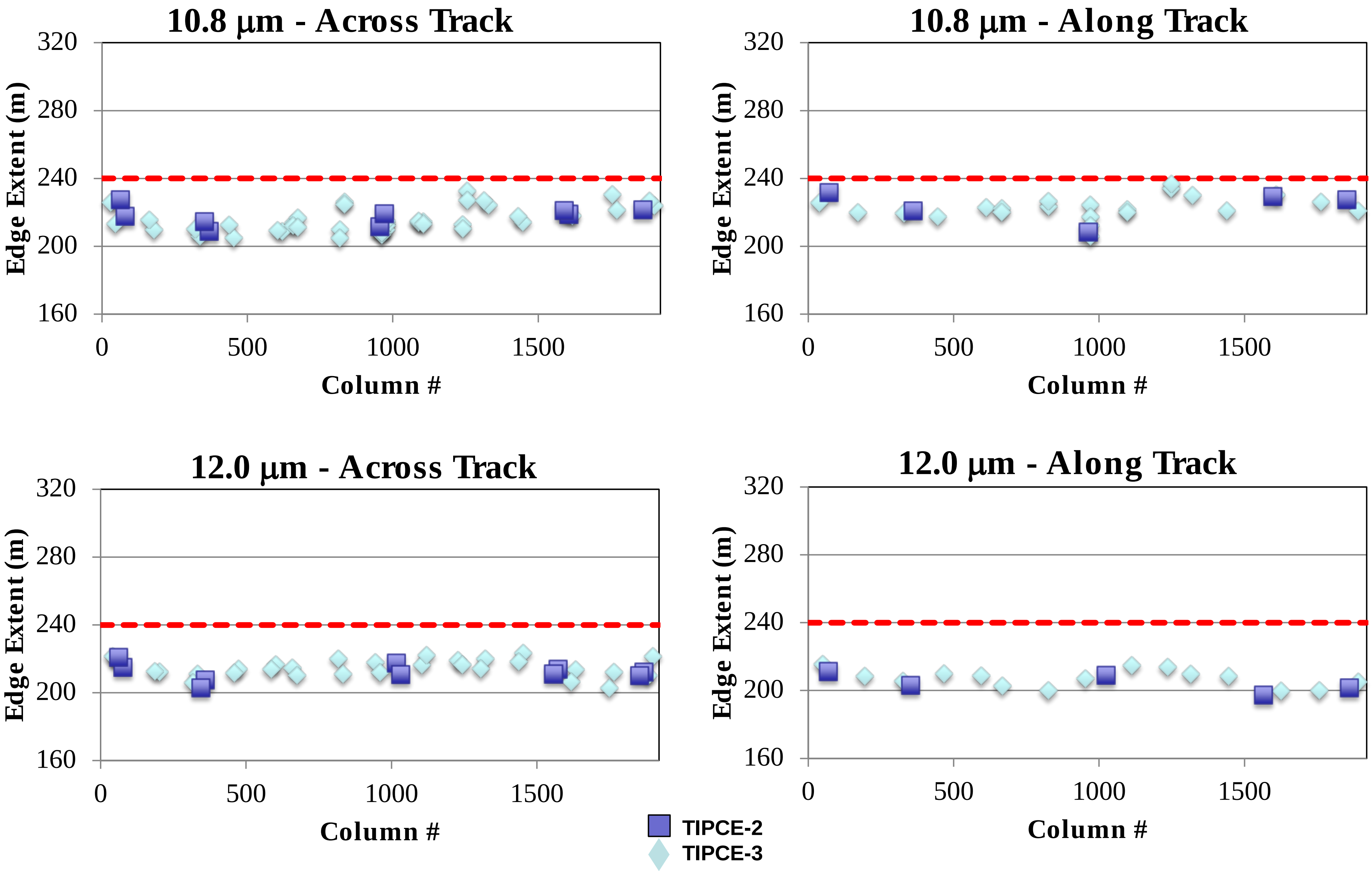
Metrics for evaluating spatial performance -- edge slope, edge extent -- derived from each edge response plot.

[Wenny et al. Remote Sens. (2015)]

Spatial Response Results: Edge Slope



Spatial Response Results: Edge Extent



Preparing for Instrument-level testing

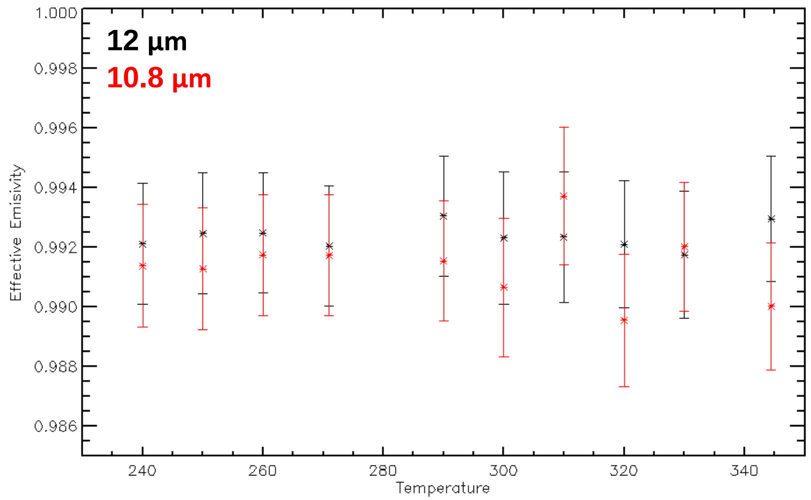
- Work closely with TIRS-2 Systems Engineering and Integration & Test teams to effectively
  - Track test requirements and verification
  - Schedule tests at various plateaus
  - Schedule and track Calibration GSE activities leading up to TV testing
- Prepare Calibration GSE
  - Mirror position calibration
  - Monochromator alignment
  - Flood source installation
- Communicate with Landsat Cal/Val team to
  - Resolve requirement deviations and waivers
  - Transfer characterization data sets
- Leveraged spatial and spectral procedures and test scripts from TIPCE
- Leveraged geometric and radiometric procedures and test scripts from TIRS-1
- Pre-Environmental Review on August 7-8, 2018

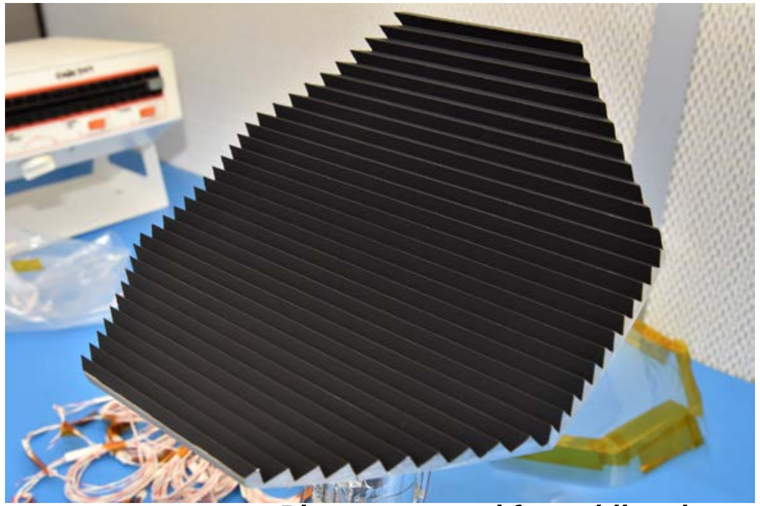
Upcoming Radiometric Measurements *at Instrument Level*

- SI traceability (via NIST)
- On-board blackbody
- Near-field stray light
- Noise metrics
- Temporal stability
- Bias/gain stability
- Uniformity metrics
- Dynamic range
- Orbit in the life (OITL)

Calibration GSE "Flood source"

Effective Emissivity (Flood Source Radiance / Planck-Predicted Radiance)





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On-Board Blackbody (OBB)

Radiometric Error Budget

TIRS-2 Absolute Radiometric Accuracy (2.0%, 4.0%)

RSS CBE = 1.7%, 2.3%

Flood Source Characterization Uncertainty (0.6%)

CBE = 0.6%

Based on 0.3% uncertainty of Flood Source characterization and its propagation to TIRS-2 aperture.

