Spectral Analysis of the Primary Flight Focal Plane Arrays for the Thermal Infrared Sensor

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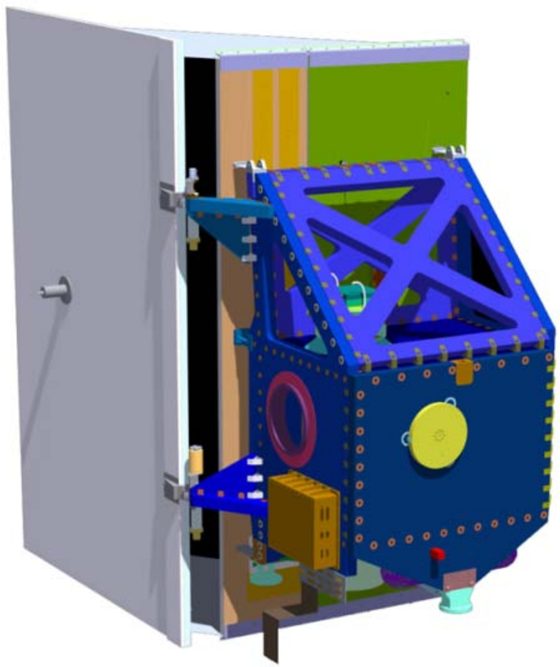
Overview

Thermal Infrared Sensor (TIRS)

- New longwave infrared (10 – 12 micron) sensor for the Landsat Data Continuity Mission
- 185 km ground swath; 100 meter pixel size on ground
- Pushbroom sensor configuration



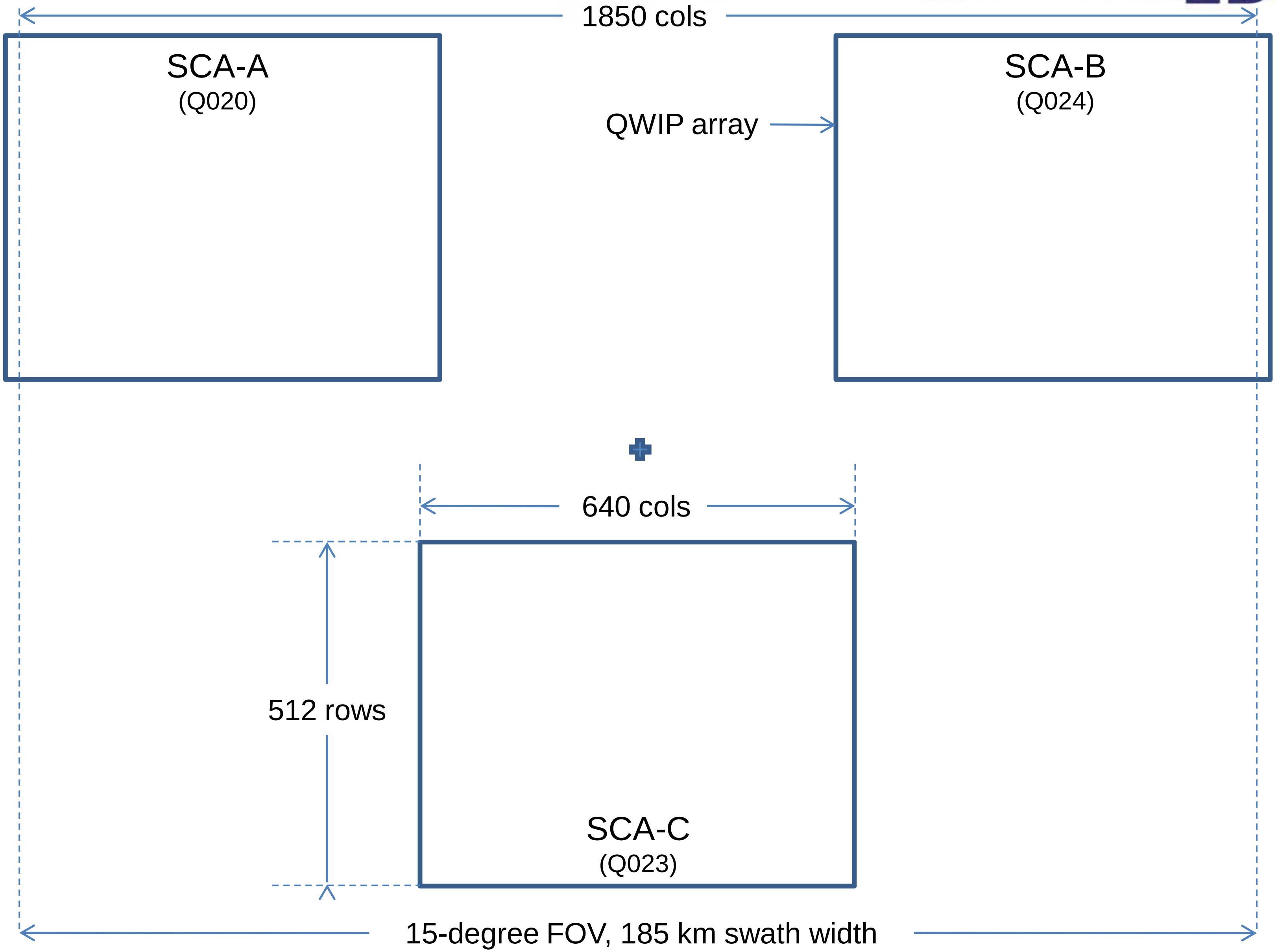
Issue of Calibration:

- Single detector – only one calibration
- Multiple detectors – unique calibration for each detector
  – leads to pixel-to-pixel artifacts

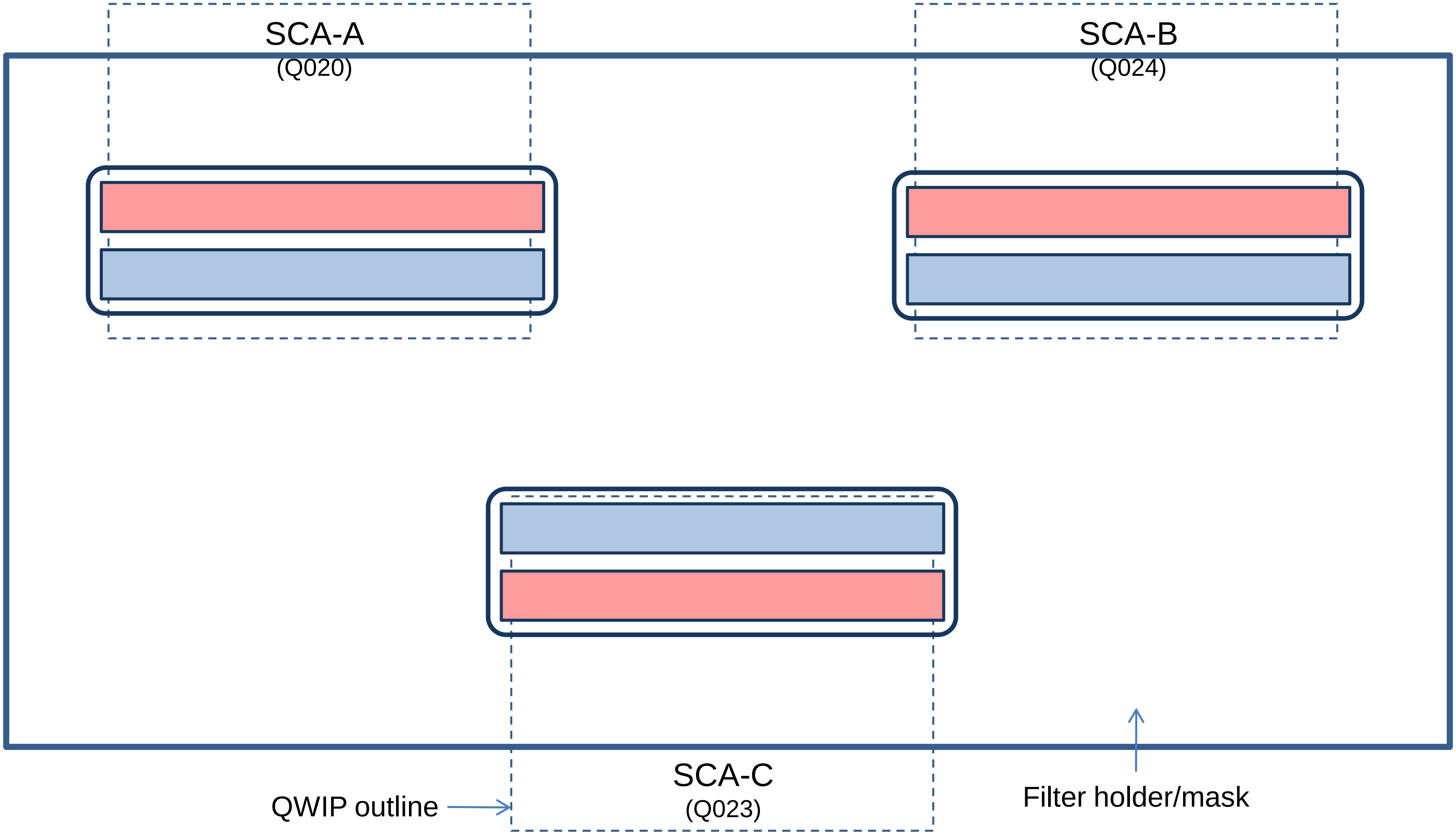
Objectives:

- Predict extent of residual striping when viewing a uniform blackbody target through various atmospheres.
- Determine how different spectral shapes affect the derived surface temperature in a realistic synthetic scene.

