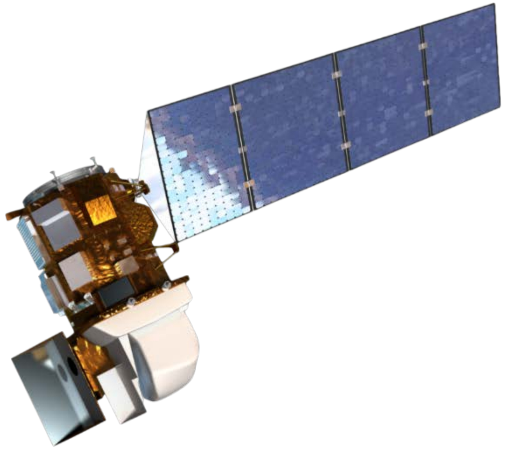
Landsat 9 TIRS-2 Spectral Response Test: Updates & Perspective

Aaron Pearlman[1]

Boryana Efremova[1], Allen Lunsford[2], Joel McCorkel[3], Amy Simon[3], and Dennis Reuter[3]

[1]GeoThinkTank LLC, [2]Catholic University of America, [3]NASA Goddard Space Flight Center

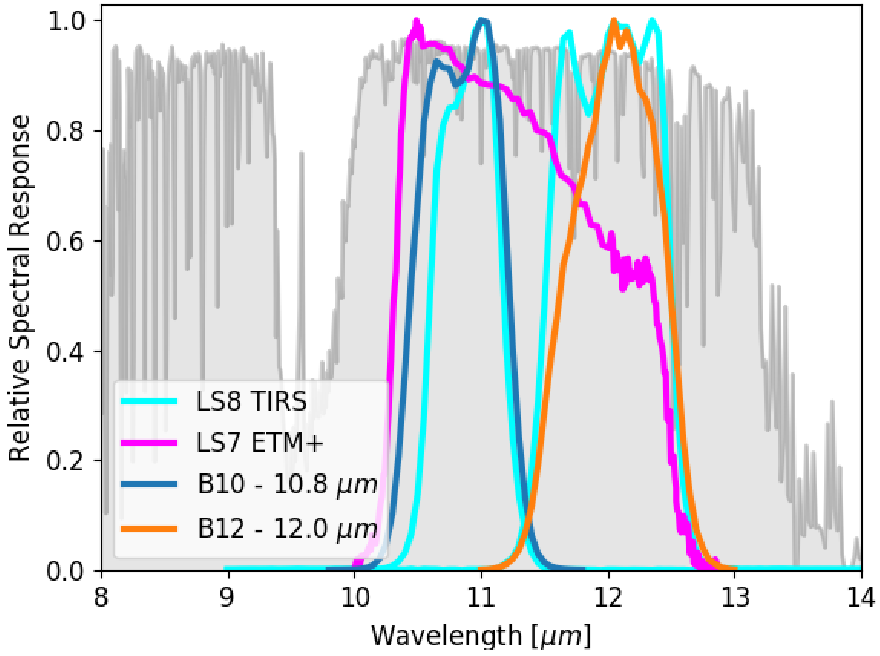


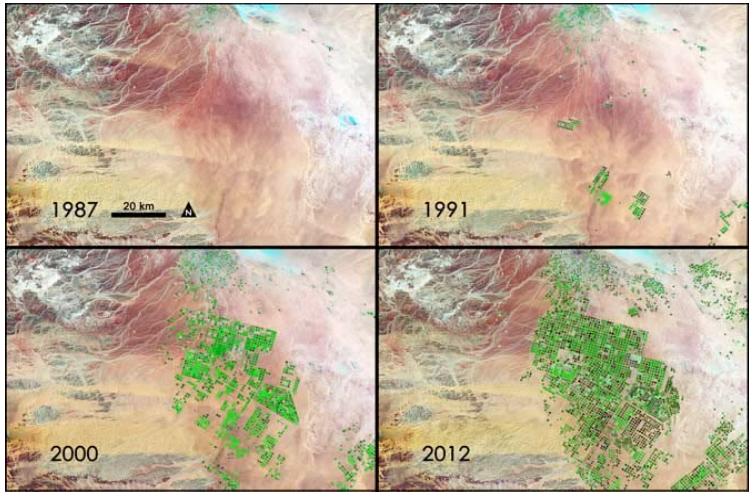
Acknowledgements:
TIRS-2 Calibration Team
Landsat 9 Cal/Val Team

IGARSS
Yokohama, Japan
August 1, 2019

TIRS-2 Project Overview

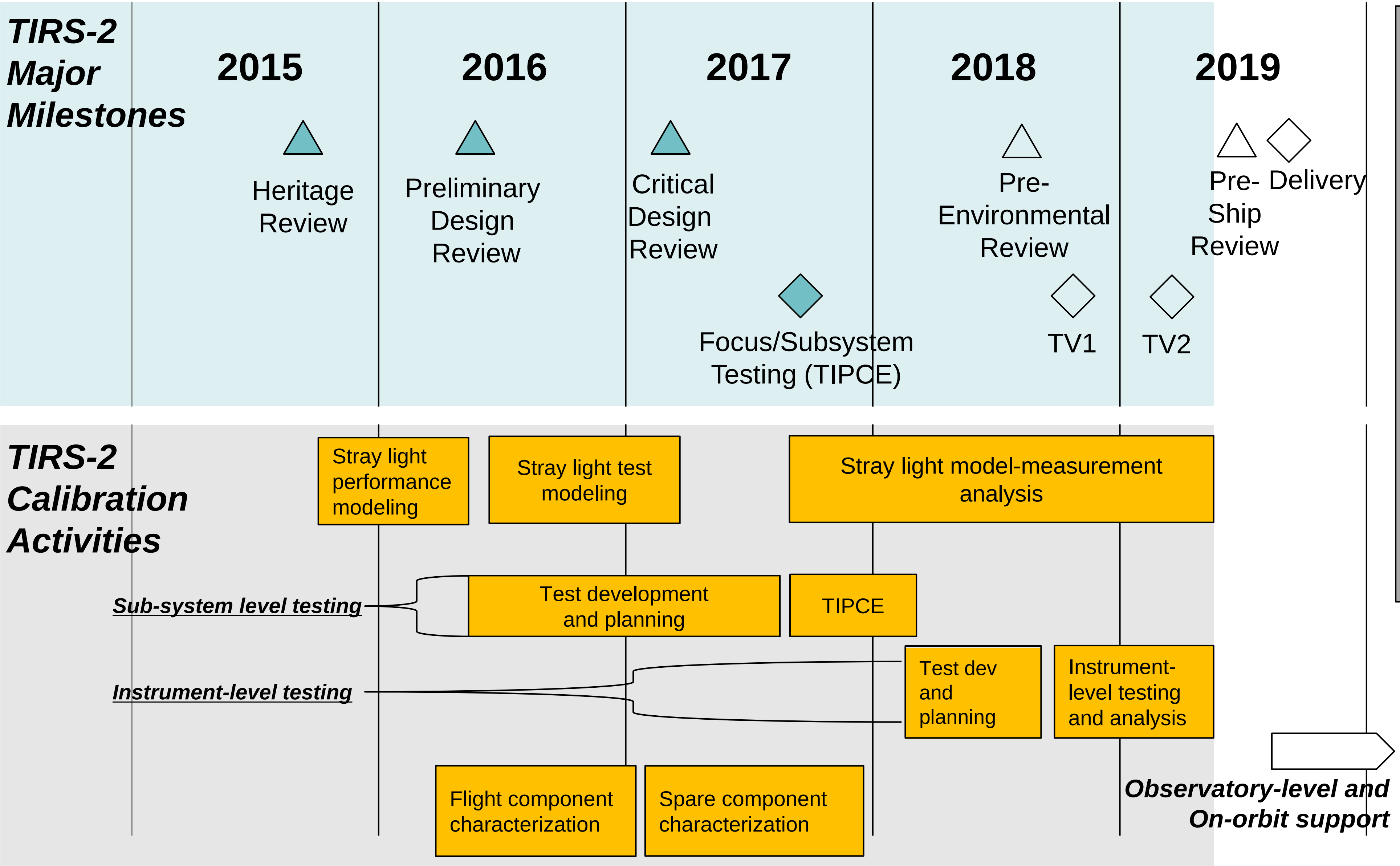
- Landsat TIRS: Provide continuity in the multi-decadal Landsat land surface observations to study, predict, and understand the consequences of land surface dynamics
- TIRS-2 will fly on the Landsat 9
  - 16 day re-visit cycle
  - 120 m resolution
  - 2 bands: 10.8 μm & 12 μm – enable land surface temperature retrievals using split window approach
- 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





–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)

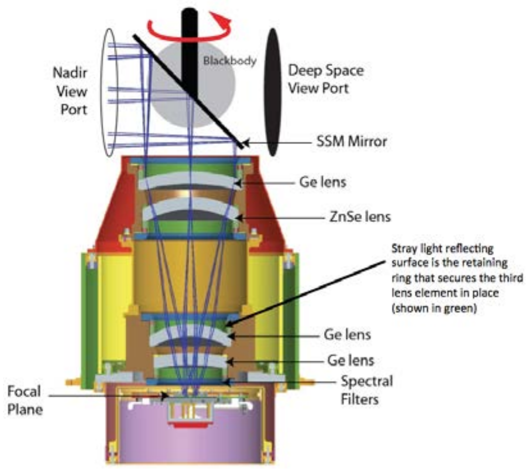
TIRS-2 Calibration Timeline

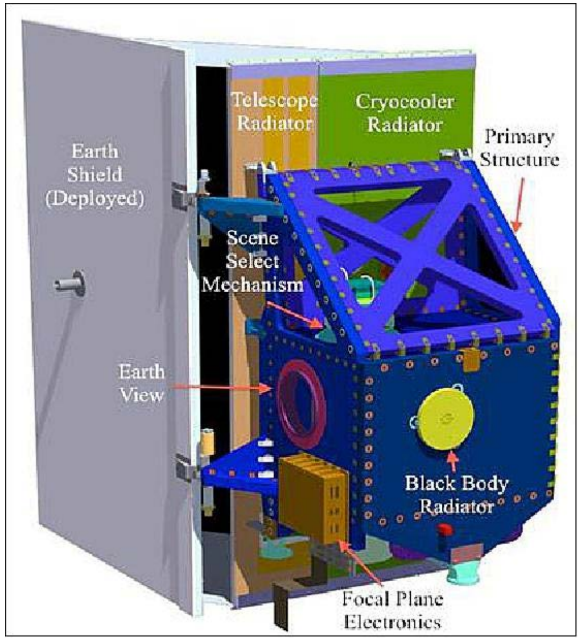


- NASA GSFC TIRS-2 team formed in 2015
- TIRS-2 completed Critical Design Review in Feb. 2017
- Instrument in fabrication at NASA GSFC
- Pre-launch testing imaging and spectral characterization Nov. 2017 – March 2018
- **Instrument-level testing (TVAC-1 and TVAC-2)**
- On target for August-2019 delivery to spacecraft

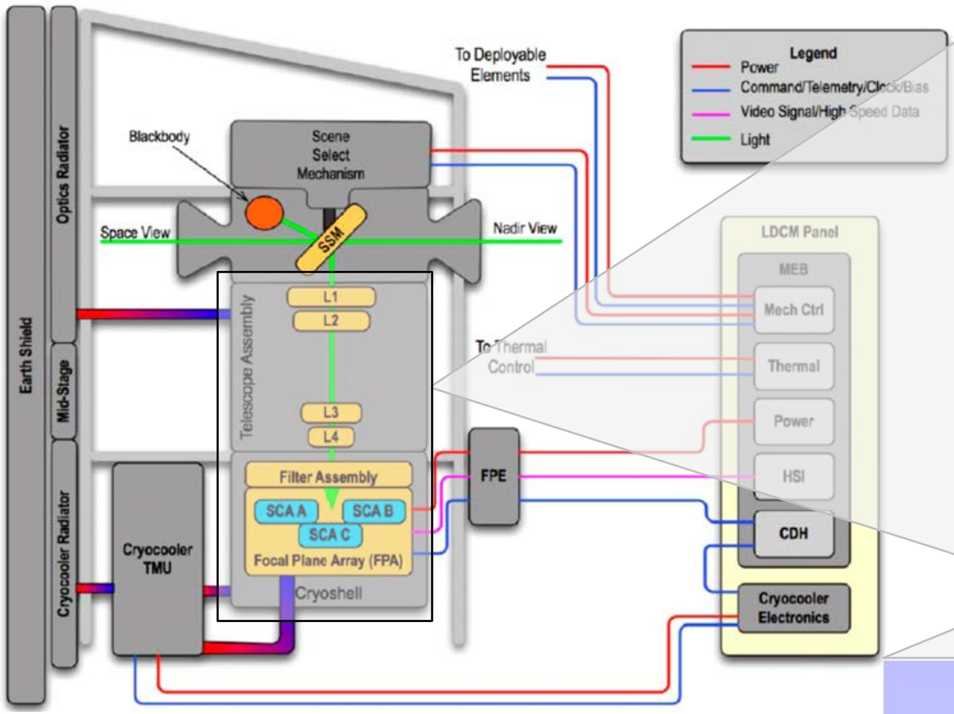
Landsat 9 TIRS-2 Requirements

Requirement	TIRS-2 Required Value	Units
NEdT (@300K)	< 0.4	Kelvin
NEdL	< 0.059, < 0.049	$W/m^2/sr/\mu m$
Saturation Radiances	20.5, 17.8	$W/m^2/sr/\mu m$
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

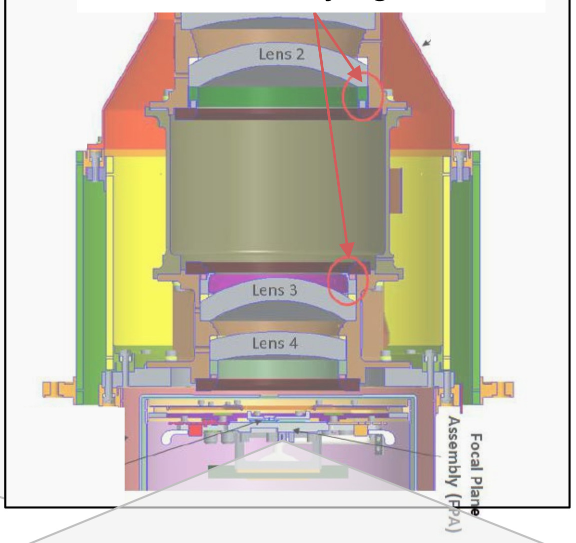




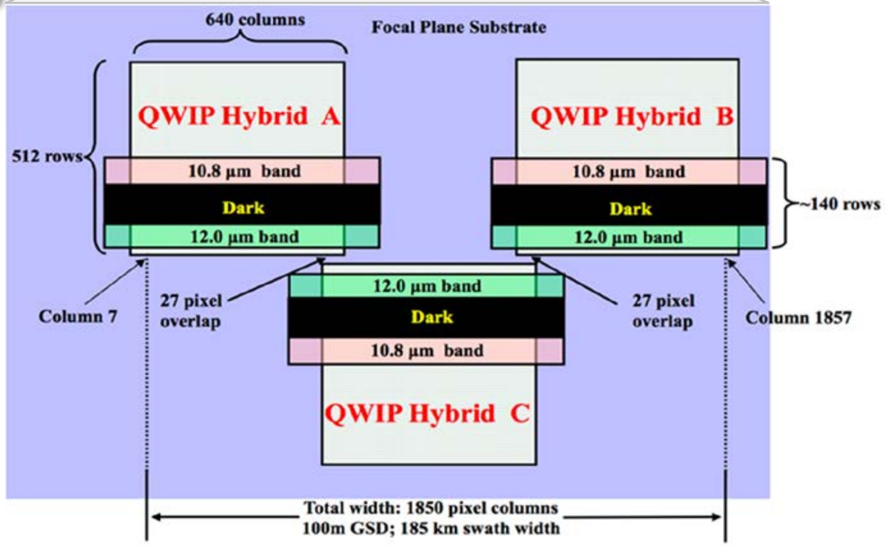
TIRS-2 Architecture



Baffles added for TIRS-2 to reduce stray light



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)