Blackbody Temp Uncertainty (0.1%)

CBE = 0.1%

Derived from accuracy/resolution/ stability of the thermal control of the OBB.

System Scattered Light (1.5%, 3.0%)

CBE = 1.4%, 2.1%

Range dependent on FPA location and out-of-field temperature. Assumes subtraction of scattered light signal of out-of-field constant temperature scene.

Background Emission (0.2%)

CBE = 0.2%

Variability of background signal knowledge. Value estimated from TIRS-1 on orbit performance. *Montanaro et al 2014.*

Blackbody Spatial Uniformity (0.1%)

CBE = 0.1%

Prediction of how much the blackbody will degrade over lifetime. MODIS-style OBB used and little degradation is expected.

Blackbody Temporal Variability (0.5%)

CBE = 0.1%

Characterized with repeated measurements during instrument TVAC.

Angular Variability (0.1%)

CBE = 0.01%

Angular variability of the OBB is negligible since SSM pointing is repeatable. Note that OBB degradation captured elsewhere.

TIRS-2 Radiometric Stability (0.1%)

CBE = 0.1%

Characterized with repeated measurements during instrument TVAC.

Ground-to-orbit (0.4%)

CBE = 0.4%

~0.4% change experienced with TIRS-1. Although origin of change not understood, the magnitude is captured and accounted for using OBB measurements in operational calibration so resulting error should be minimal.

Summary

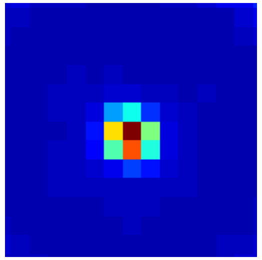
- The results show that TIRS-2 performance is expected to meet all of its performance requirements with few waivers and deviations.
  - ❑ The scatter survey showed improved stray light rejection compared to TIRS-1 the total stray light effect of 1% or less (TIRS-1 – 8%).
  - ❑ Spectral response results show good agreement with component-level measurements accounting for the angular dependence of the detector spectral response.
- Current preparations for instrument-level thermal vacuum in the fall testing are now underway and delivery is expected Aug 2019.
- TIRS-2 team is on track to deliver a well-characterized instrument that will meet data users' needs for a variety of environmental applications.

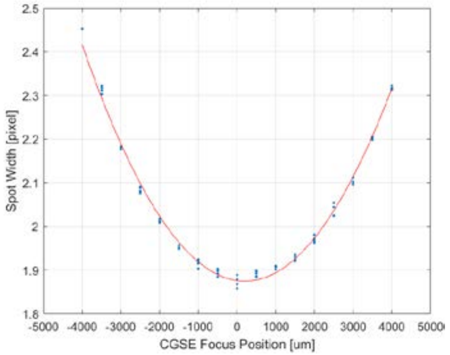
Backup

Focus Test Methodology

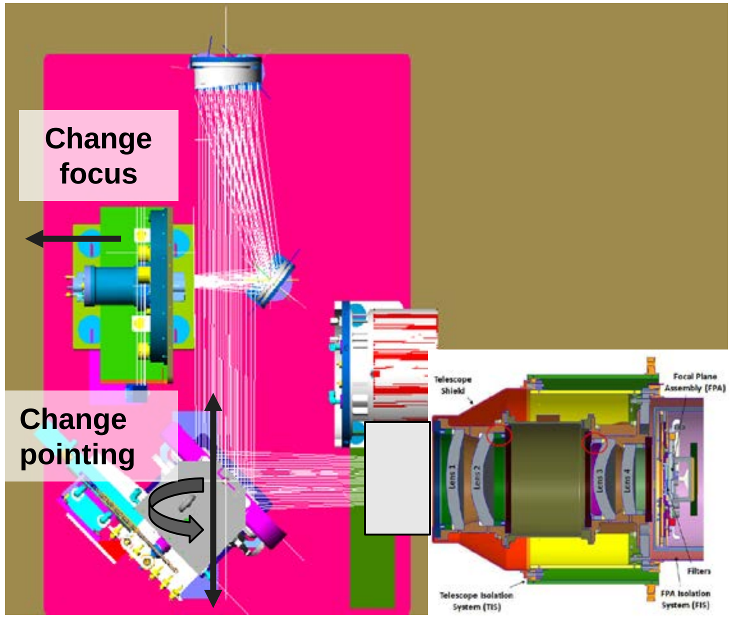
- The Focus Test is used to determine the optimal focus position of the TIRS-2 focal plane assembly (FPA) relative to the optical telescope.
- Optimal focus is determined by minimizing the full-width, half-maximum (FWHM) of a Gaussian-based model fit to the image created by an input two-pixel source.
- ***This focus map is then reported to the instrument team so that proper shims can be fabricated and installed.***
- These measurements are first performed at the telescope-FPA assembly (TIPCE level) to find best focus, then repeated at the full instrument level to validate consistency and characterize focus as function of telescope temperature.