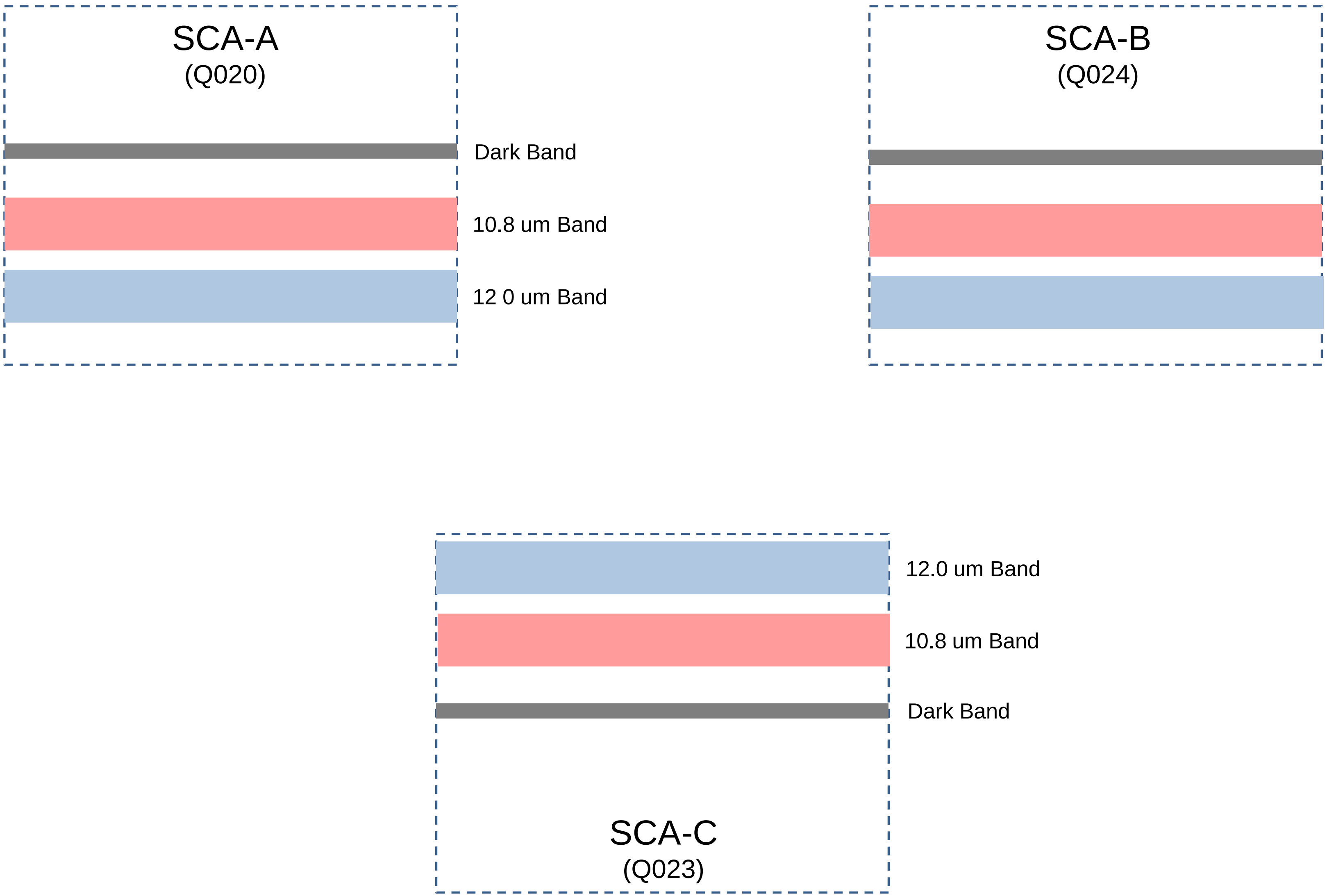
TIRS Focal Plane Layout



Spectral Filter Mask



TIRS Bands

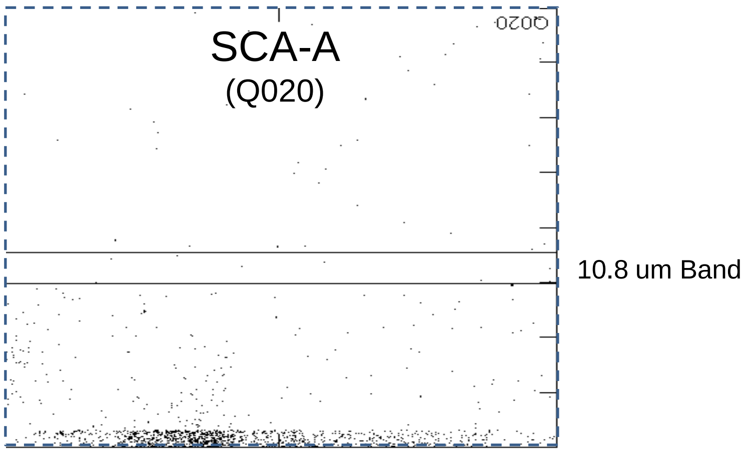

SCA-A
(Q020)
Dark Band
10.8 um Band
12 0 um Band
SCA-B
(Q024)
12.0 um Band
10.8 um Band
Dark Band
SCA-C
(Q023)