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

TIRS-2 Characterization

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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 Response	Preliminary	X
Spectral Response	Preliminary	X
Scatter	X	Subset
Radiometry		X
Bright Target Recovery		X
Special Tests		X
Orbit-In-The-Life (OITL)		X

Expect to use instrument-level spectral response for operational version

This Talk

Spectral Response Test Introduction

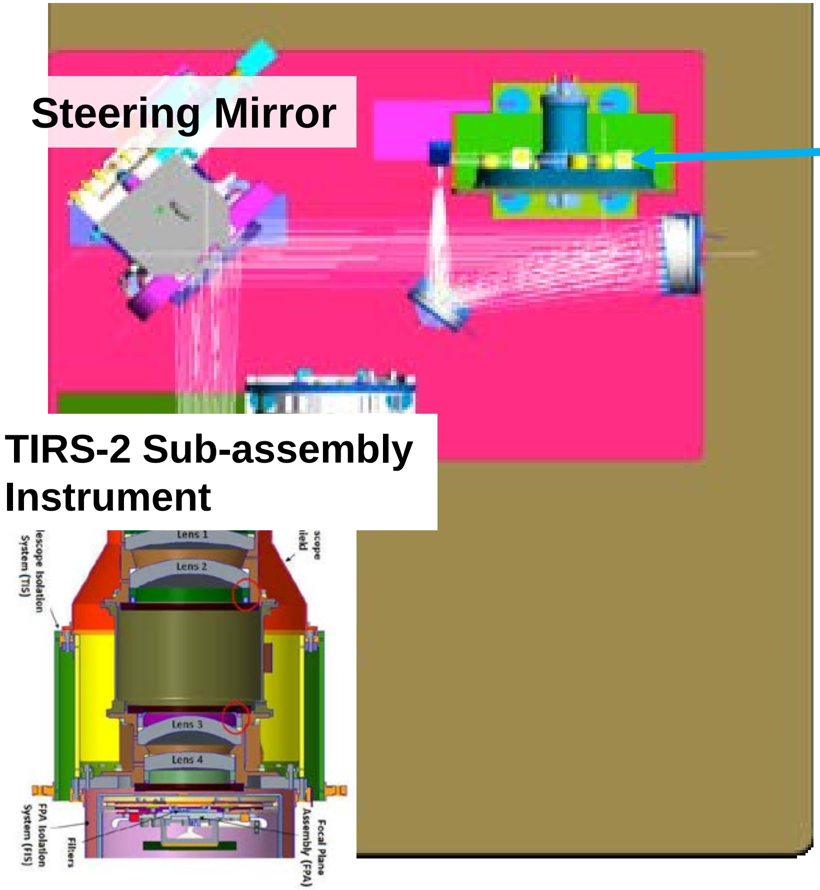
- Cal GSE in “monochromator mode” where collimated beam from the setup outside the chamber is focused and then re-collimated

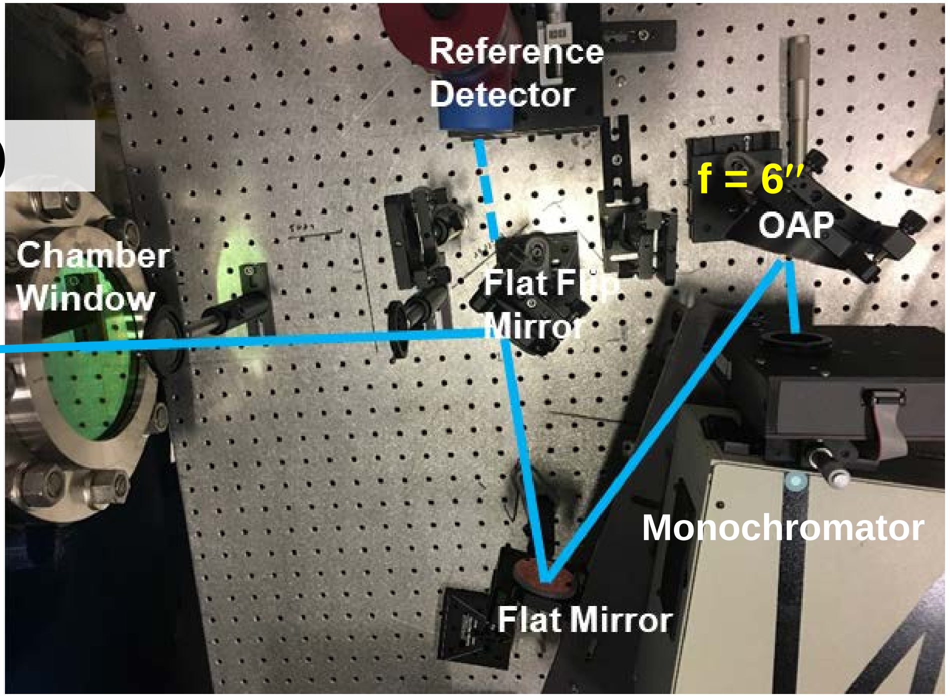
Results from sub-assembly [reference]

- Found to provide reasonable first-look but wanted to make some improvements:

- to address the lack of systematic wavelength dispersion across slit
- Improve repeatability of optical alignment process
- Improve SNR
- Improve repeatability of reference measurements

Calibration Ground Support Equipment (GSE)





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

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

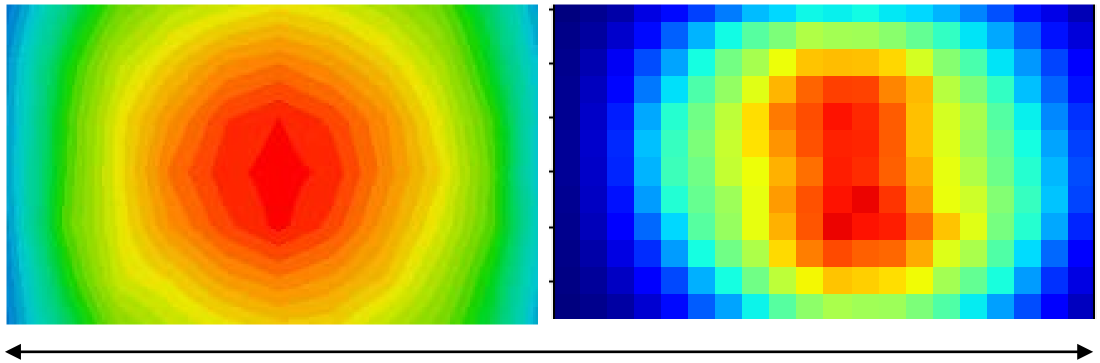
Optical Modeling

- Simplified model used distances/sizes of optical components along the entire optical train to predict transmission and image spot shape
- Also incorporated blackbody-illumination geometry

Comparison with sub-assembly-level spectral setup

Previous Setup (Sub-Assembly-Level Testing)

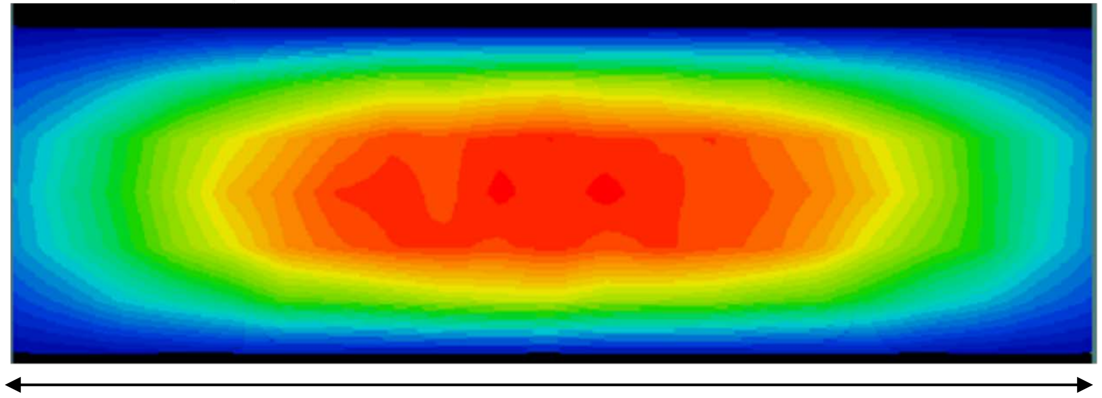
Simulation Measurement



40 pixels

Comparison with System-level spectral setup (OAP with longer focal length)

Simulation



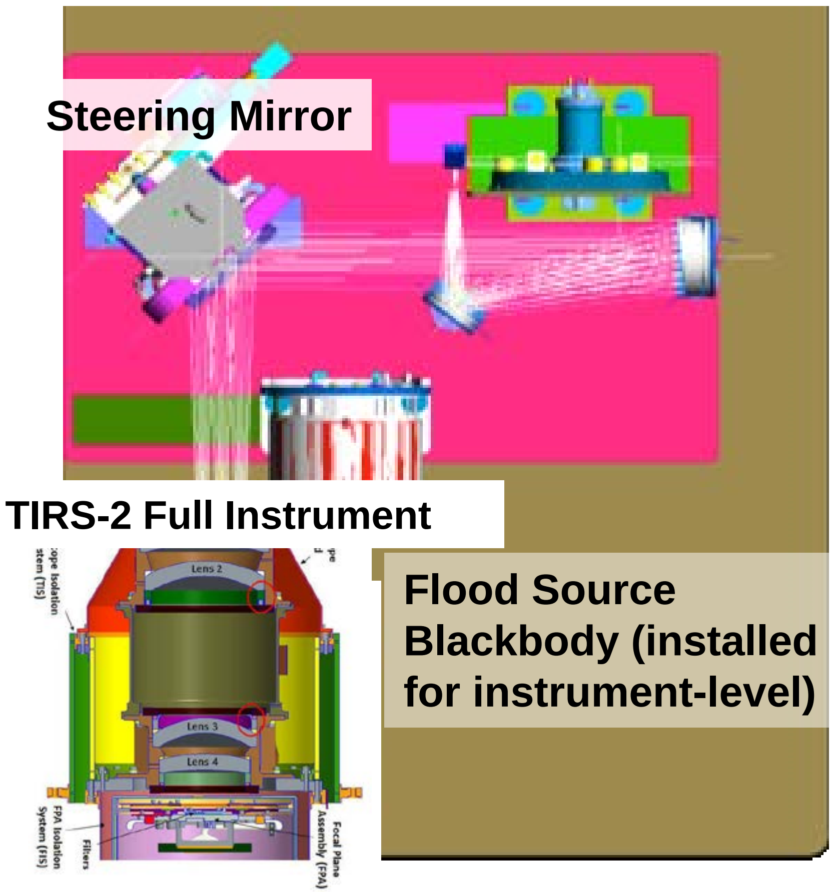
40 pixels

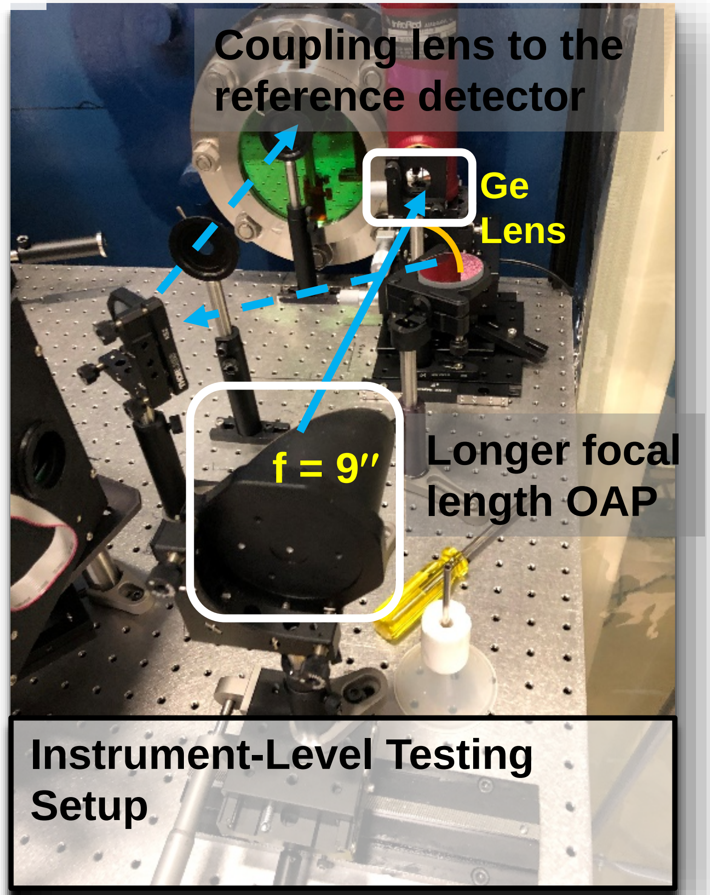
Predicts more slit-like shape and higher transmission

Spectral Response Test Upgrades

- Coupling lens to increase reference detector signal/stability
- Longer focal length OAP to increase transmission

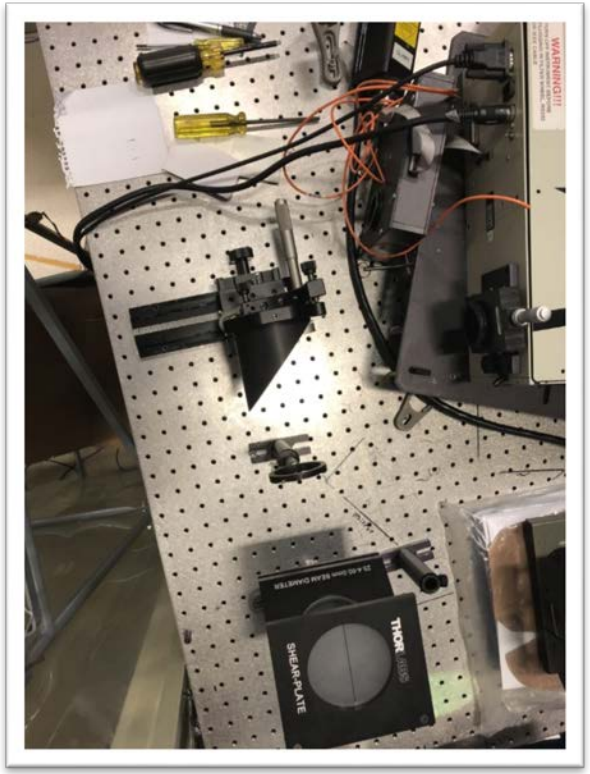
Calibration Ground Support Equipment (GSE)