Two-Pixel Source





Focus Test Methodology

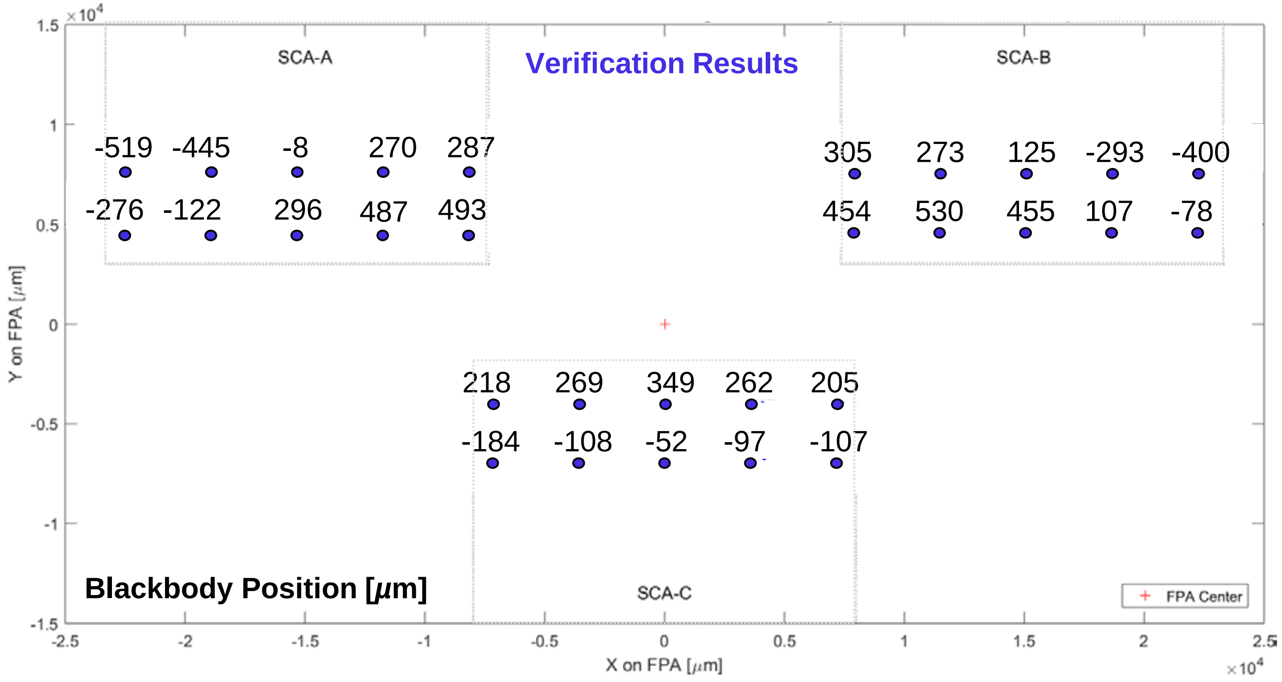


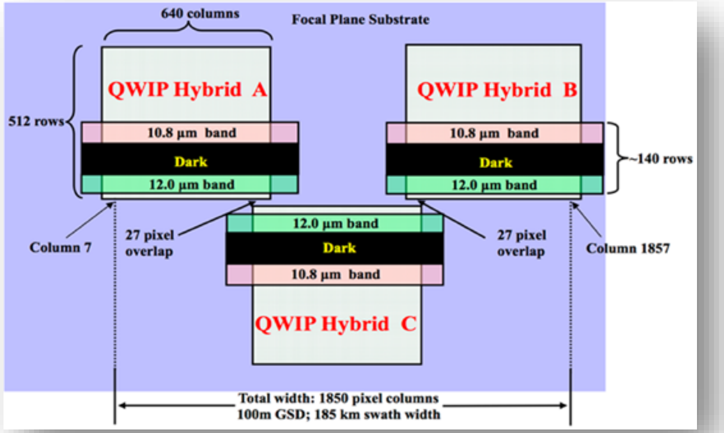
Focus Test Results

- Full focus survey collected during TIPCE with telescope at nominal temperature

- *Shims calculated, manufactured, and installed*

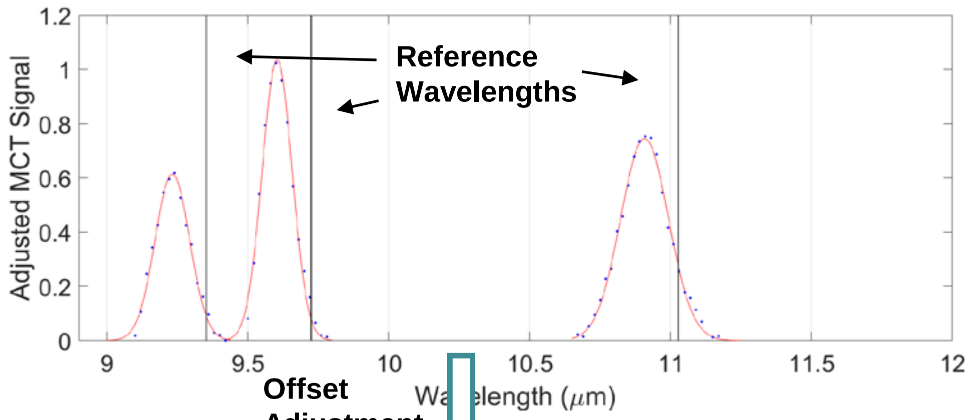
- Full focus survey for verification collected during another phase of TIPCE at nominal telescope temperature and at nominal +5 K.
  - Found average piston defocus of +90 microns of CGSE z-axis
  - shim deltas to be only: +0.0003", +0.0002", -0.0002"
  - **Decided on NO shim adjustment**
  - **Decided on NO telescope temperature adjustment**





Spectral Shape Setup – Monochromator Wavelength Calibration/Validation

- Used NIST wavelength standard (1921b) to calibrate the monochromator wavelength scale using absorption lines closest to the TIRS-2 bands
- The adjustment was programmed into the monochromator to correct an 120 nm offset before TIPCE
- **The wavelength calibration was validated pre/post TIPCE phases**
  - **Monochromator wavelength < 10 nm from wavelength reference throughout TIPCE.**



Offset Adjustment

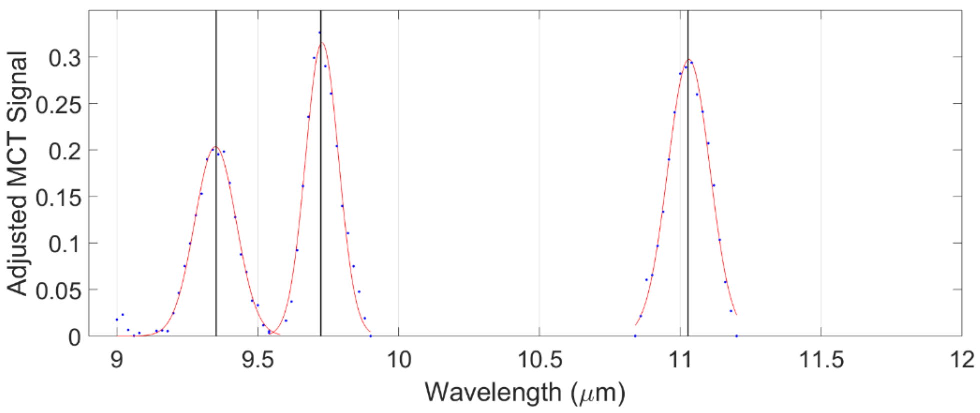
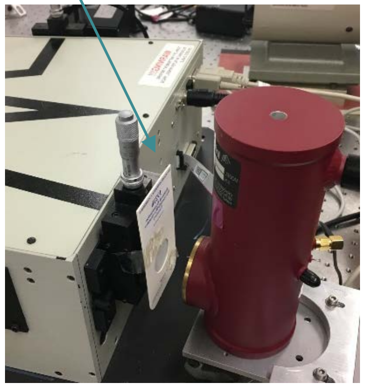


Table 1. Certified Band Centroid Wavelength Values (in Vacuum)

Band Number	Band Wavelength (µm)	Expanded Uncertainty, *U* (µm)
1	18.3512	8.2×10^{-2}
2	11.8751	1.8×10^{-2}
3	11.0276	1.3×10^{-3}
4	9.7237	2.5×10^{-3}
5	9.3522	6.8×10^{-3}
6	8.6608	7.0×10^{-4}
7	6.3169	3.4×10^{-4}
8	6.2446	4.1×10^{-4}
10	3.50853	1.5×10^{-4}
11	3.33178	1.0×10^{-4}
12	3.30421	1.0×10^{-4}
13	3.26782	9×10^{-5}
14	3.24442	1.0×10^{-4}