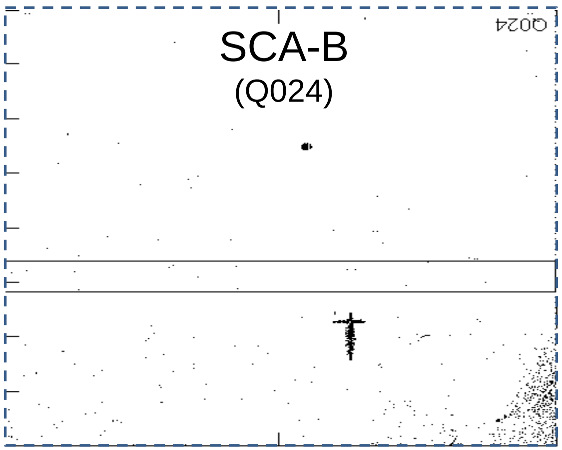
TIRS Requirements

- Spectral Uniformity*:
  - Bandcenter: <= 50 nm of mean
  - Bandwidth: <= 5% of mean
  - Average in-band response: >= 0.8
  - Response between 0.5 response points : >= 0.4
  - Response between 0.8 response points: >= 0.7
  - Band edge slope (0.01-to-0.50): <= 0.4 microns
  - Band edge slope (0.05-to-0.50): <= 0.3 microns
- CE stability: < 0.4%
- Dark current instability: < $5.1*10^5$ electrons/sec
- Noise: < 1000 electrons
- Dark current: < $8.4*10^7$ electrons/sec
- Absolute in-band CE: >= 0.3%

* LDCM Thermal Infrared Sensor Requirements Document. 427-15-02 TIRS RD 20090514 Rev A

Requirements Map: 10.8 micron Band

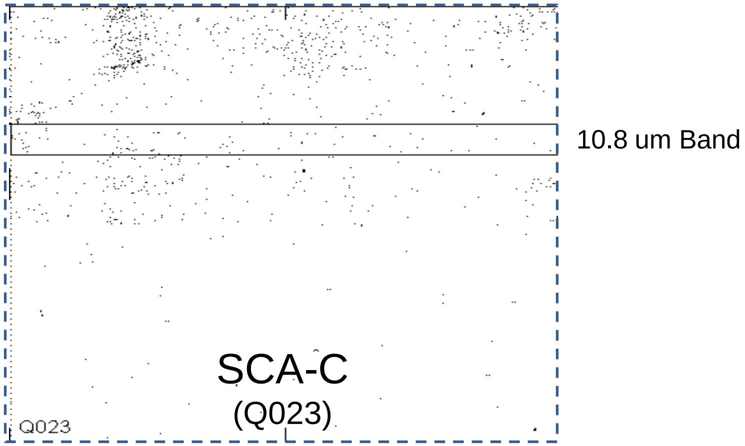




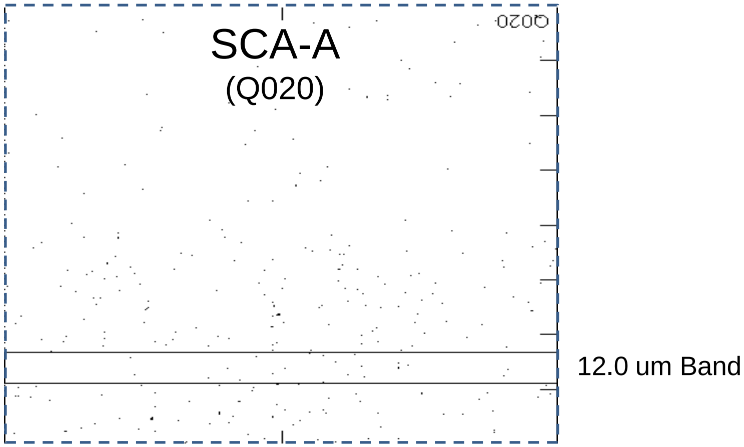
Requirements Map:

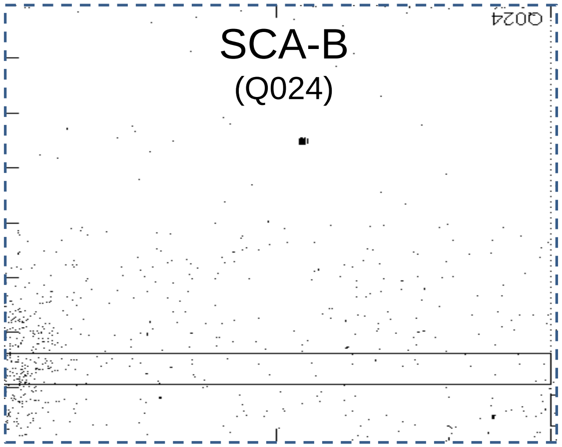
White (1) = Pass all requirements

Black (0) = Fail at least one requirement



Requirements Map: 12.0 micron Band

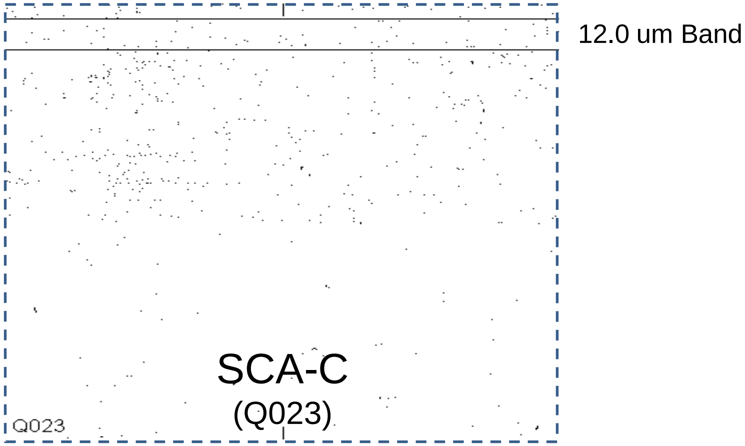




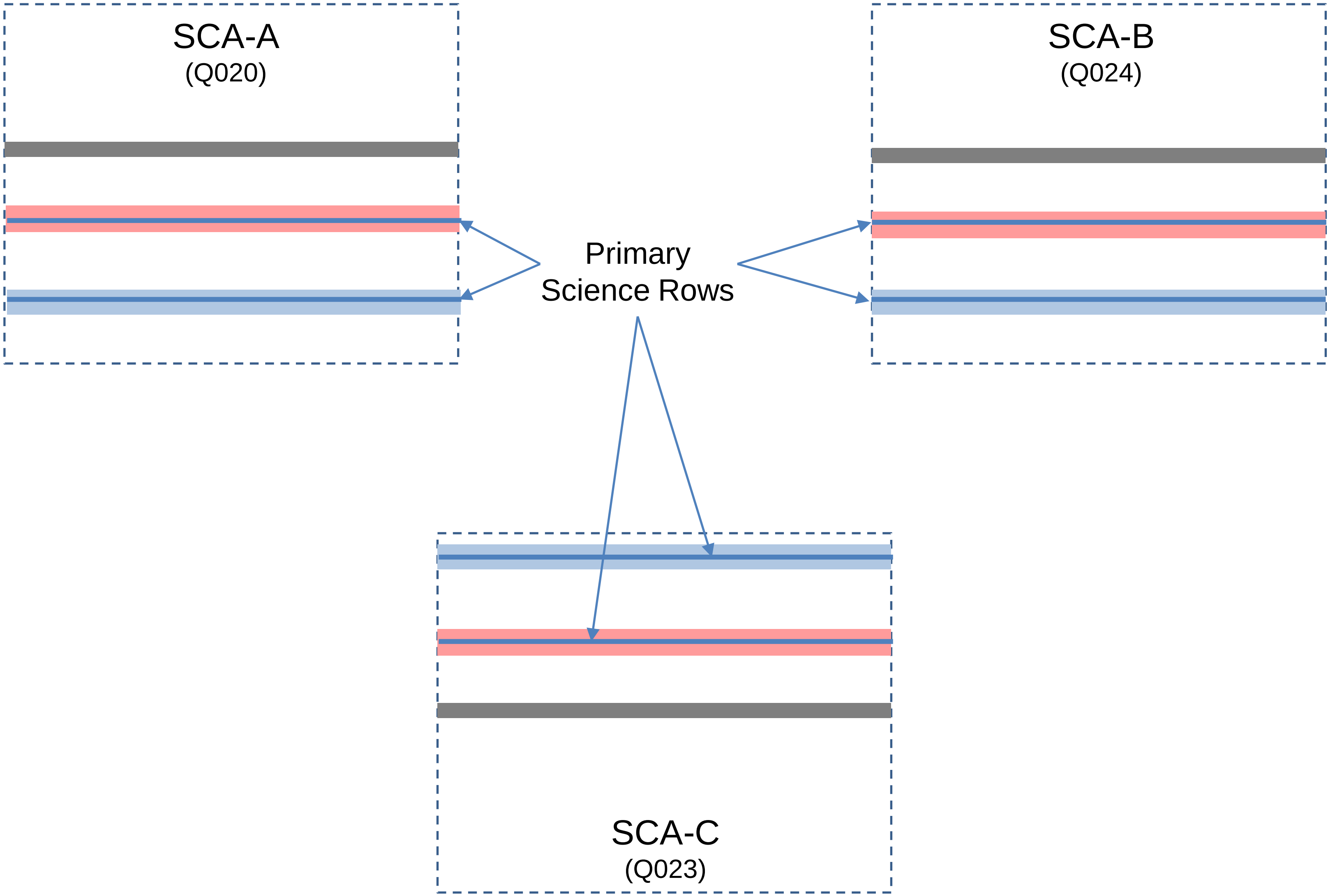
Requirements Map:

White (1) = Pass all requirements

Black (0) = Fail at least one requirement

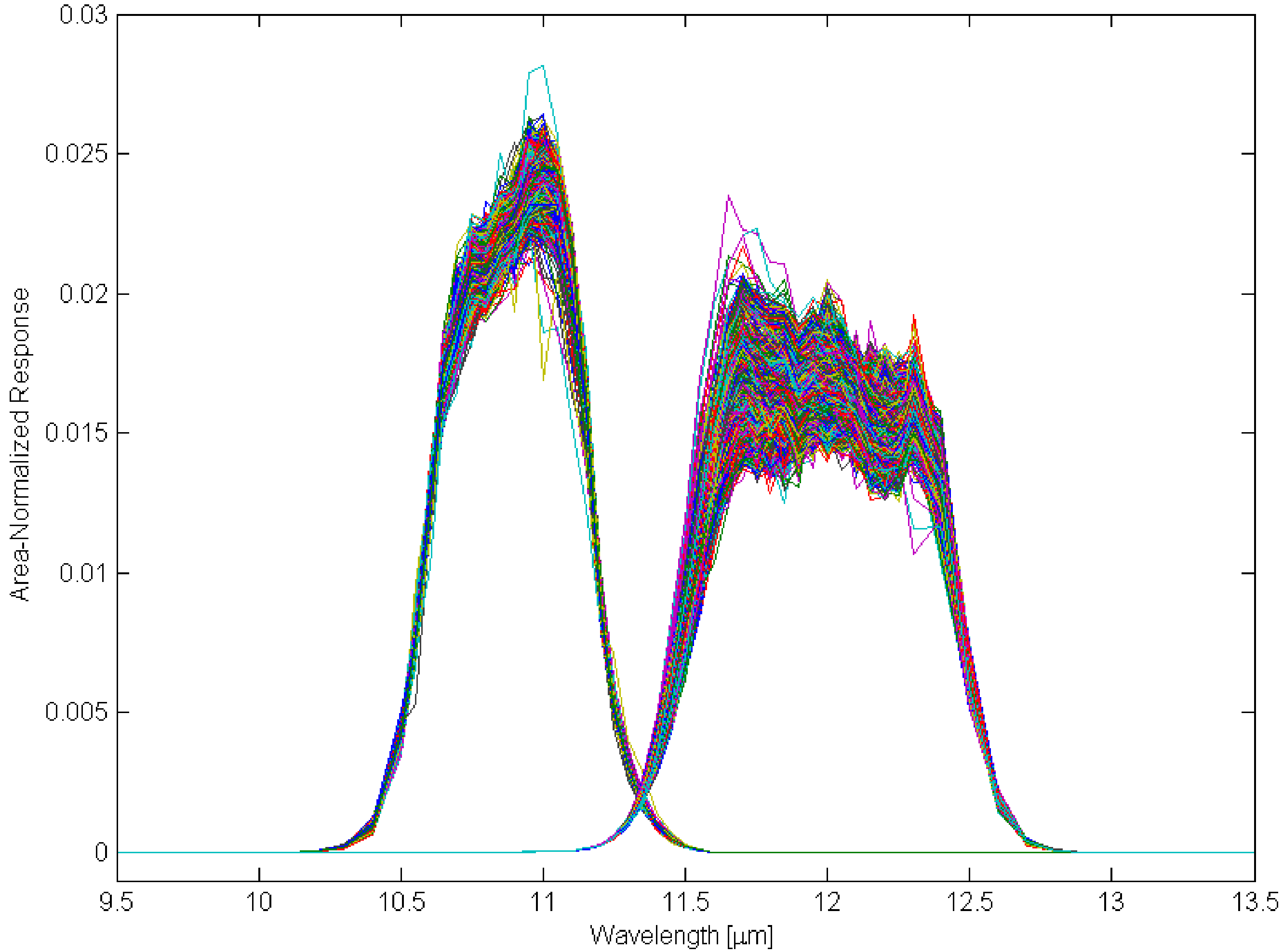


Science Rows



Pixel Responses

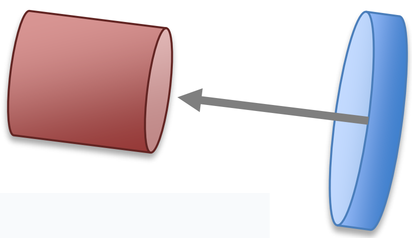
Every pixel has a slightly different spectral response



To what extent do these different spectral shapes contribute to striping?