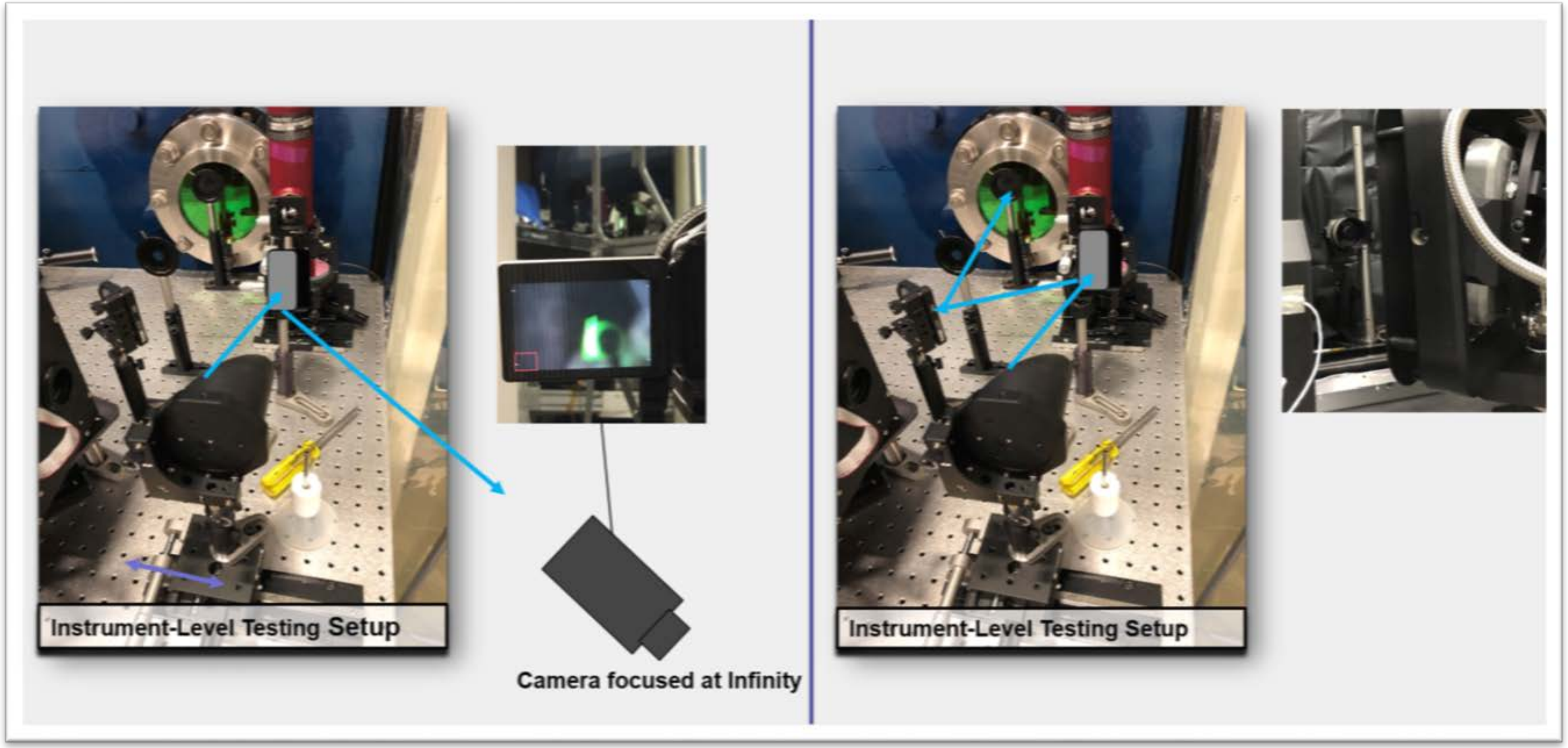


Alignment/Collimation with Visible Sources

Collimate with shear plate interferometer - laser illumination:
- Adjust mirror distance and azimuth/elevation until observe fringes in appropriate direction

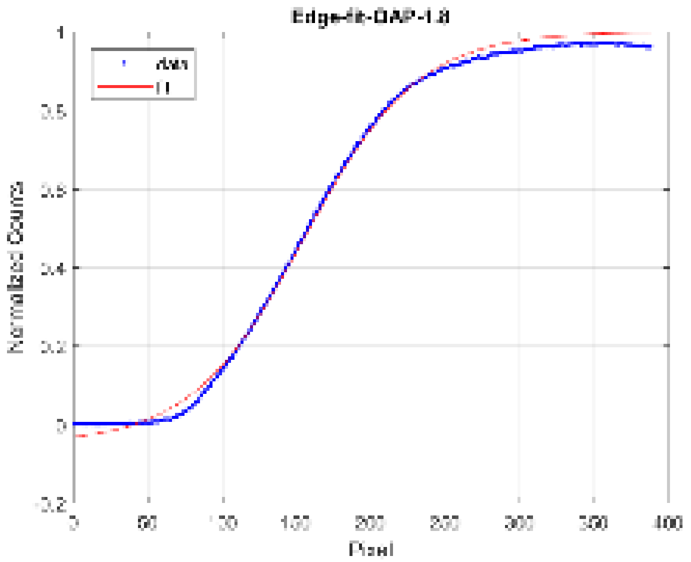


Collimate with shear plate interferometer - lamp illumination (more-blackbody-like illumination):
- Adjust mirror to distance where observe highest contrast image
- Set with camera a few mirrors from setup
- Verify results for images taken after propagating through calibration GSE path

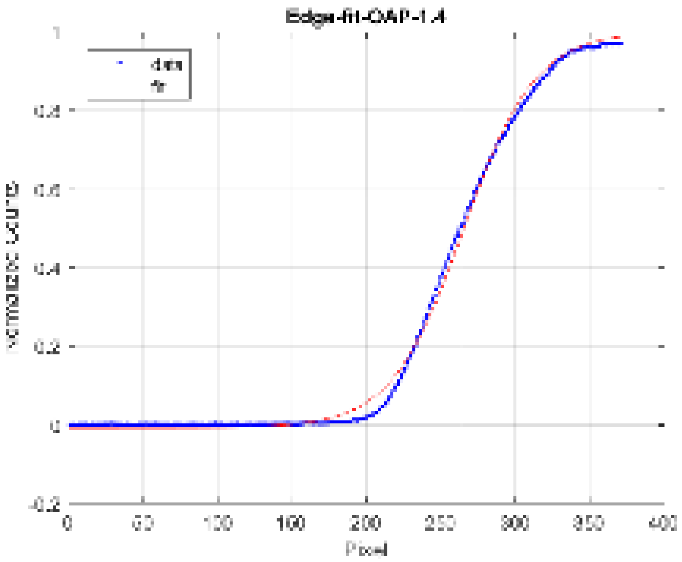


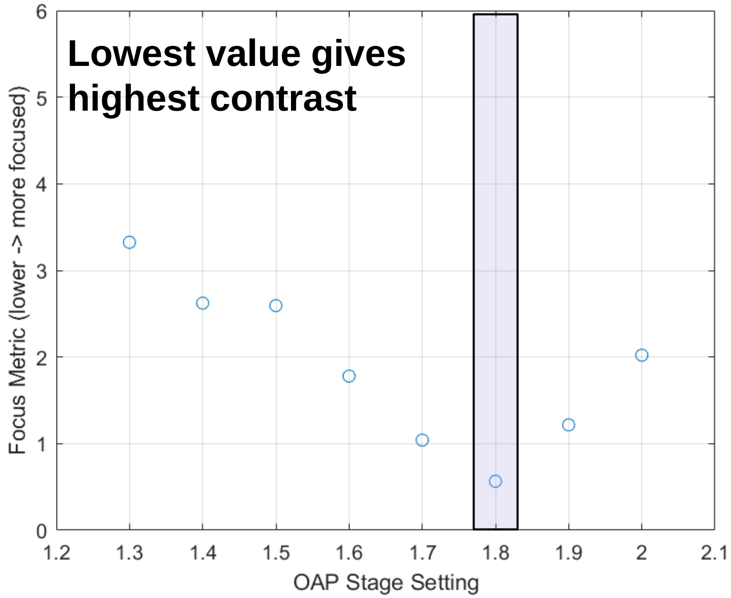
Alignment/Collimation Results

OAP distance setting = 1.8

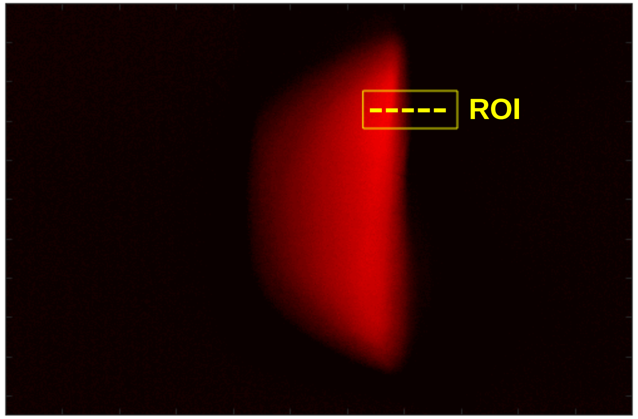


OAP distance setting = 1.4

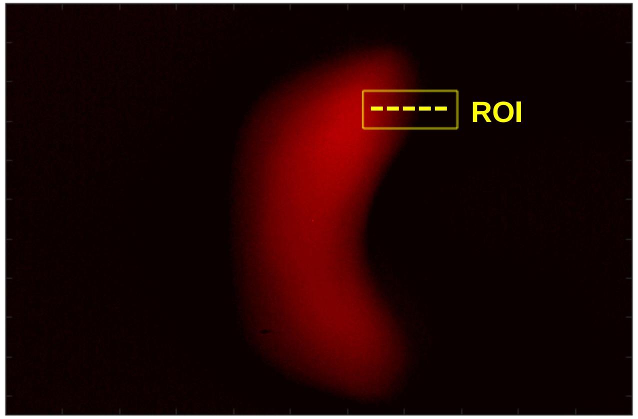




OAP Stage Distance Setting = 1.8

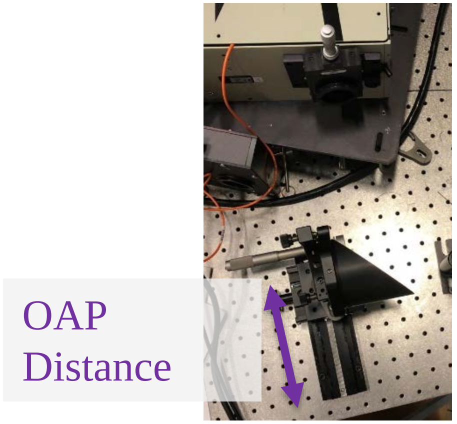


OAP Stage Distance Setting = 1.4



$$f = 1 - \frac{d}{\exp\frac{x-b}{c} + 1}$$

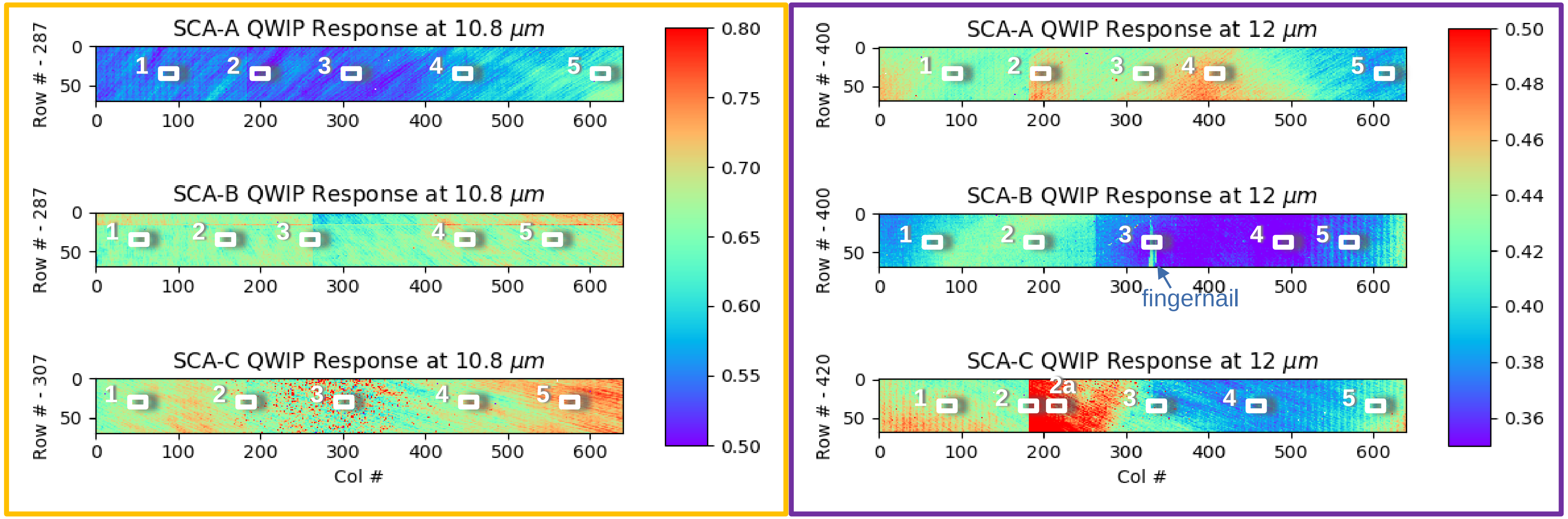
Focus Metric



Spectral Shape Test Data Collection

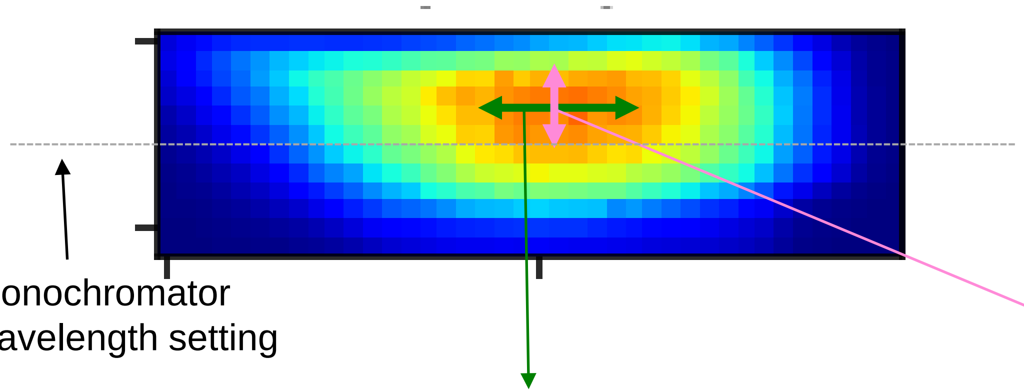
- Spectral data was taken over two phases of TVAC testing
- The spectral data collects are sampled over ~5 locations/filter (one per filter repeated during second TVAC)

Locations overlaid on component level relative detection efficiency at band center

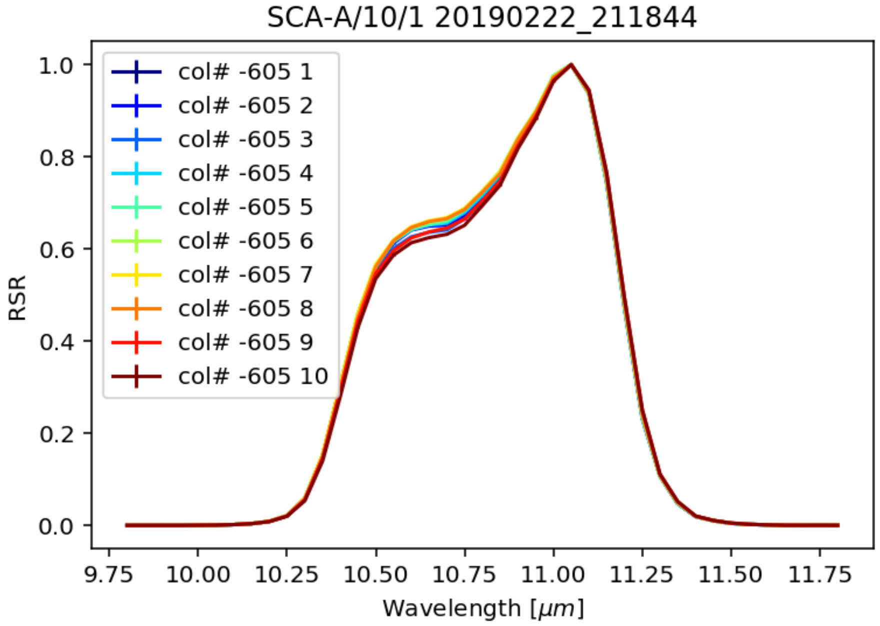


i) ii)