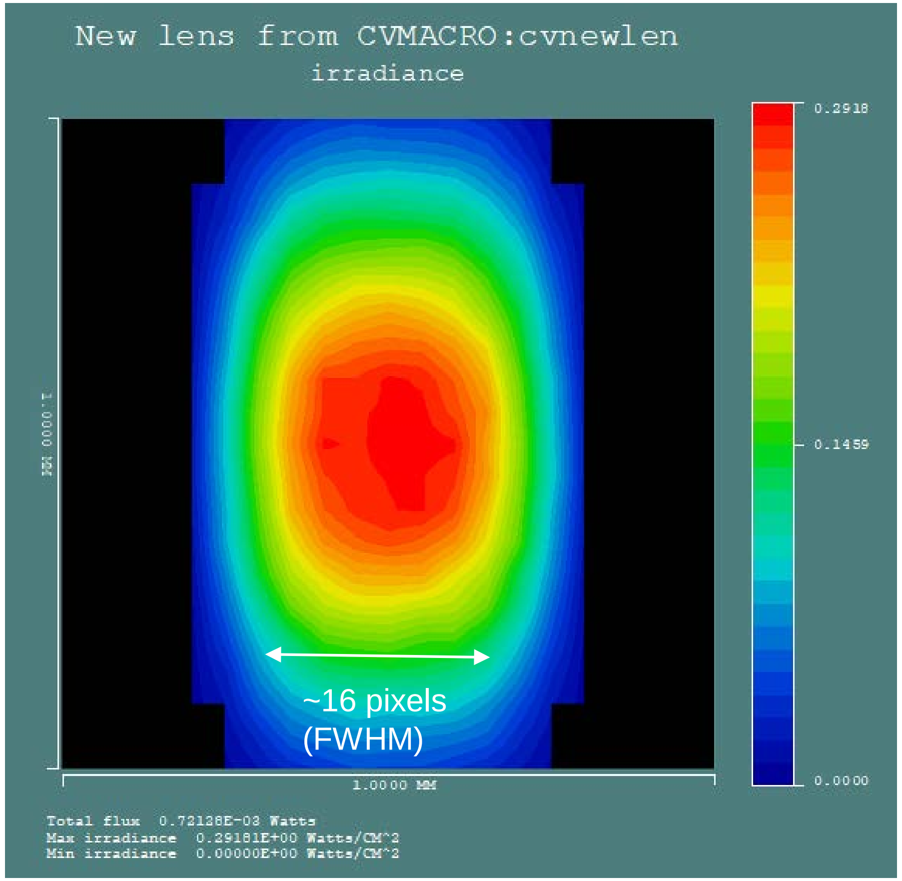
NIST Certificate SRM 1921b



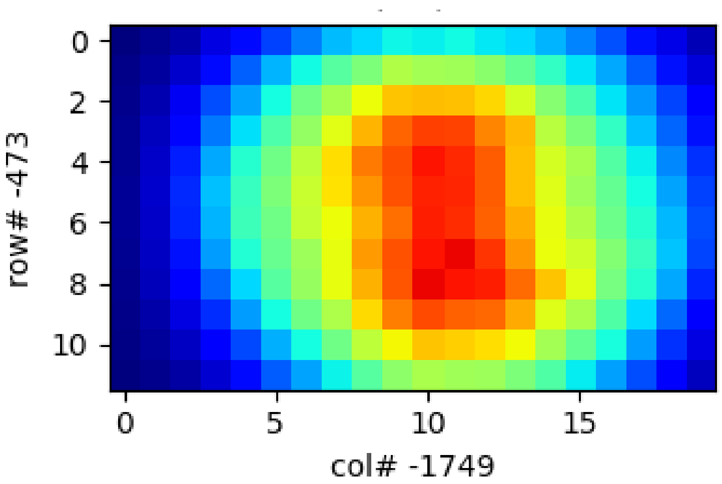
Spectral Shape - Optical Modeling

Model and TIPCE show slit images with similar shapes & sizes

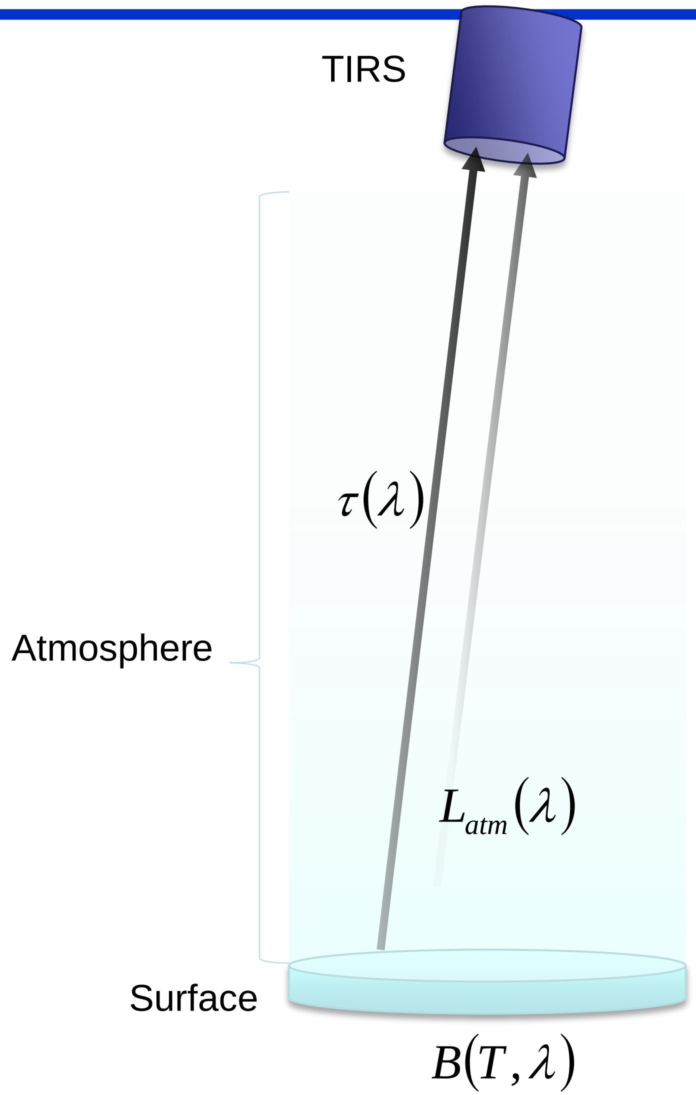
Simulated Image on TIRS focal plane



Measured Image on TIRS focal plane

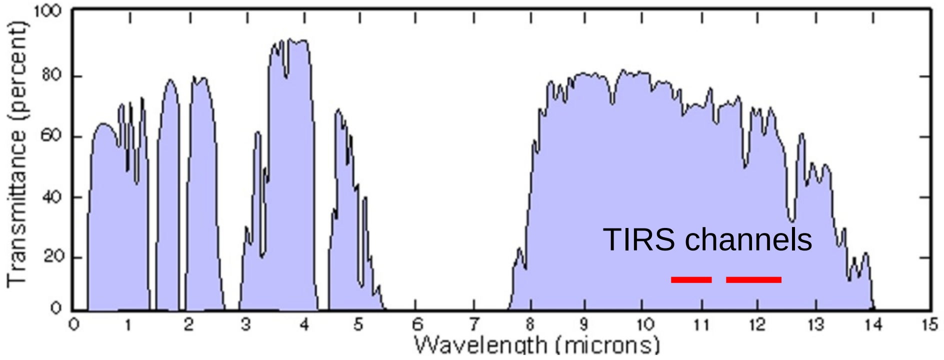


Thermal Radiance Detected by TIRS-2 from Surface and Atmosphere



$$L_s = \frac{\int \left(B(T,\lambda)\cdot\tau(\lambda) + L_{atm}(\lambda)\right)\cdot R'(\lambda)\cdot d\lambda}{\int R'(\lambda)\cdot d\lambda}$$

- $B(T,\lambda)$ • Emitted and reflected surface radiance
- $\tau(\lambda)$ • Transmission of atmosphere
- $L_{atm}(\lambda)$ • Emitted and scattered radiance of atmosphere
- $R'(\lambda)$ • Spectral response of pixel
- L_s • Pixel integrated radiance