Study 1: Uniform Scenes

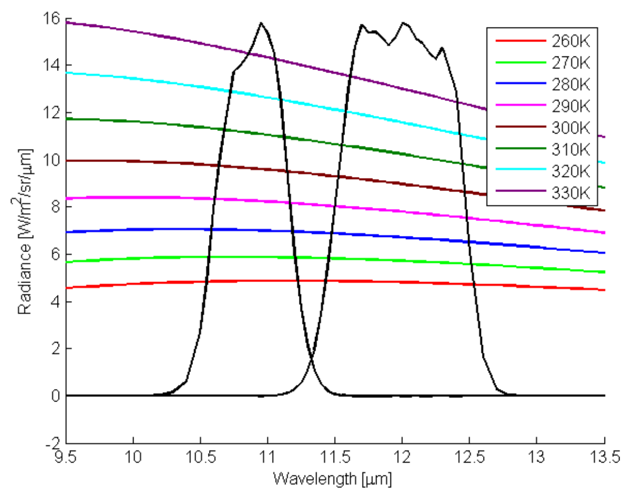
Calibration

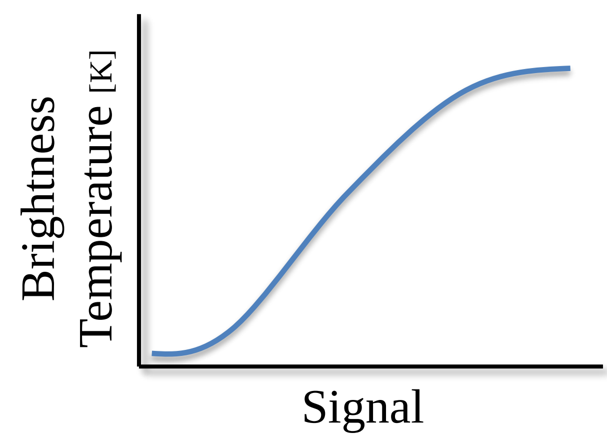


$$B(T,\lambda)$$

$$S_i = \frac{\int B(T,\lambda)\cdot R_i(\lambda)\cdot d\lambda}{\int R_i(\lambda)\cdot d\lambda}$$