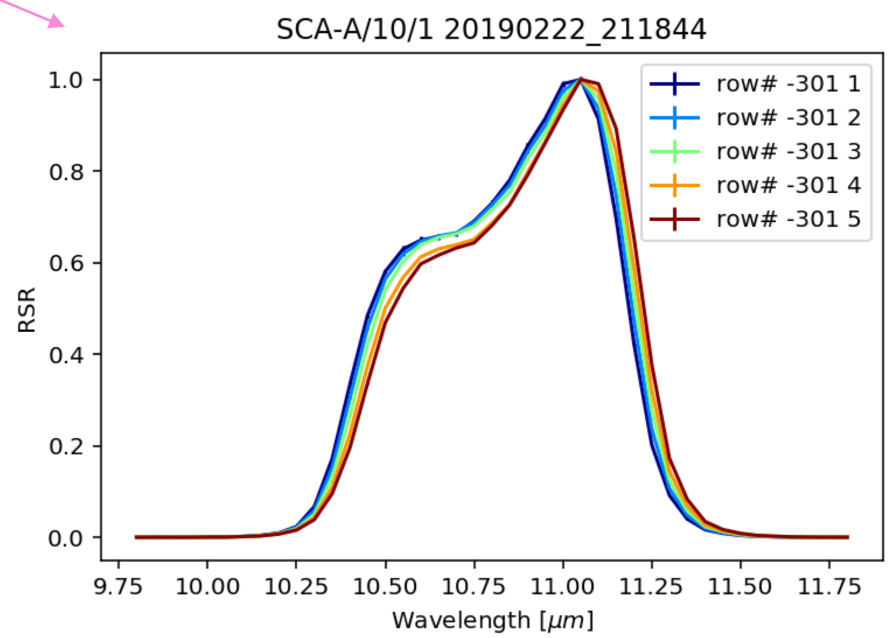
Instrument-level RSR: Per-detector Example - B10 SCA-A



- For each slit image location, the RSR of 26 detectors with highest signal are averaged to derive location-average RSR.
- The dispersion across the monochromator slit is evident in the left plot (across rows).
- Wavelength correction implemented for image location distance from center of slit



Per-pixel RSR by column (along the silt) at row 306



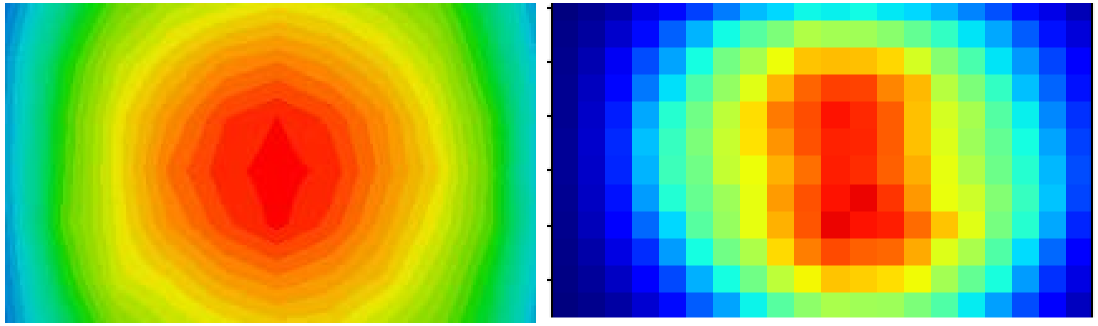
Per-pixel RSR by row (across the slit) at col 610

Optical Modeling and Results

Comparison with sub-assembly-level spectral setup

Previous Setup (Sub-Assembly-Level Testing)

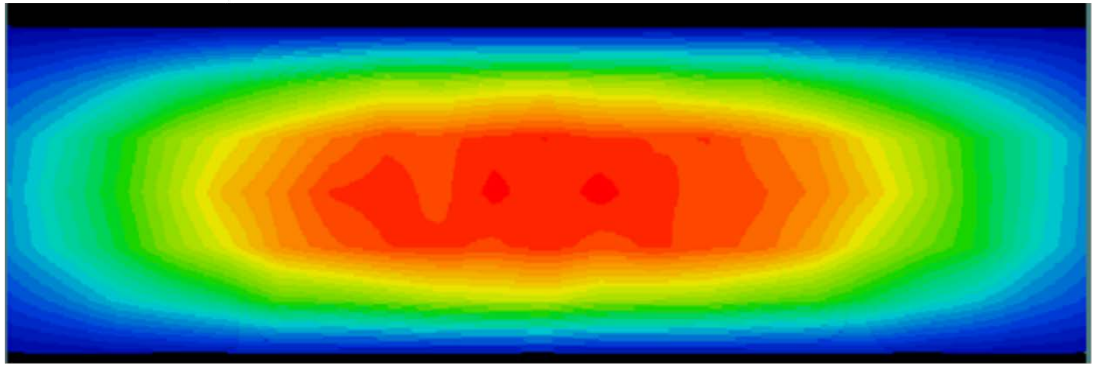
Simulation Measurement



40 pixels

Comparison with System-level spectral setup

Simulation



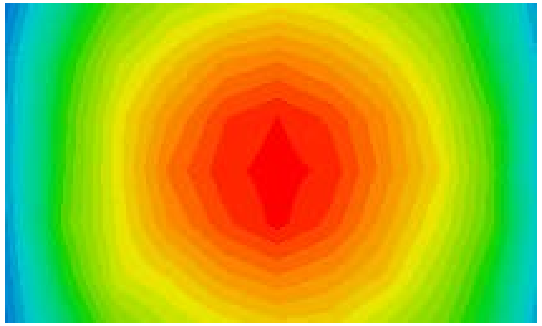
40 pixels

Predicts more slit-like shape and higher transmission

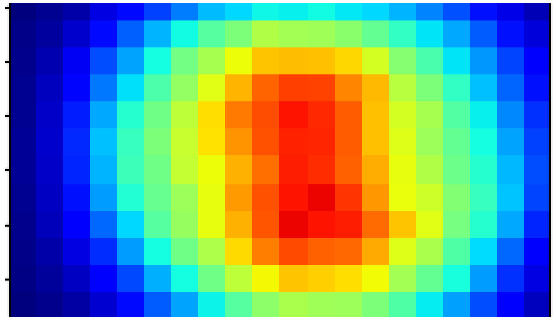
Optical Modeling and Results

Previous Setup (Sub-Assembly-Level Testing)

Simulation



Measurement

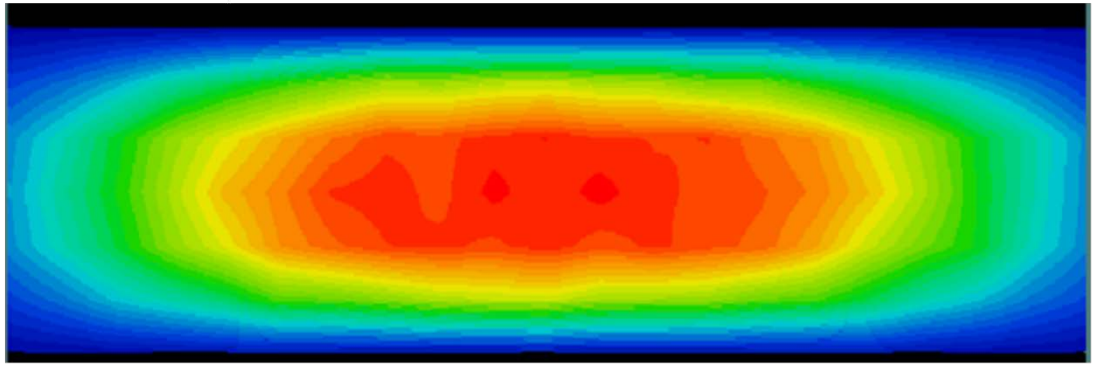


40 pixels

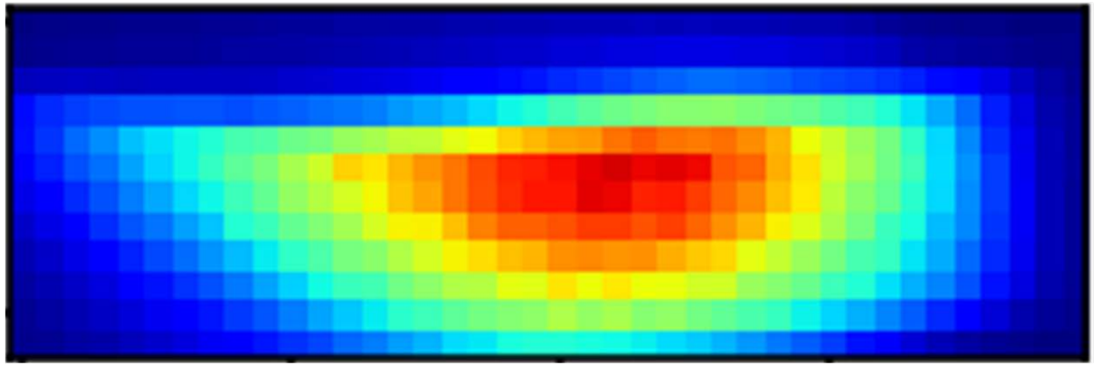
Observed more slit-like shape and higher transmission

After Implementing Upgrades

Simulation



Measurement

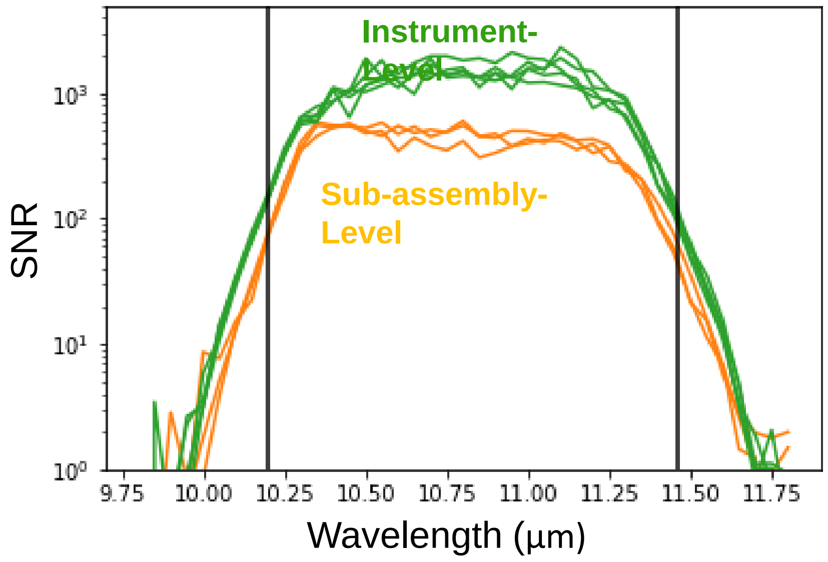


12 Pixels

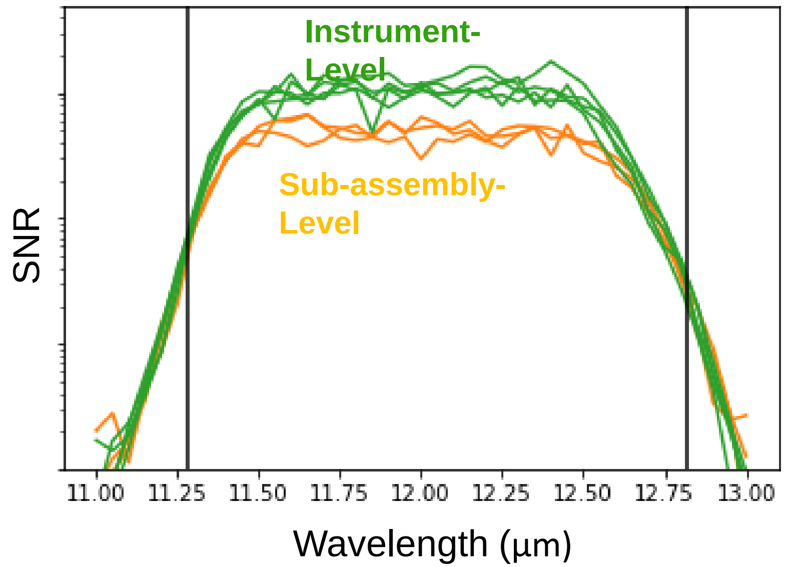
40 pixels

Band-Average RSR

10.8 µm Band



12.0 µm Band



- SNR increased from sub-assembly level to instrument-level due to higher transmission through system
- Reference detector measurements had higher stability due to higher coupling efficiency

SNR for location-average RSR:

$$SNR(\lambda) = \frac{\sum dn\,(\lambda, pix)}{\sqrt{\sum \Delta dn(\lambda, pix)^2}}$$

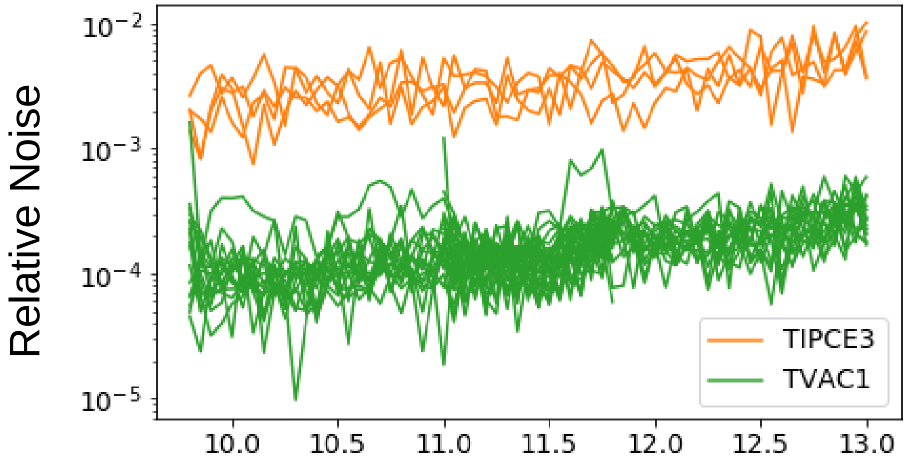
For each pixel:

$dn = \overline{DN_{sr}} - \overline{DN_{bg}}$

– DN_{sr} – counts at source view

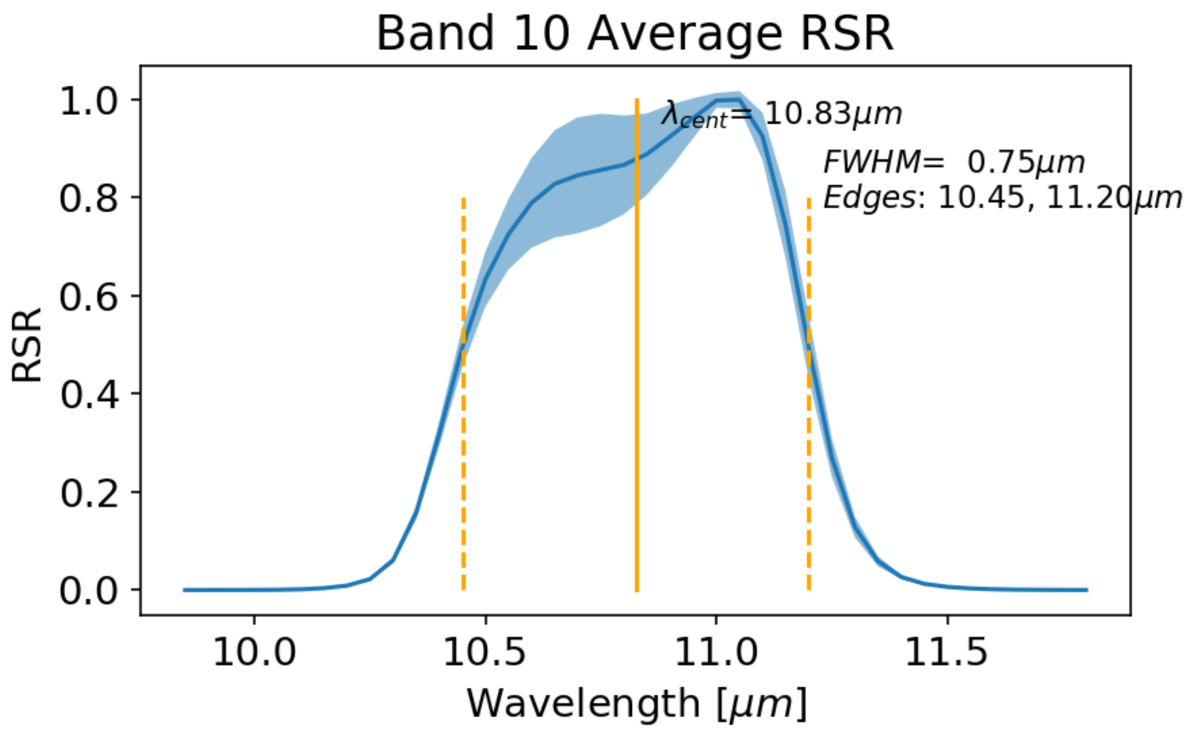
– DN_{bg} – background counts

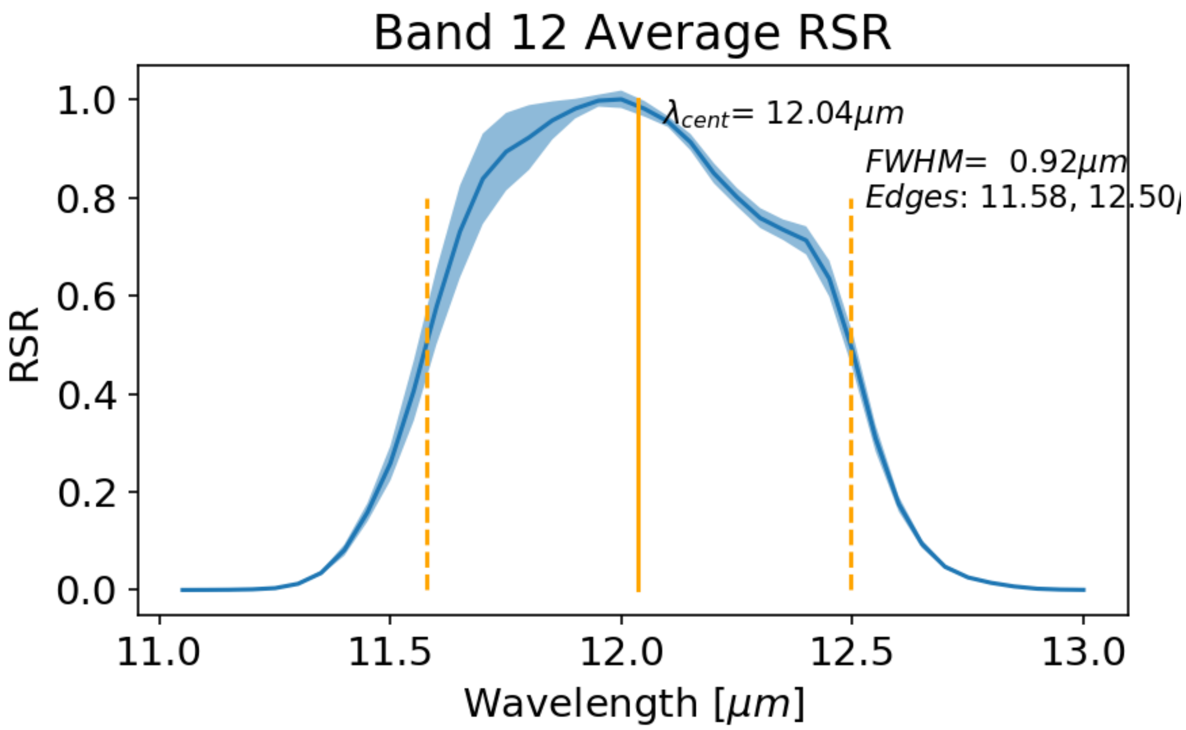
$$\Delta dn(\lambda, pix) = \sqrt{\left(\frac{std(DN_{sr})}{\sqrt{Nsr}}\right)^2 + \left(\frac{std(DN_{bg})}{\sqrt{Nbg}}\right)^2}$$



Band-Average RSR

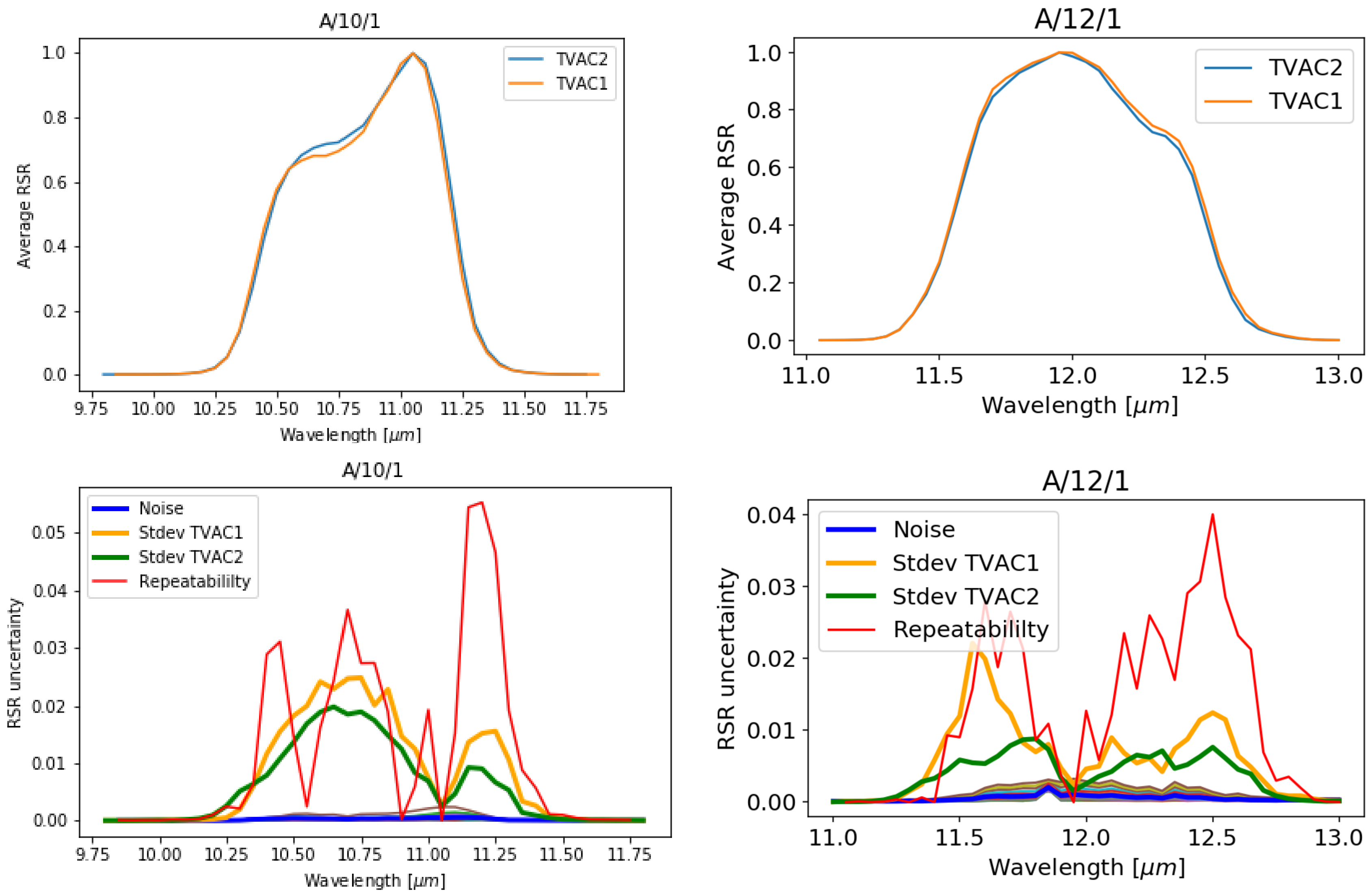
- All location-average RSRs are further averaged to derive a band-average RSR (TVAC-1 data).
- The standard deviation of the per-location RSRs (5 per SCA, 15 in total) is shown as shading.





Reproducibility (TVAC-1 vs TVAC-2)

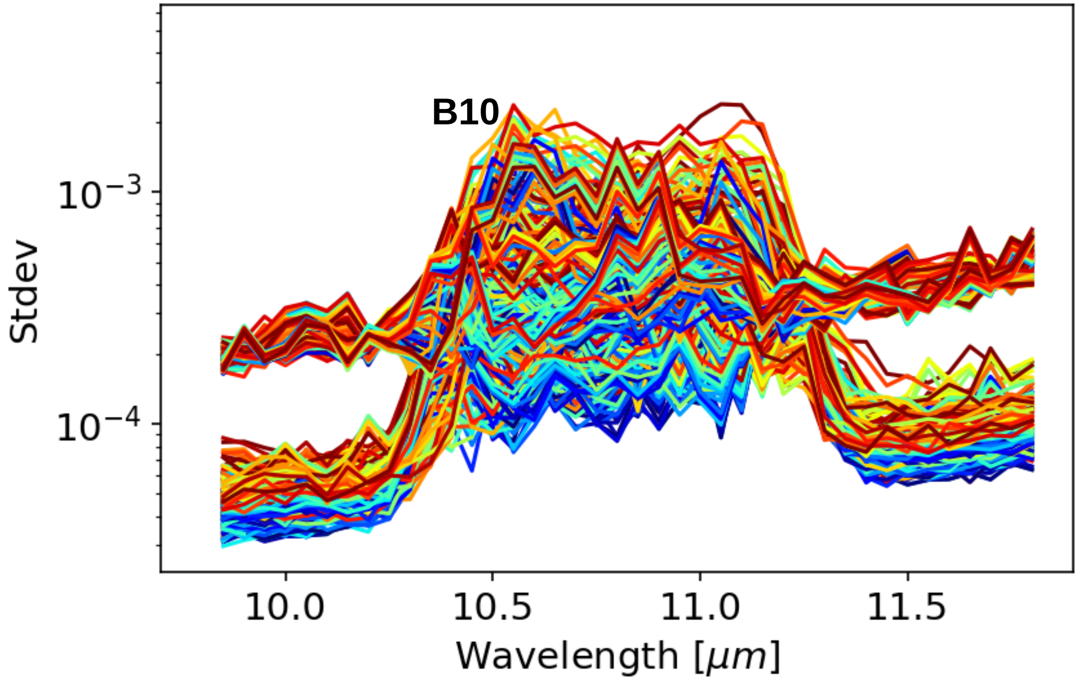
- The reproducibility is on the order of 2 times the standard deviation derived within one location, which given the 15nm wavelength uncertainty, is a very consistent result
- This is compared with the uncertainty due to measurement noise and variability within a location



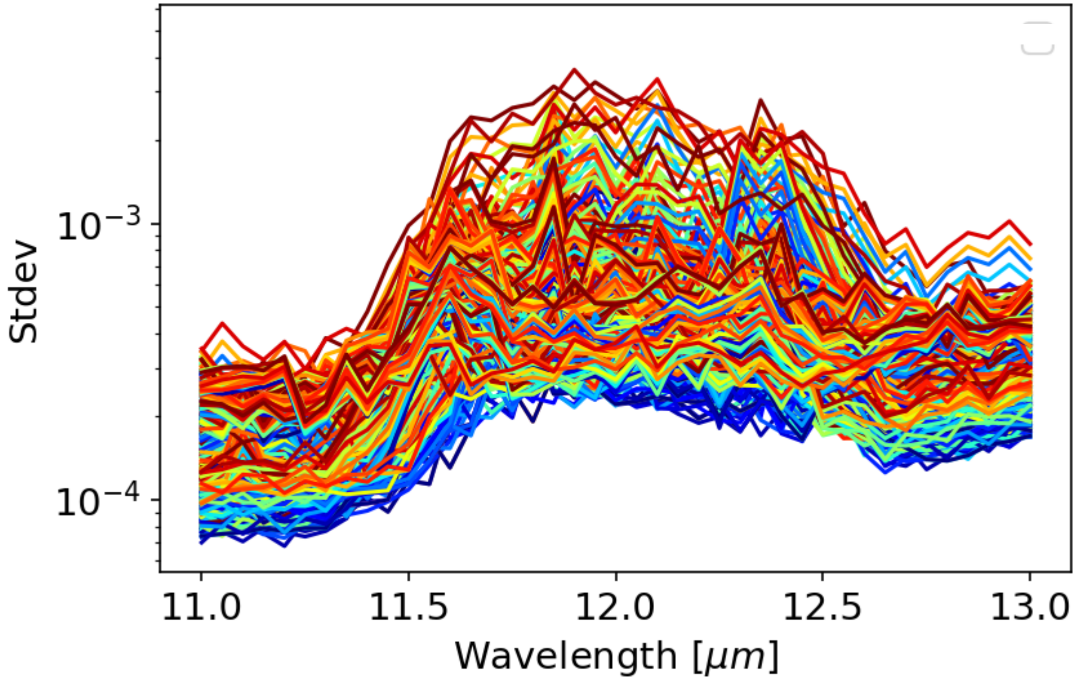
Noise Impact
(TIRS-2 & Reference Detector Measurement)

- The noise derived for each pixel used in the location-average RSRs (all pixels for all locations) is shown below. It meets the SCTR-041 sensitivity requirement (red line).

10.8 μm Channel



12.0 μm Channel



For each pixel the noise is calculated as:

$$\boldsymbol{\sigma_{RSR}}(\lambda, \boldsymbol{pix}) = \boldsymbol{RSR}(\lambda, \boldsymbol{pix})\sqrt{\left(\frac{\Delta dn}{\boldsymbol{dn}}\right)^{\boldsymbol{2}} + \left(\frac{\Delta \boldsymbol{MCT}}{\boldsymbol{MCT}}\right)^{\boldsymbol{2}}}$$

TIRS noise (↑ $\Delta dn / dn$) MCT noise (↑ $\Delta MCT / MCT$)

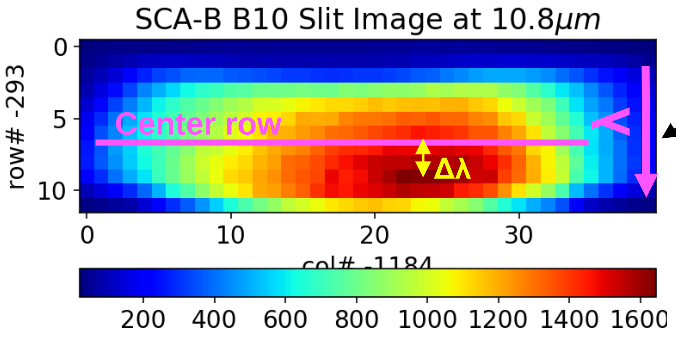
$$dn = \overline{DN_{sr}} - \overline{DN_{bg}}$$

DN_{sr} – TIRS counts at source view
DN_{bg} – TIRS background counts

$$\Delta dn(\lambda, pix) = \sqrt{\left(\frac{std(DN_{sr})}{\sqrt{Nsr}}\right)^2 + \left(\frac{std(DN_{bg})}{\sqrt{Nbg}}\right)^2}$$

Wavelength Correction

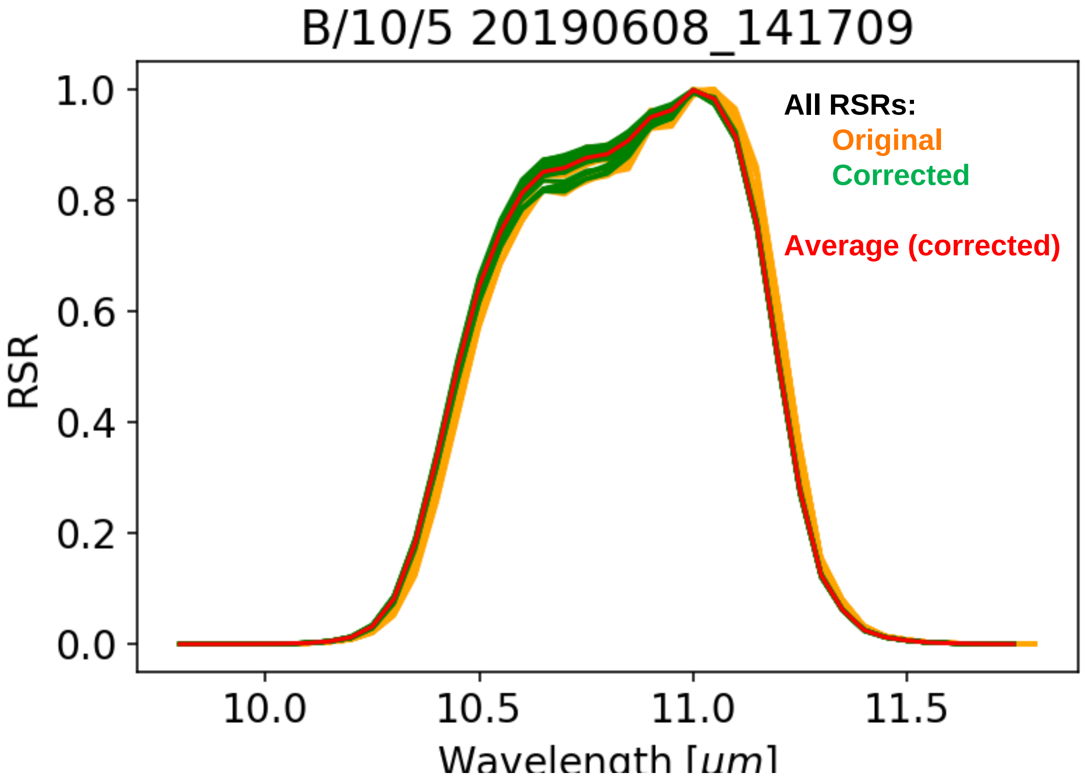
A correction is applied to account for dispersion across the monochromator slit. Each pixel's RSR is corrected (10nm per row) for the distance from the center of the silt (where the wavelength is equal to the monochromator setting).