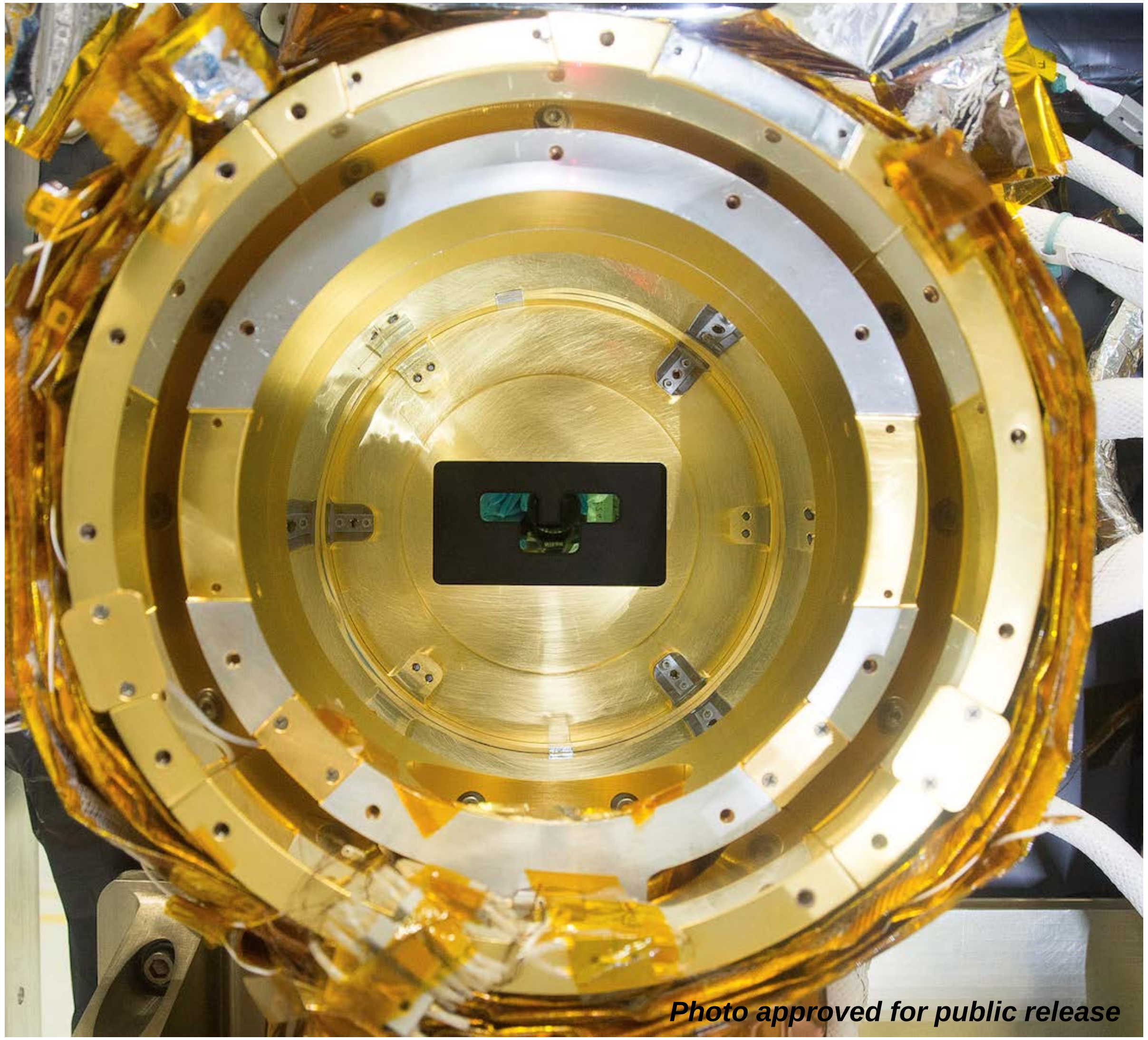
Two channel “split window” techniques correct for atmosphere and improve retrieved surface temperature

Spatial Response: TIRS-2-TIRS-1 Comparison

	Channel	Direction	TIRS-2 (TIPCE-3) Mean	TIRS-2 (TIPCE-3) σ	TIRS Pre-launch Mean	TIRS Pre-launch σ
Edge Slope ($pixel^{-1}$)	10.8 µm	Cross	0.0059	0.0001	0.0059	0.0002
	10.8 µm	Along	0.0058	0.0002	0.0053	0.0003
	12.0 µm	Cross	0.0059	0.0001	0.0061	0.0001
	12.0 µm	Along	0.0060	0.0001	0.0063	0.0002
Edge Extent (m)	10.8 µm	Cross	215.6	7.3	202.8	9.1
	10.8 µm	Along	222.8	6.8	234.0	17.1
	12.0 µm	Cross	214.9	5.1	197.6	6.9
	12.0 µm	Along	207.5	5.2	184.3	11