Max illumination at row #9
Center of the slit at row #7.5
Wavelength correction -15nm

–The monochromator slit width is 1.2mm, corresponds to ~94nm (78.3 nm/mm).

–The slit image is about 9 rows so we have approximately 10 nm per row.



All pixels averaged at a given location are shown before the correction (orange) and after the correction is applied (green). The final average RSR per location is shown in red.

Monochromator Wavelength Validation

–Monochromator wavelength validated to ~3 nm

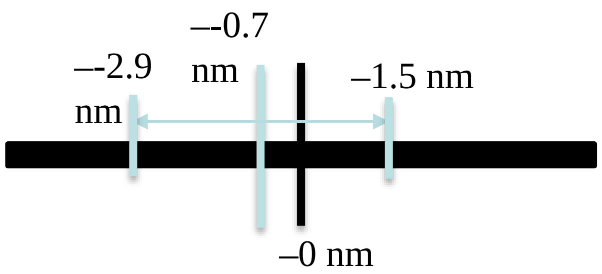
–Monochromator does not need further offset adjustment

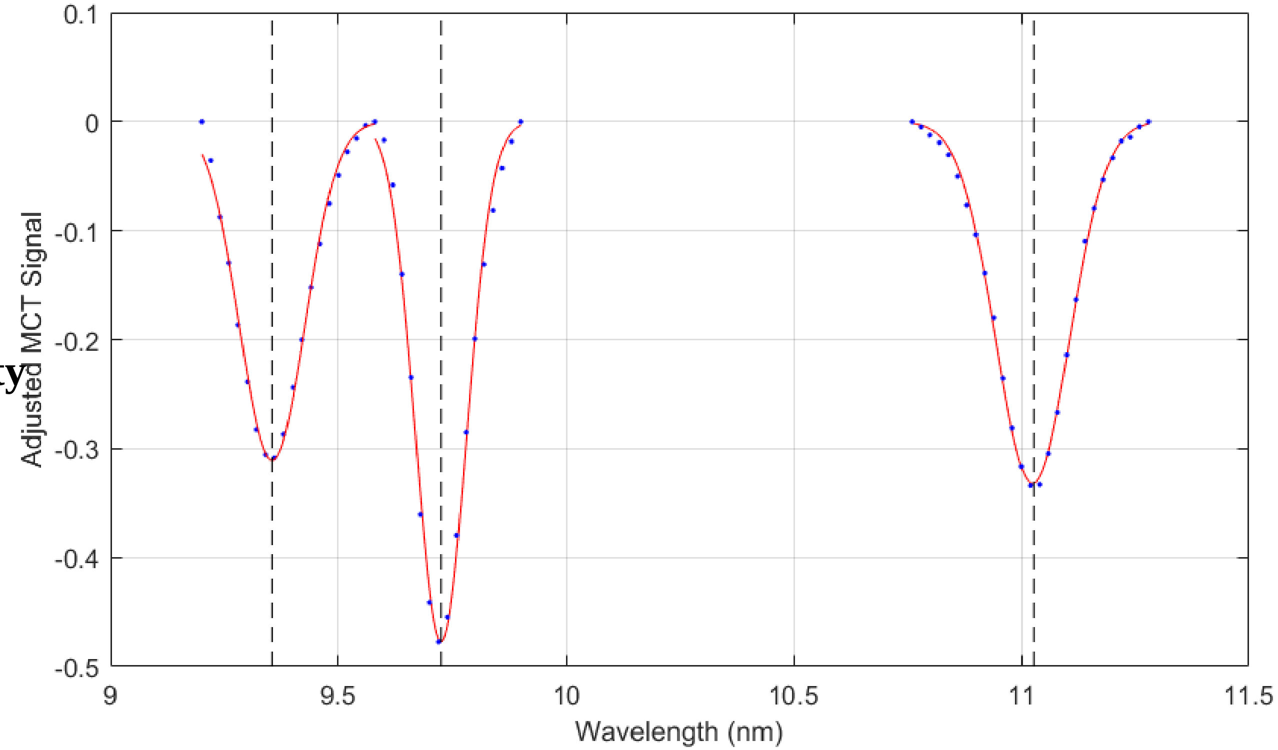
–Results

reference lines (NIST)	difference [nm]	uncertainty (k=1) [nm]
9.3547	0.30	1.58
9.7257	0.30	1.38
11.0276	-2.70	0.72
	-0.70	**2.22**

–**Mean Difference** –**RSS Uncertainty**

–*k* = 1 confidence interval

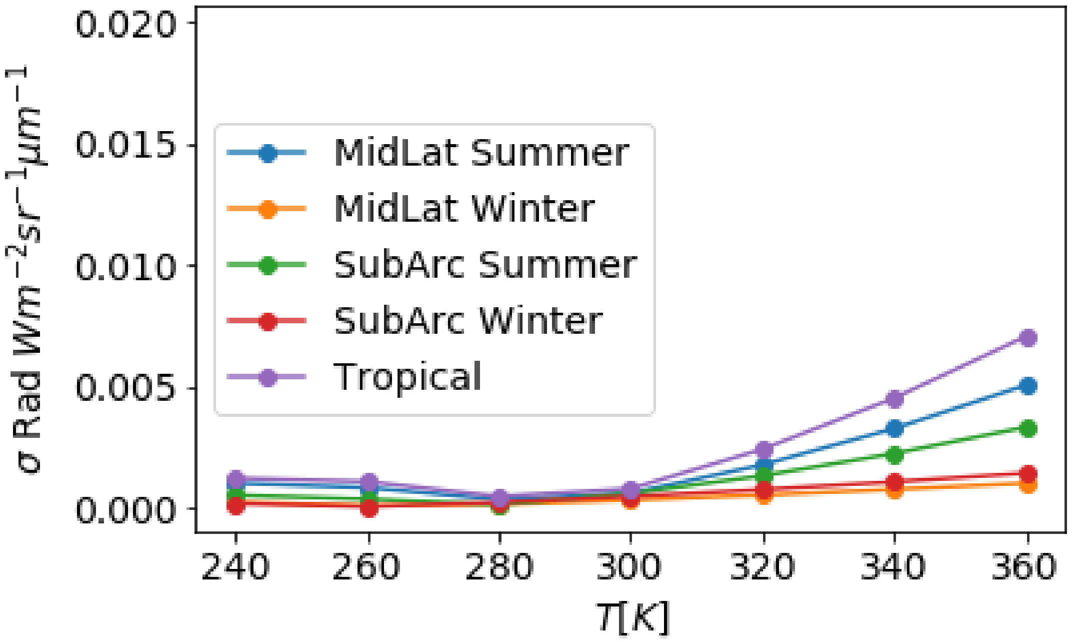




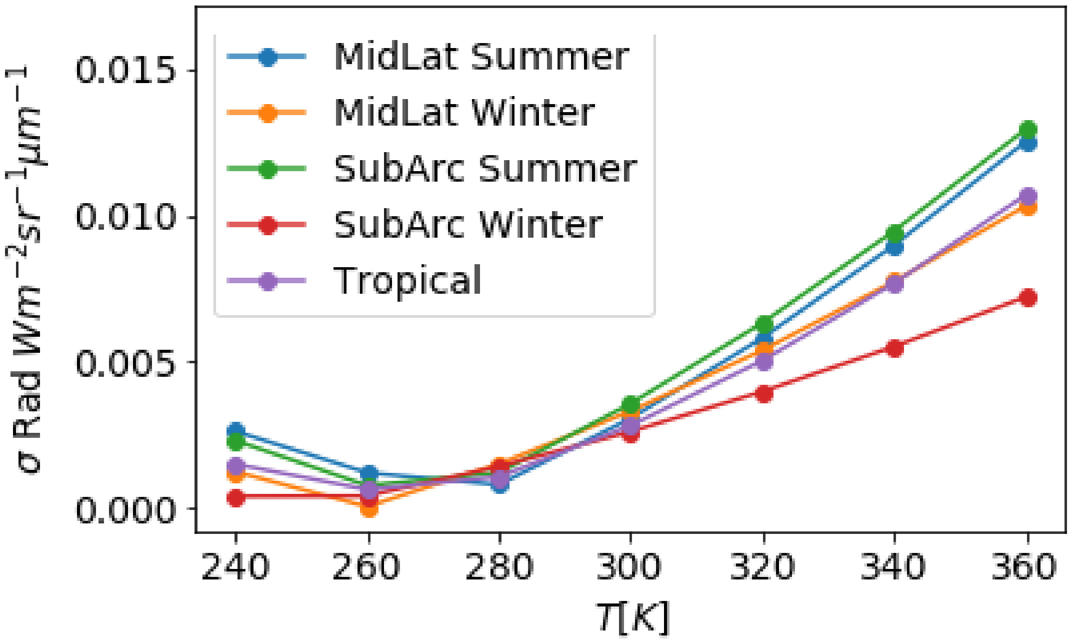
Spectral Non-uniformity Impacts

- Spectral Uniformity Impact small relative to total radiometric uncertainty:
  - Impact expressed in radiance below -> Corresponds to ~0.1-0.3% for 10.8 µm channel and 0.1-0.2% for 12.0 µm channel

10.8 µm Band



12.0 µm Band



Spectral Response Uncertainty Budget

Spectral Response Uncertainty

CBE = 0.10%, 0.30% (10.8 µm)
CBE = 0.10%, 0.26% (12.0 µm)

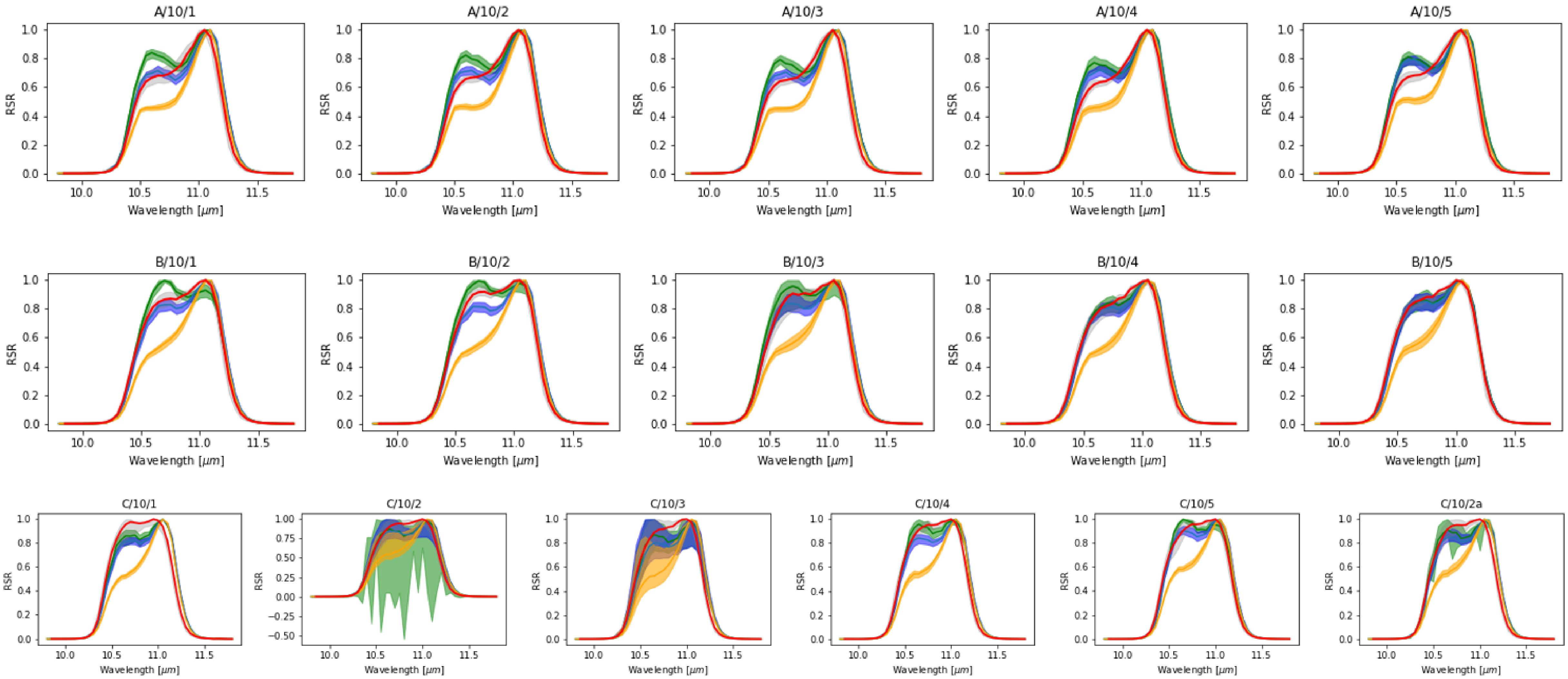
- **Spectral Non-Uniformity**
  CBE = 0.1%, 0.3% (10.8 µm)
  CBE = 0.1%, 0.2% (12.0 µm)
- **HgCdTe Signal Variability/Noise**
  CBE = 1.2e-4%, % (10.8 µm)
  CBE = 2.7e-4%, % (12.0 µm)
- **Component Transmittance/ Reflectance**
  CBE = 0.0026%, 0.0059% (10.8 µm)
  CBE = 0.0032%, 0.0050% (12.0 µm)
- **Wavelength**
  CBE = 0.001%, 0.001% (10.8 µm)
  CBE = 0.006%, 0.01% (12.0 µm)
- **TIRS-2 Noise**
  CBE = 7.7e-6%, 1.2e-5% (10.8 µm)
  CBE = 1.3e-5%, 2.1e-5% (12.0 µm)
- **Reproducibility**
  CBE = 0.009%, 0.006% (10.8 µm)
  CBE = 0.0035%, 0.17% (12.0 µm)

– Uncertainty is well within allocation to meet radiometric uncertainty
– It is dominated by spectral uniformity (intrinsic to detector arrays, not measurement setup/methodology)

Comparison to Component-Level RSR 10.8 µm SCA-A,B,C

The shading represents the min/max envelope of the averaged pixels

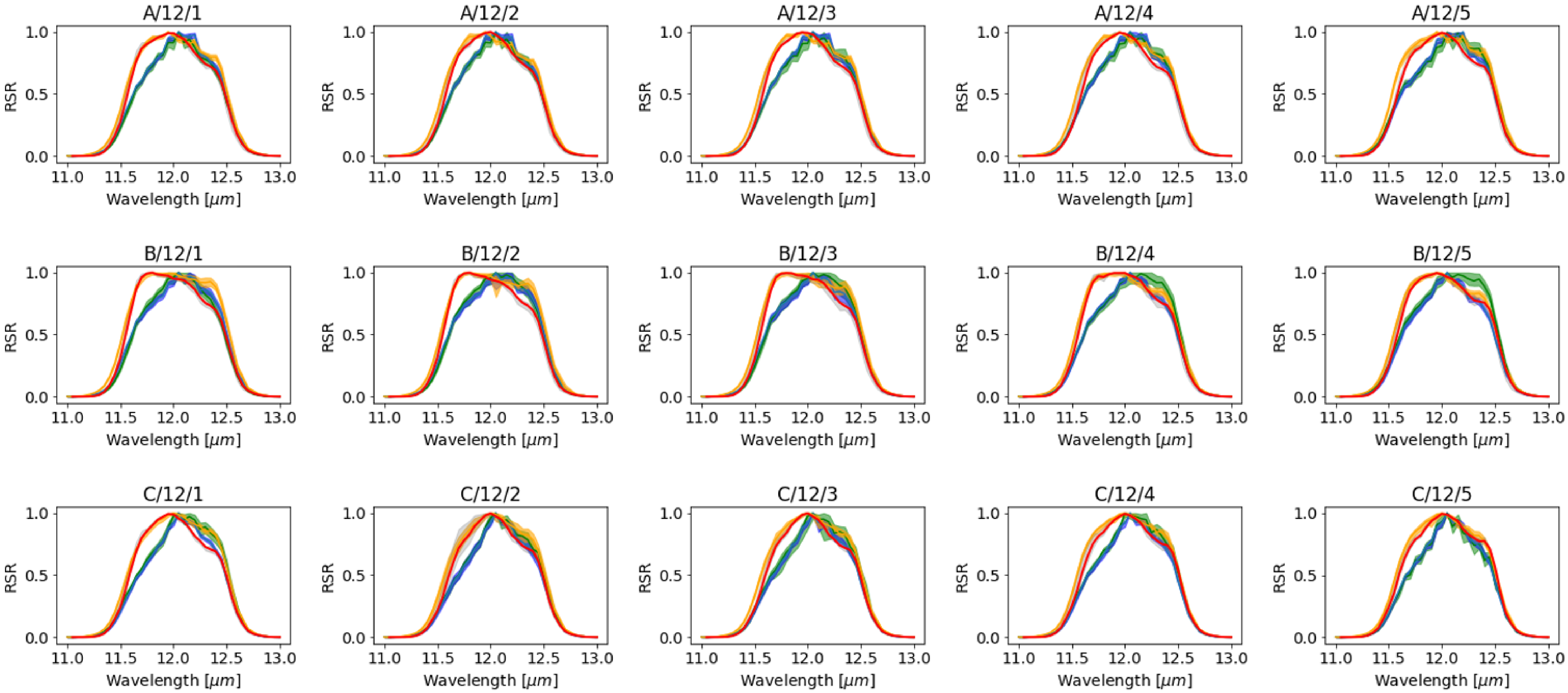
Instrument-level (TVAC1) FPA-level (with F/1.6 correction) SCA-level (with F/1.6 correction) Normal Inc (no correction)



The shading represents the min/max envelope of the averaged pixels

Comparison to Component-Level RSR 12.0 µm SCA-A,B,C

Instrument-level (TVAC1) FPA-level (with F/1.6 correction) SCA-level (with F/1.6 correction) Normal Inc (no correction)



The shading represents the min/max envelope of the averaged pixels

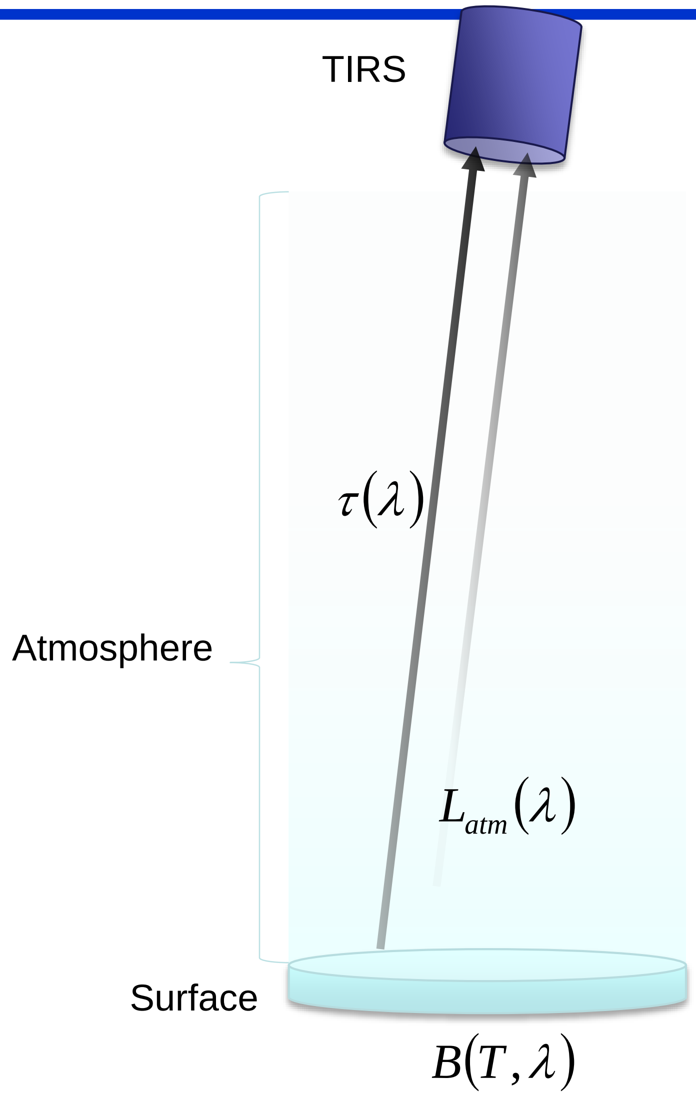
Summary

- The spectral response was well-characterized during instrument-level testing and is expected to meet its performance requirements with few waivers and deviations.
  - ❑ Setup improvements led to reduced measurement uncertainties
  - ❑ The instrument-level measurements are expected to be used as the operational versions and delivered to USGS.

- TIRS-2 team is on track to deliver a well-characterized instrument by August 2019 that will meet data users' needs for a variety of environmental applications.

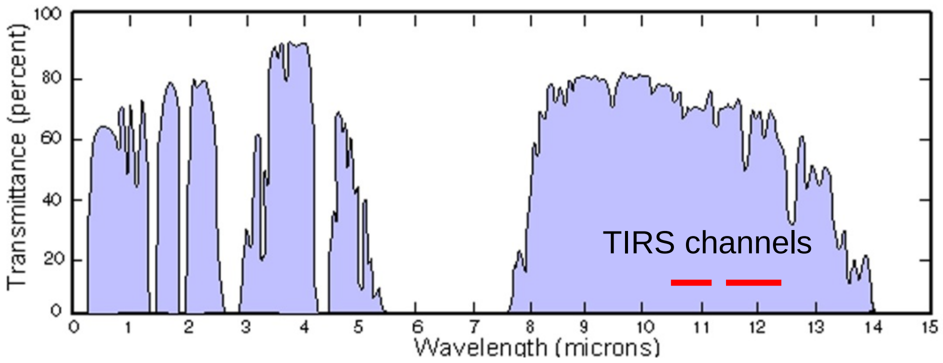
Backup

Thermal Radiance Detected by TIRS-2 from Surface and Atmosphere



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

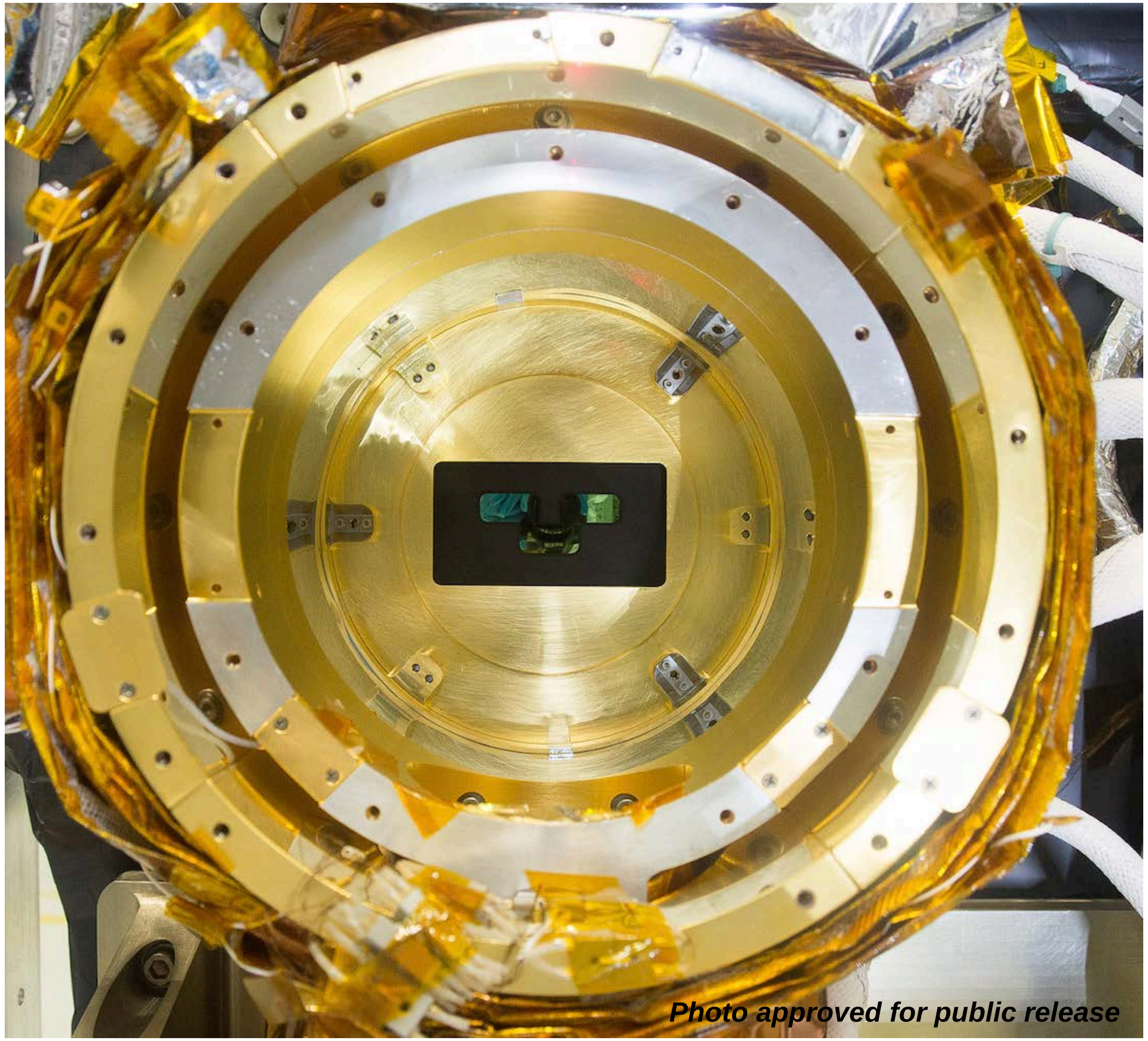
- $B(T,\lambda)$ Emitted and reflected surface radiance
- $\tau(\lambda)$ Transmission of atmosphere
- $L_{atm}(\lambda)$ Emitted and scattered radiance of atmosphere
- $R'(\lambda)$ Spectral response of pixel
- L_s Pixel integrated radiance