TIRS-2 photos

Filters/FPA before final telescope shim, Feb 2018

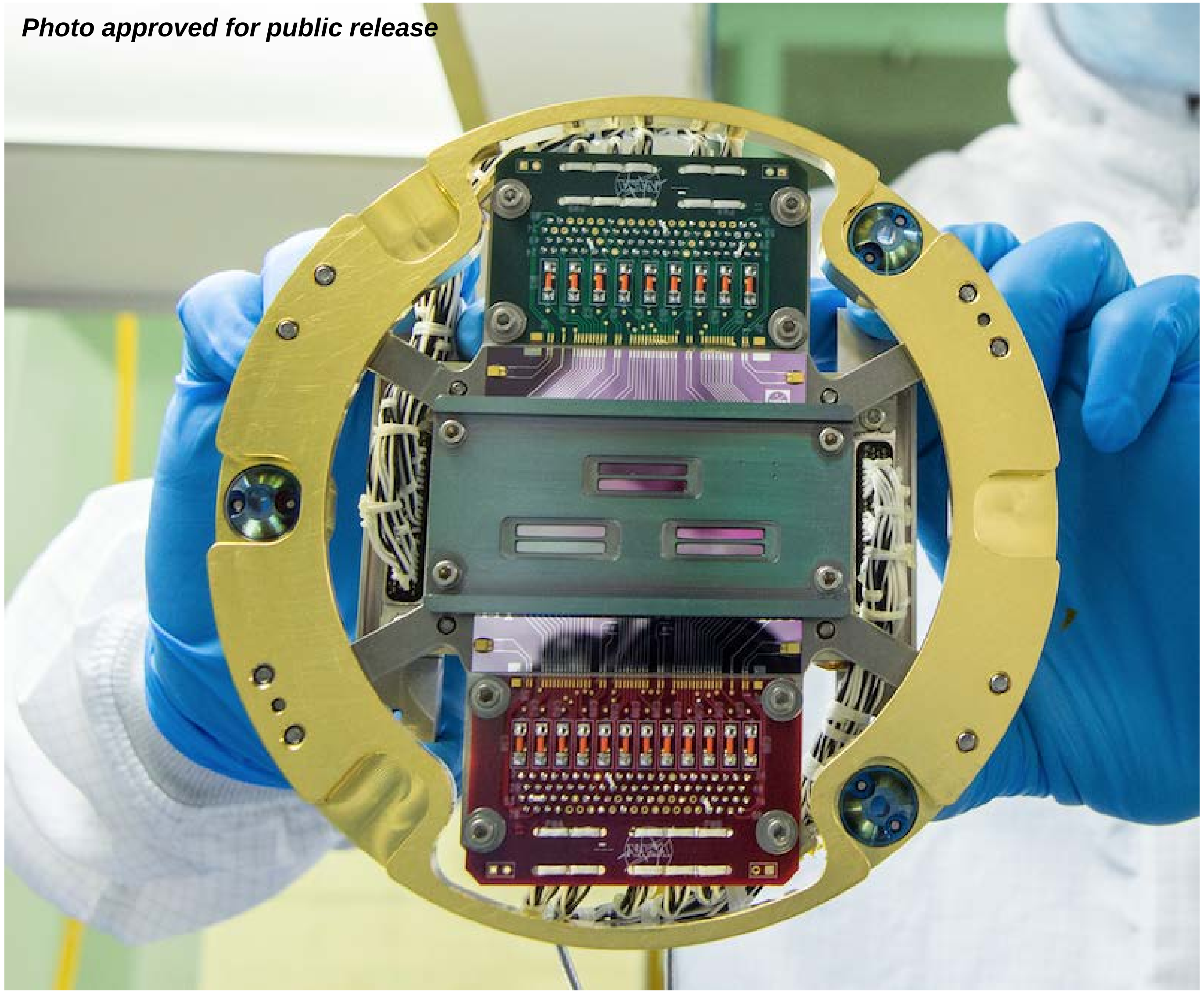


TIRS-2 photos

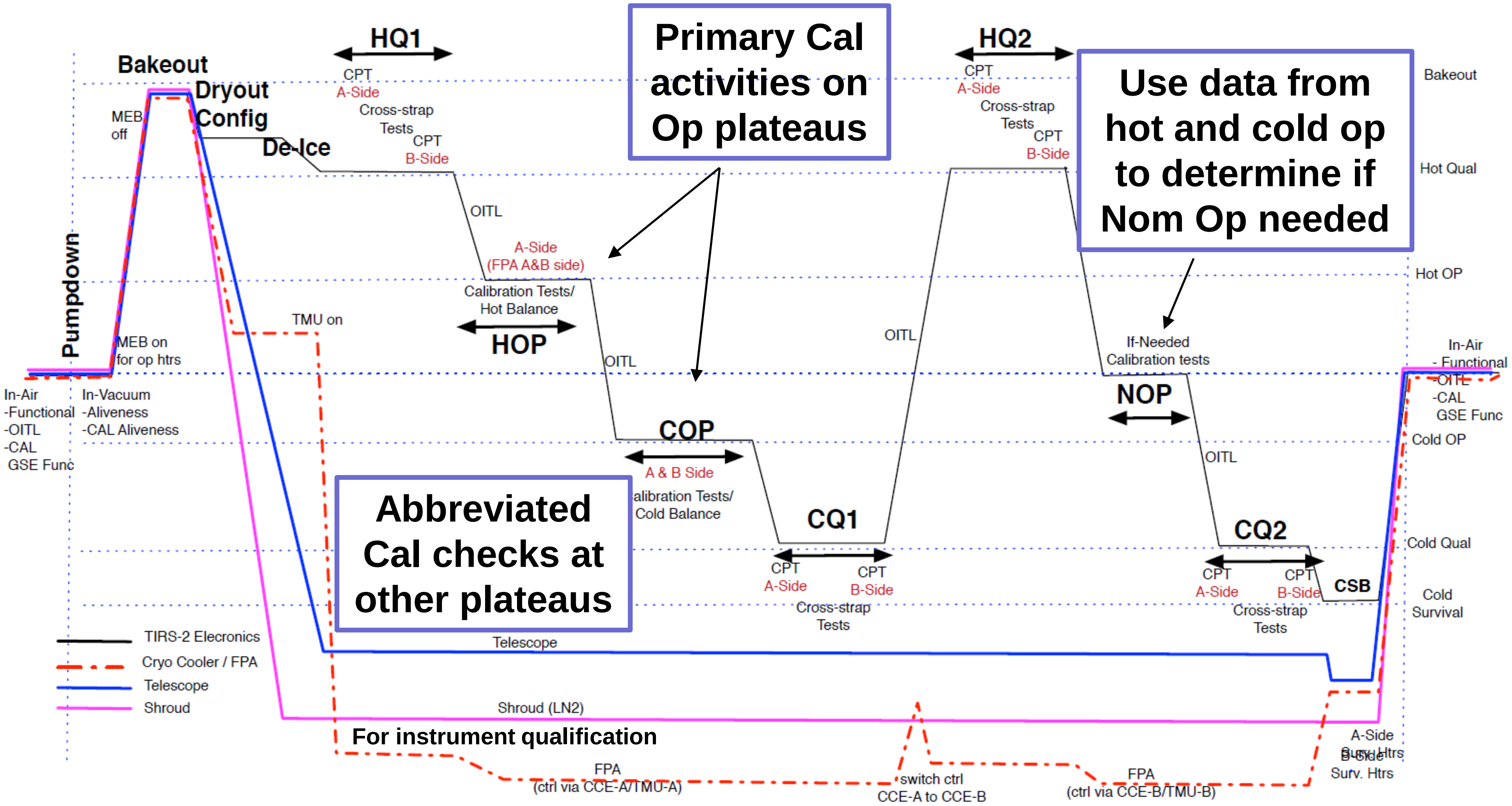
Telescope installation, March 2018

TIRS-2 photos

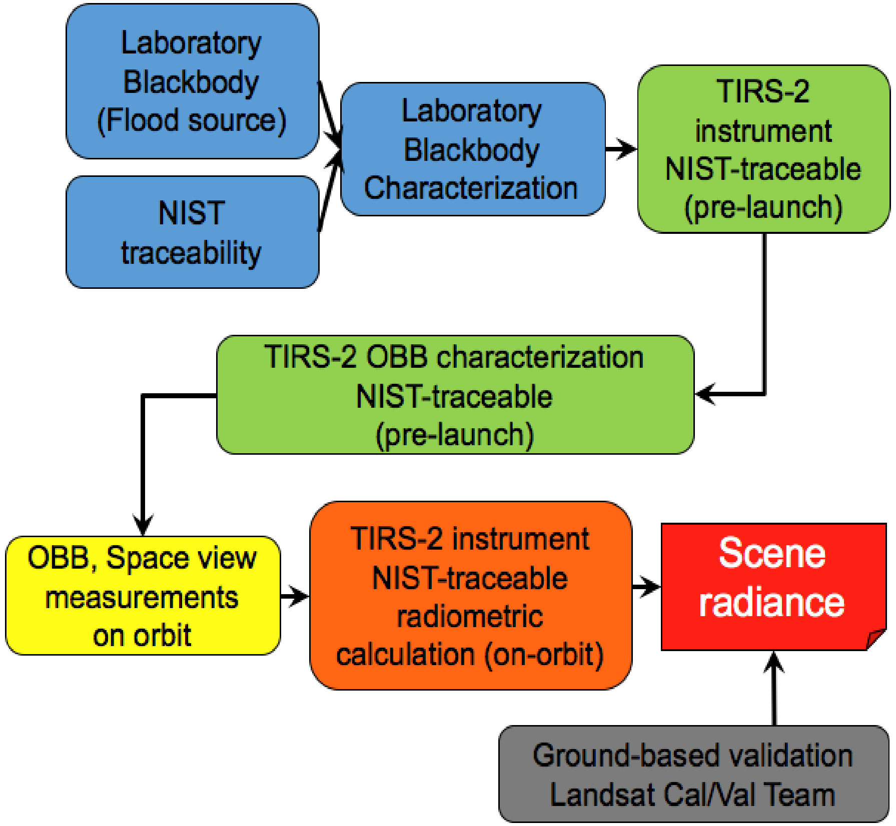
FPA prior to integration, December 2017



Instrument-level test timeline



Radiometric traceability



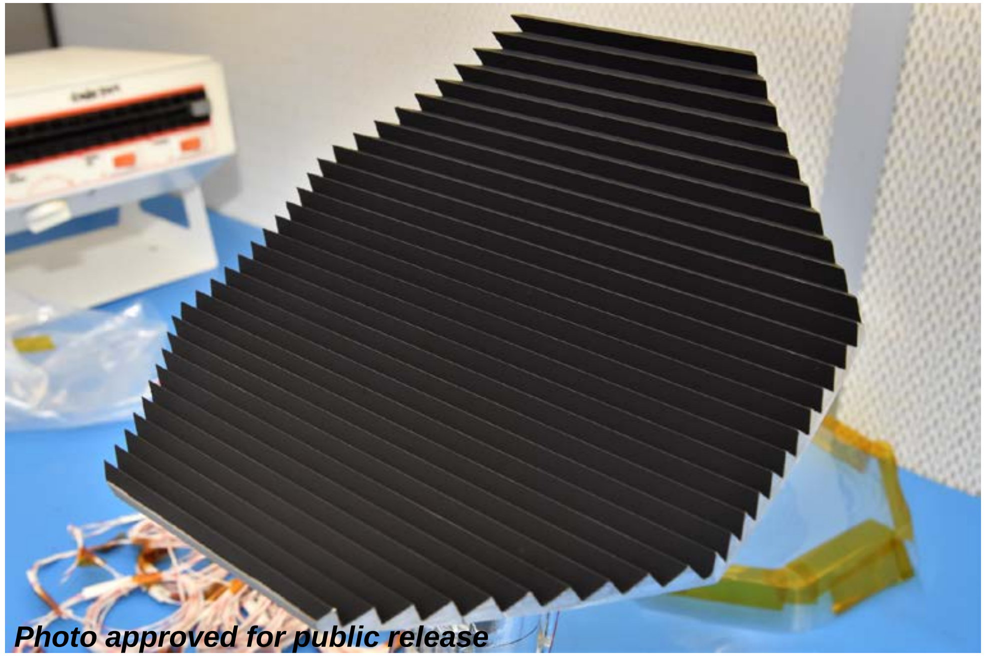
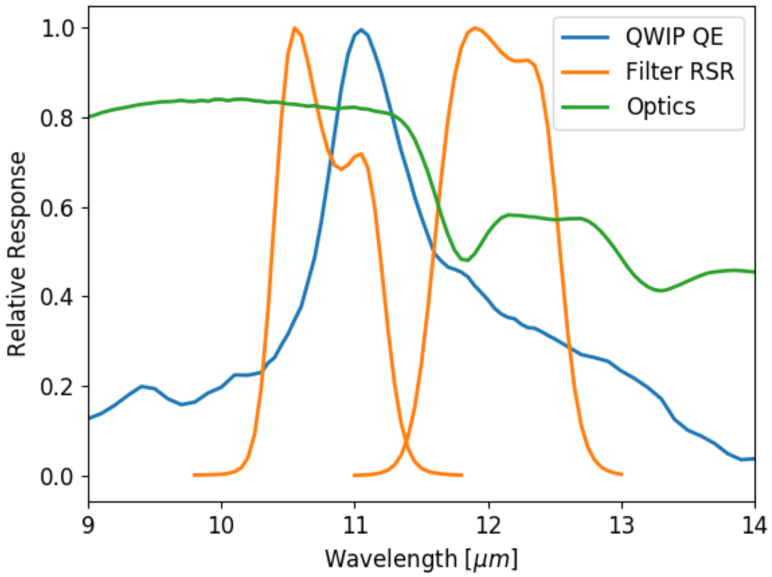


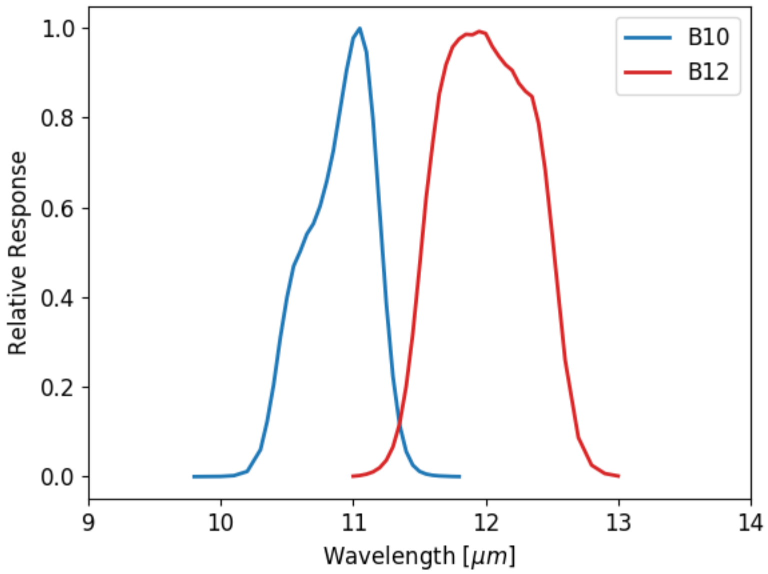
Photo approved for public release