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

TIRS-2 photos

Filters/FPA before final telescope shim, Feb 2018

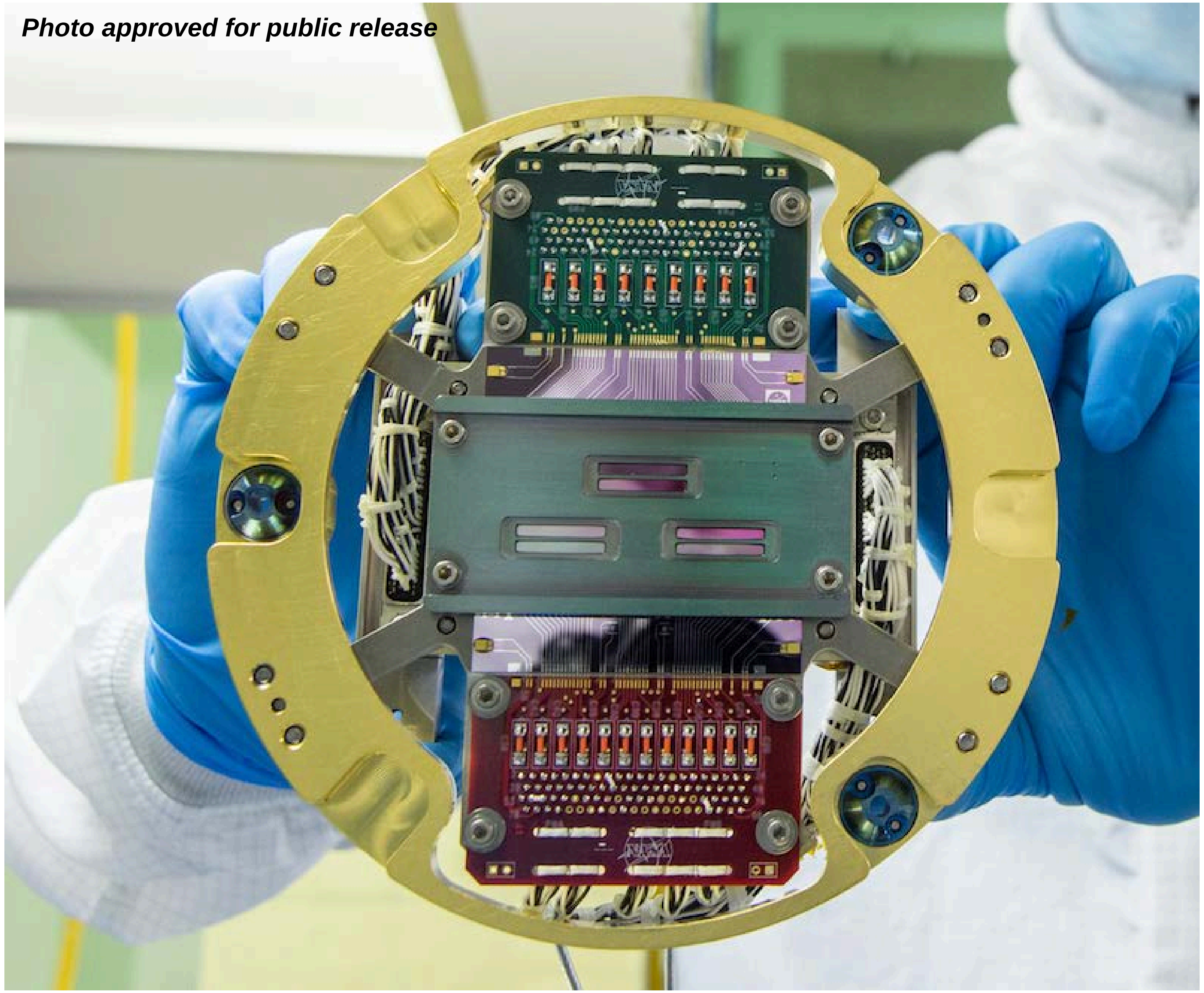


TIRS-2 photos

Telescope installation, March 2018

TIRS-2 photos

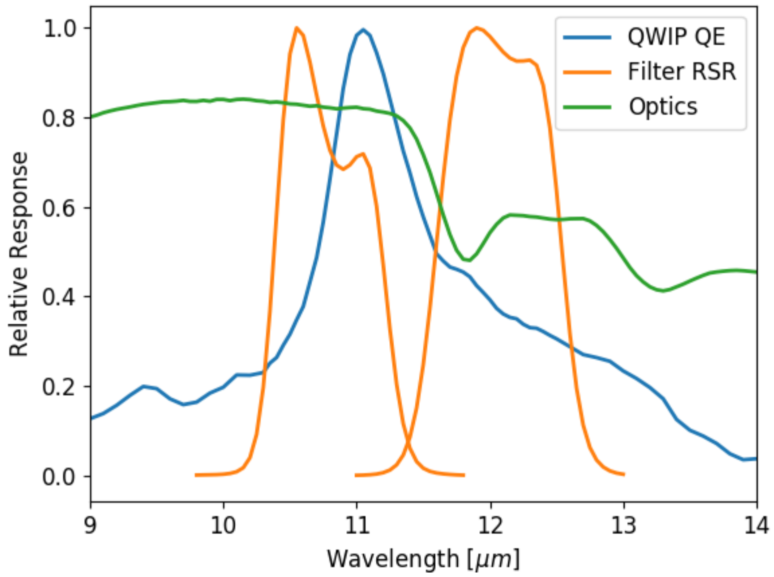
FPA prior to integration, December 2017

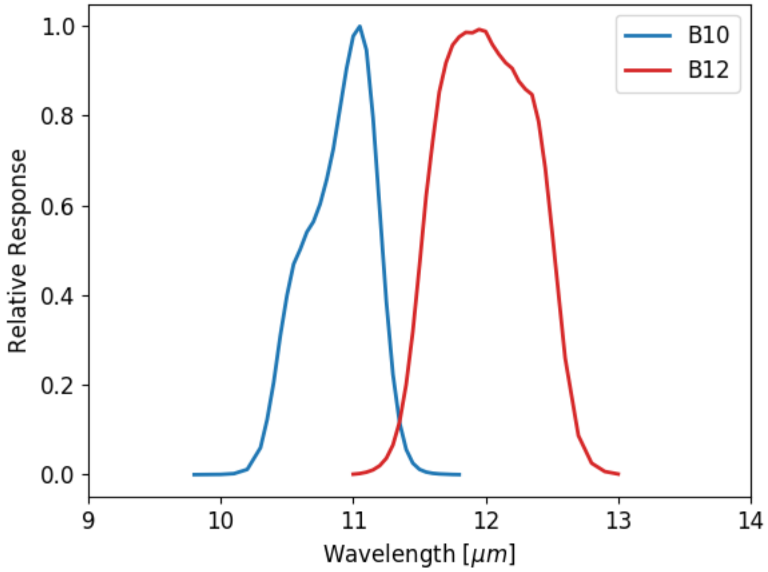


Relative Spectral Response (RSR) Component-level Measurements

- 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).

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





Reworked Radiometric Uncertainty Budget

( ) = allocation

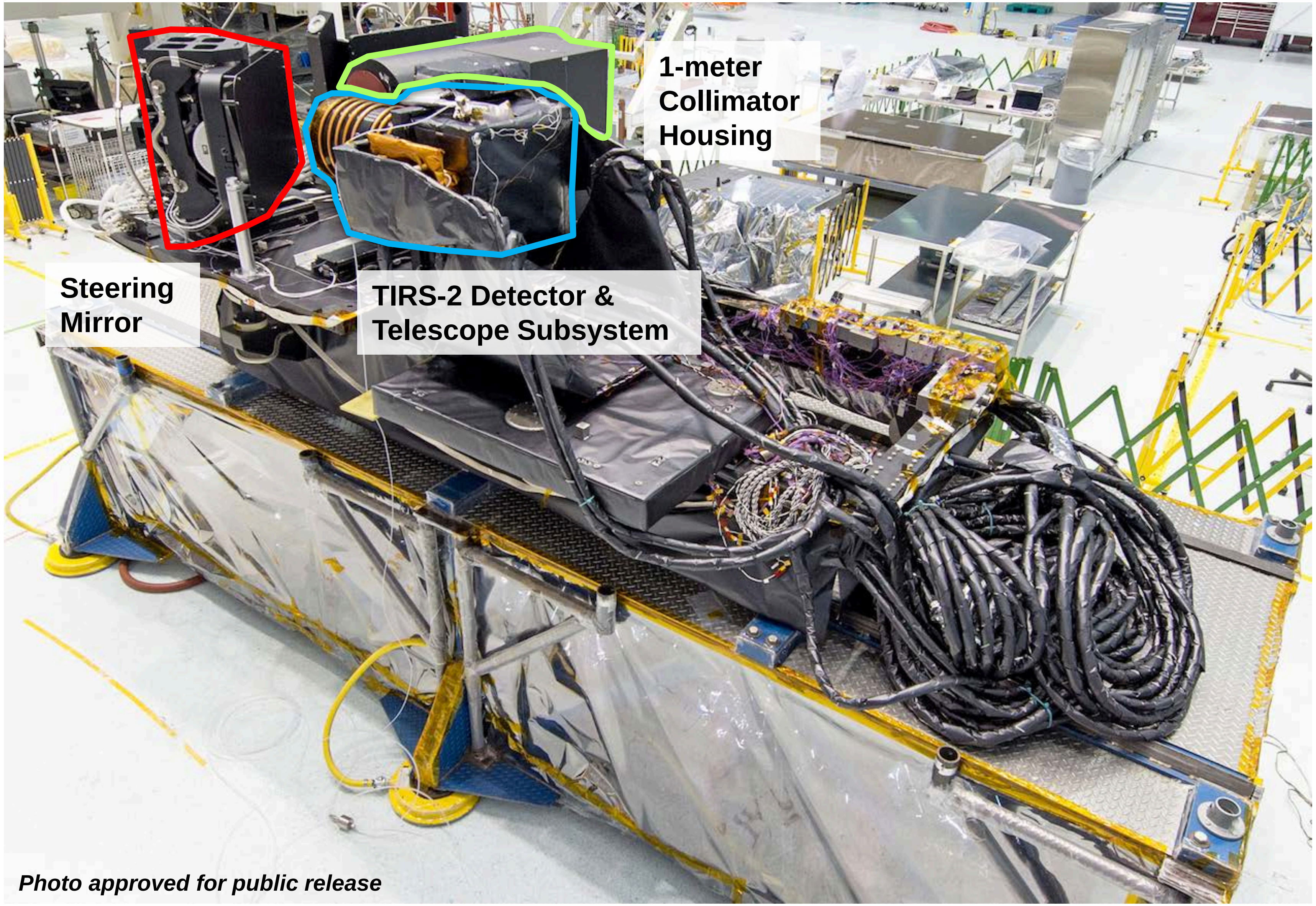
- **TIRS-2 Total Uncertainty (2%, 4%)** — CBE = 1.0%, 1.5% (10.8 µm); CBE = 1.0%, 1.3% (12.0 µm)
  - Spectral Response Uncertainty (0.4%,0.4%) — CBE = 0.3% (10.8 µm); CBE = 0.2% (12.0 µm)
  - Flood Source Temperature Uncertainty (0.2%) — CBE = 0.14%, 0.18%
  - Flood Source Calibration Uncertainty (0.6%) — CBE = 0.2%
  - System Scattered Light (1.5%, 3.0%)
    - Out of Field (1.5%, 3.0%) — CBE = 0.57%, 0.83%
    - Near- Field (0.1%) — CBE = 0.016%, 0.029%
  - On-orbit OBC Adjustment (0.4%)
    - TIRS-2 OBC Response Reproducibility (0.8%) — CBE = 0.4% (10.8 µm); CBE = 0.6% (12.0 µm)
    - Angular Variability (0.1%) — CBE = 0.02%
    - OBC Temp Uncertainty (0.2%) — CBE = 0.14%, 0.18%
    - Background Emission (0.2%) — CBE = 0.2%
    - Blackbody Degradation (0.2%) — CBE = 0.2%
  - TIRS-2 Radiometric Reproducibility (0.5%) — CBE = 0.41% (10.8 µm); CBE = 0.35% (12.0 µm)
  - TIRS-2 Radiometric Stability (0.1%) — 0.035% (10.8 µm); 0.047% (12.0 µm)
  - Linearization & Interpolation (0.4%, 1.0%) — 0.37,0.97% (10.8 µm); 0.20%,0.52% (12.0 µm)

–The flood source is used as the primary calibration and the OBC is used to make adjustments on orbit
– Correction modeled as a ratio between OBC and Flood Source inverse gains
– Budget is reordered to separate pre-launch calibration process and on-orbit adjustment for clarity

$$L_{earth} = m_{fs}\,\Delta c$$

$$L_{earth} = m_{fs}\left(\frac{m_{obc}}{m_{fs}}\right)\Delta c$$

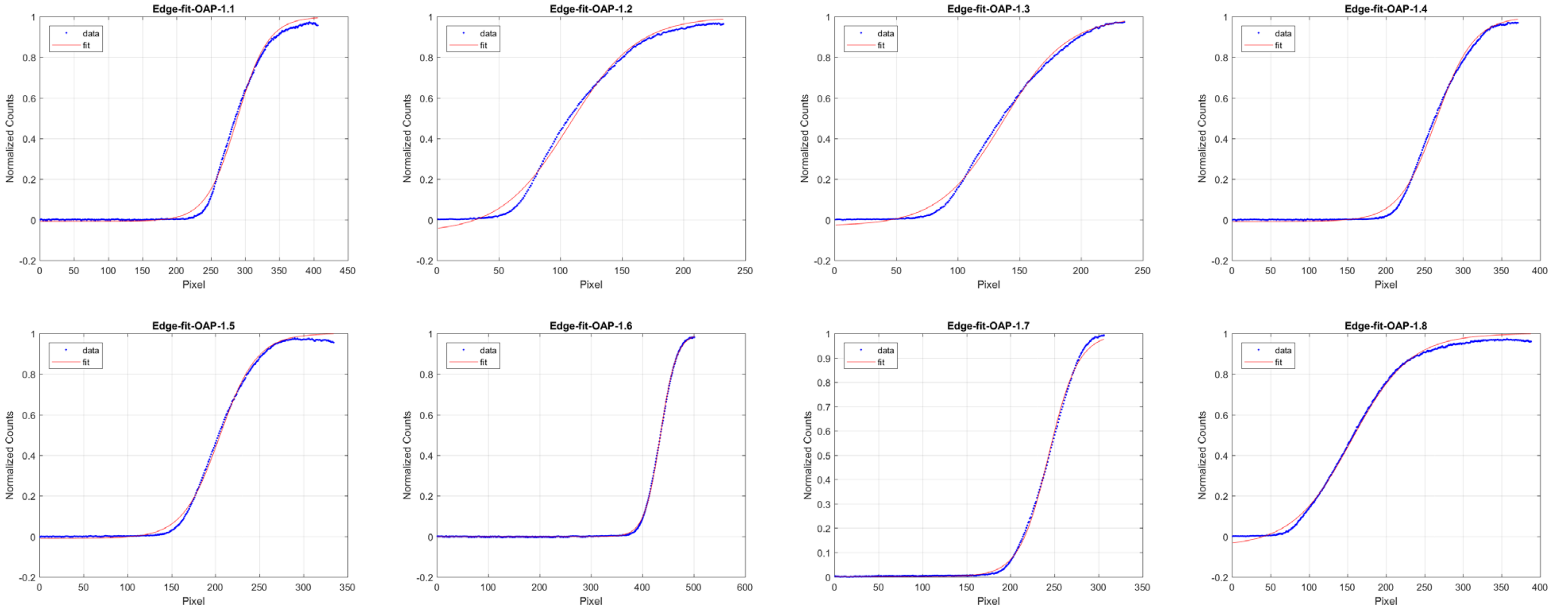
Calibration Ground Support Equipment



Collimation – Lamp/Camera

–Fits (Fermi) using rising edge of average profile over ~200 rows

$$-s = 1 - \frac{d}{\exp\frac{x-b}{c}+1}$$

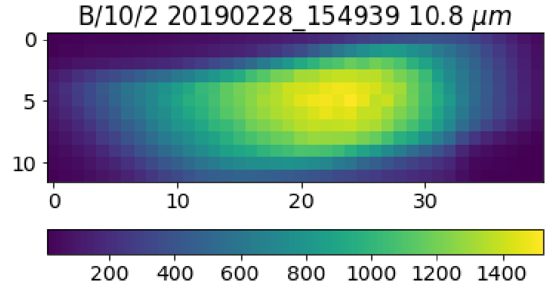


Instrument-level RSR: Data Processing

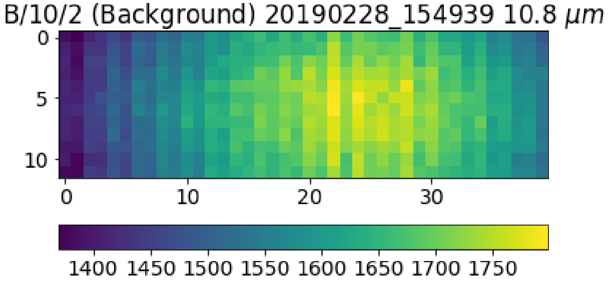
Processing for each pixel in a 40x12 pix area centered at the illumination max:

- Identify source (DNsr) and background (DNbg) samples.
  100 samples BG, followed by 100 samples signal are taken (*spectral-shape-TIRSonly*).
- Derive background subtracted dn= <DNsr> - <DNbg> for each pixel at each wavelength.
- Derive noise and SNR.
- Correct for the source (1000C BB) spectrum and common optical path between reference MCT detector and TIRS2; there is excellent repeatability of the MCT measurements. Low noise <0.1%
- Apply additional correction for TIRS only optical path (cal GSE, chamber window, etc.). See next slide for details.
- Normalize at the peak signal to derive the RSR; derive the RSR metrics subject to spectral requirements.
- Average the RSR derived from the max. illuminated detectors to produce one average RSR for each slit image location.

Slit Image example - 10.8 micron

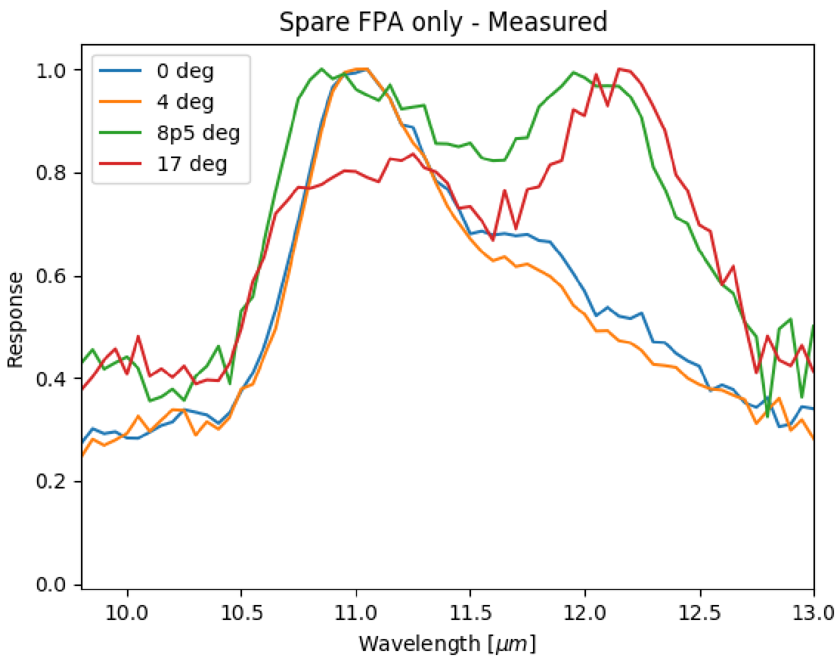


Background example - 10.8 micron



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:

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