Relative Spectral Response (RSR) Component-level Measurements

- DCL measured the QWIP QE for all SCAs at operational temperature at normal incidence
- Filter vendor provided spectral response at operational temperature and F/ #
- Component-level measurements are combined to simulate the instrument response
- QWIP QE was measured at F/ 4 (NA=7deg) while TIRS has F/ 1.64 (NA=17deg).

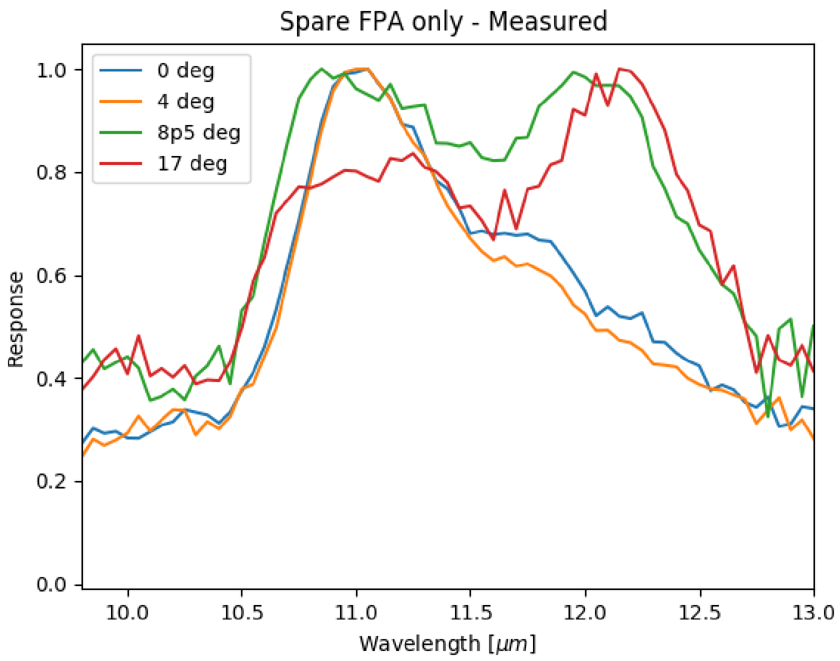
$$RSR(\lambda) = QE(\lambda)\lambda\tau_{filter}(\lambda)\tau_{optics}(\lambda)$$





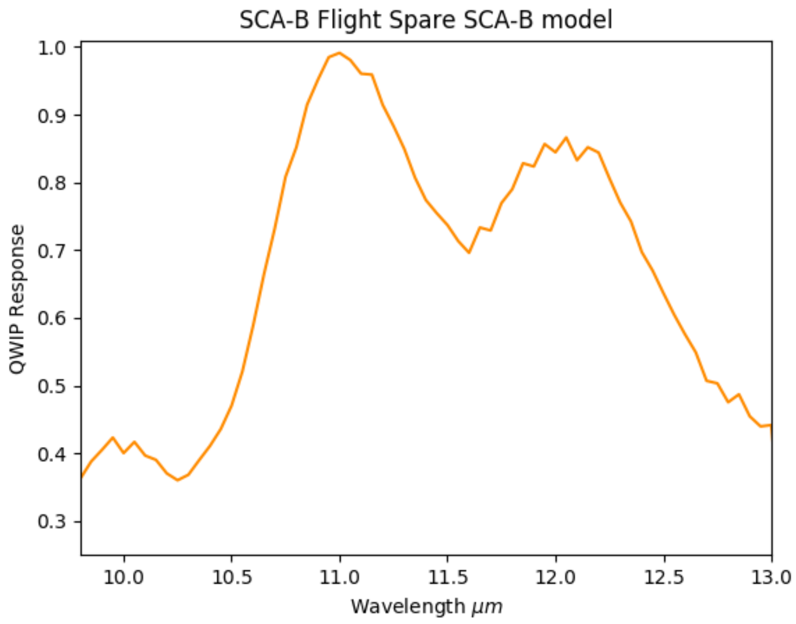
QWIP Response Model at F/1.64

- The QWIP response for SCA-B is measured at 4 angles and is weight-averaged over the solid angle subtended by the TIRS aperture
- The resulting per pixel QWIP F/1.64 response of SCA-B is averaged over the unvignetted rows 0-340, and over columns 307-469.
- The ratio between the resulting average QWIP F/1.64 response to the average (over the same pixels) QWIP response at normal incidence is used as multiplication factor to correct the per pixel normal incidence QWIP response for all detectors of all SCAs.



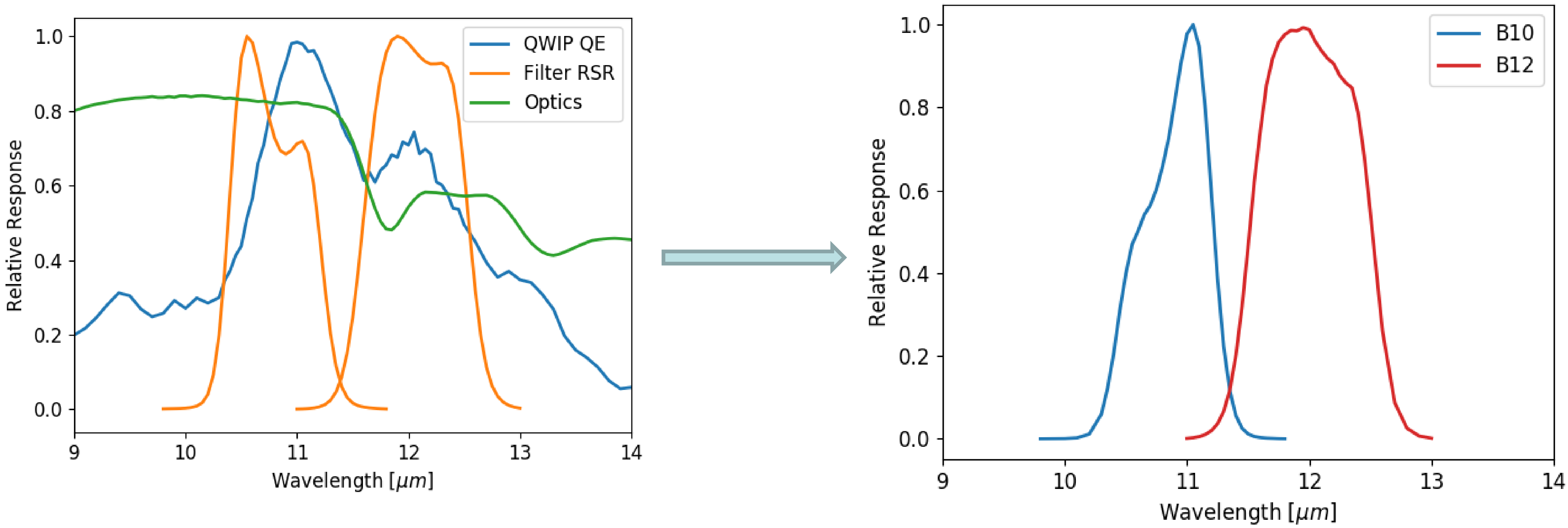
–Weight-average over solid angle:

–$RSR_{av} = \sum_i [RSRi(\alpha_i)\sin(\alpha_i)\,\Delta\alpha_i\,]/[1 - \cos(\alpha_{max})]$



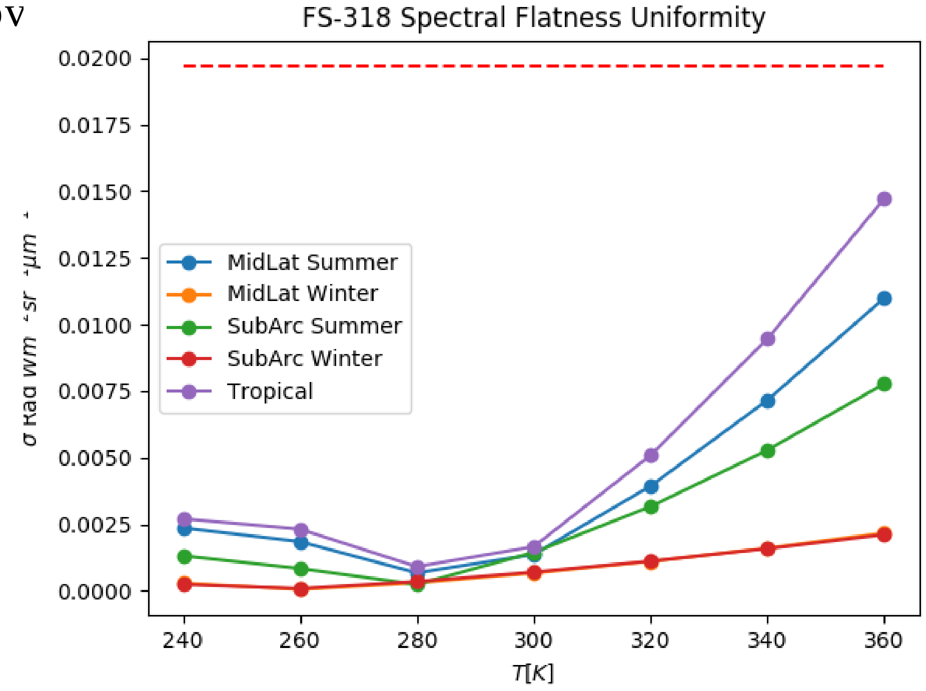
Relative Spectral Response (RSR) Component-level F/1.64

- Component-level measurements are combined to simulate the instrument response, after accounting for F/ # of TIRS-2.



Spectral Flatness Uniformity

- Average RSR for each location
  - ✓ For each 12x20 pixel area we derive per pixel RSR.
  - ✓ Since the pixel-to-pixel variations appear to be related to the test setup rather than to be specific to the detectors the RSR of all pixels above certain signal threshold are averaged and one RSR per location derived.
- Spectral Flatness Uniformity
  - ✓ Compute the spectral flatness uniformity using only the average per location RSR, so e.g. for B10 there are 10 points (3 locations on each SCA-A, and C, and four on SCA-B) ov



$$-std = \sqrt{\frac{\sum_i (Li - Lmean)^2}{N}}$$

–where N=10 for B10 TIPCE3

  - ✓ The TOA radiance L_i above is computed using MODTRAN simulation for five atmospheres; at scene temperatures in the range 240-360K; averaged over each location's RSR; flatfielded using BB radiance of the scene temperature; and compared to NEdL/ 3 :

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