- For each detector: calibration curve of signal to BB temperature

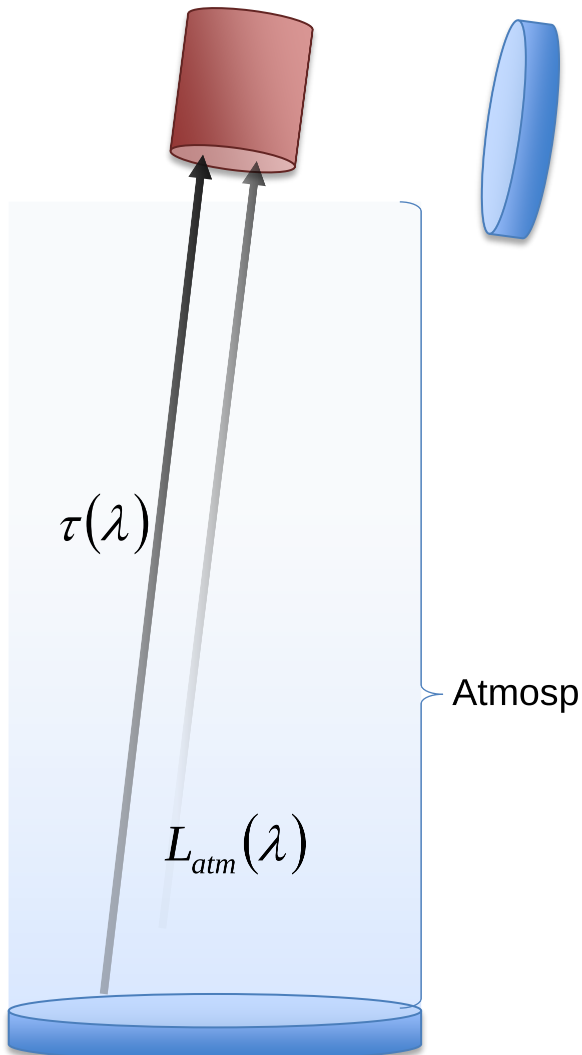




- Each pixel signal now represented as a <u>brightness temperature</u>

Uniform Scene

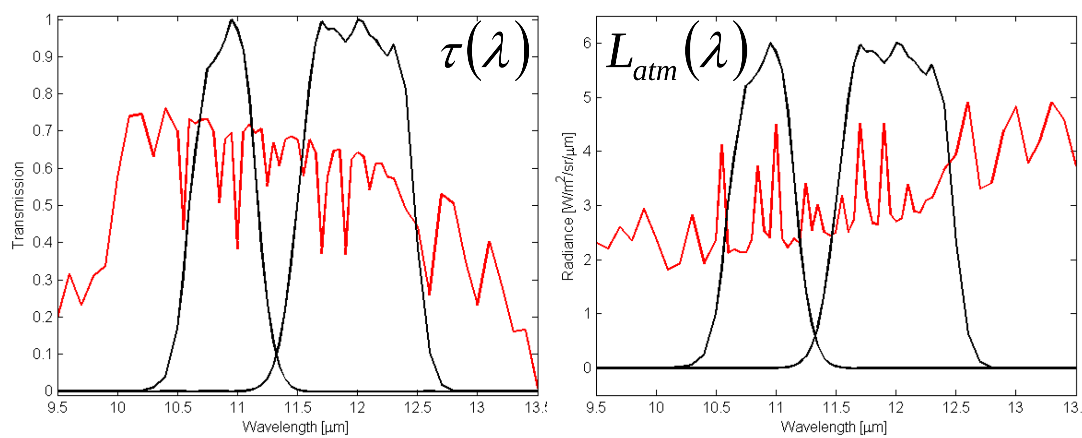
Infrared Sensor



Uniform Blackbody $B(T,\lambda)$

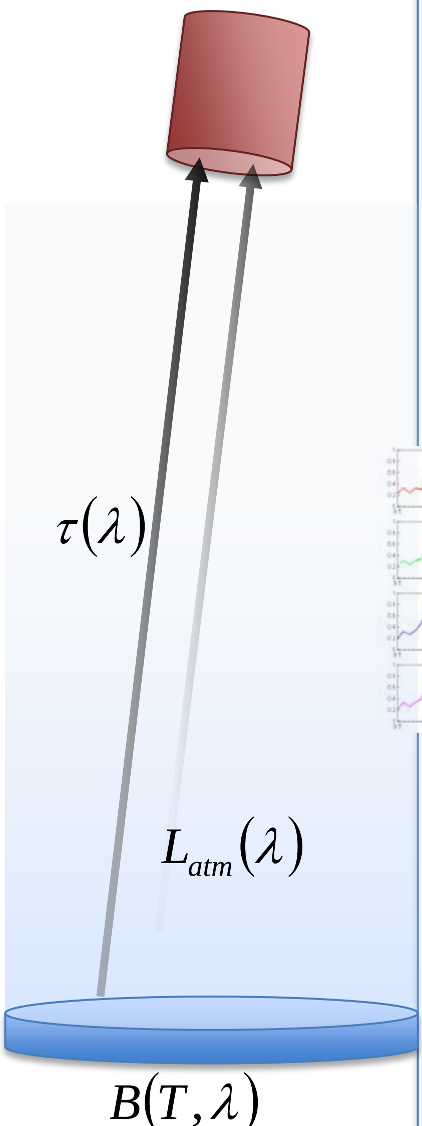
$$S_i = \frac{\int [B(T,\lambda)\cdot \tau_{atm}(\lambda) + L_{atm}(\lambda)]\cdot R_i(\lambda)\cdot d\lambda}{\int R_i(\lambda)\cdot d\lambda}$$

- Same calibration on uniform scene through atmosphere
- Will not return same brightness temperature due to atmospheric terms

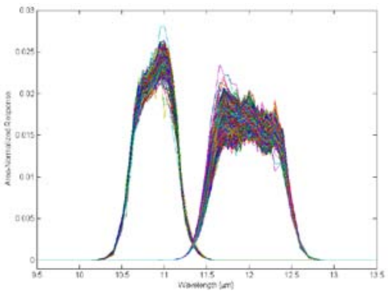


- What is the residual striping effect due to the atmosphere when viewing a uniform blackbody?

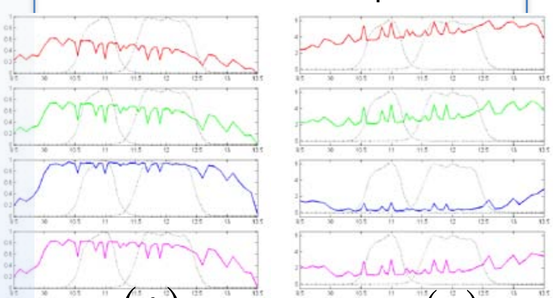
Study 1 Procedure



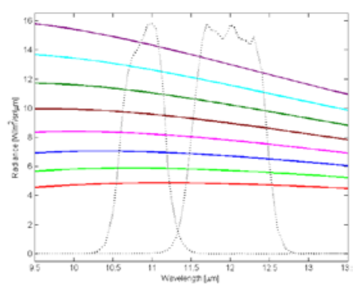
1850 Pixel Responses (x2)



4 MODTRAN Atmospheres

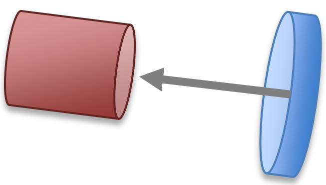


8 Blackbody Temperatures



$$S_i = \frac{\int [B(T,\lambda)\cdot \tau_{atm}(\lambda) + L_{atm}(\lambda)]\cdot R_i(\lambda)\cdot d\lambda}{\int R_i(\lambda)\cdot d\lambda}$$

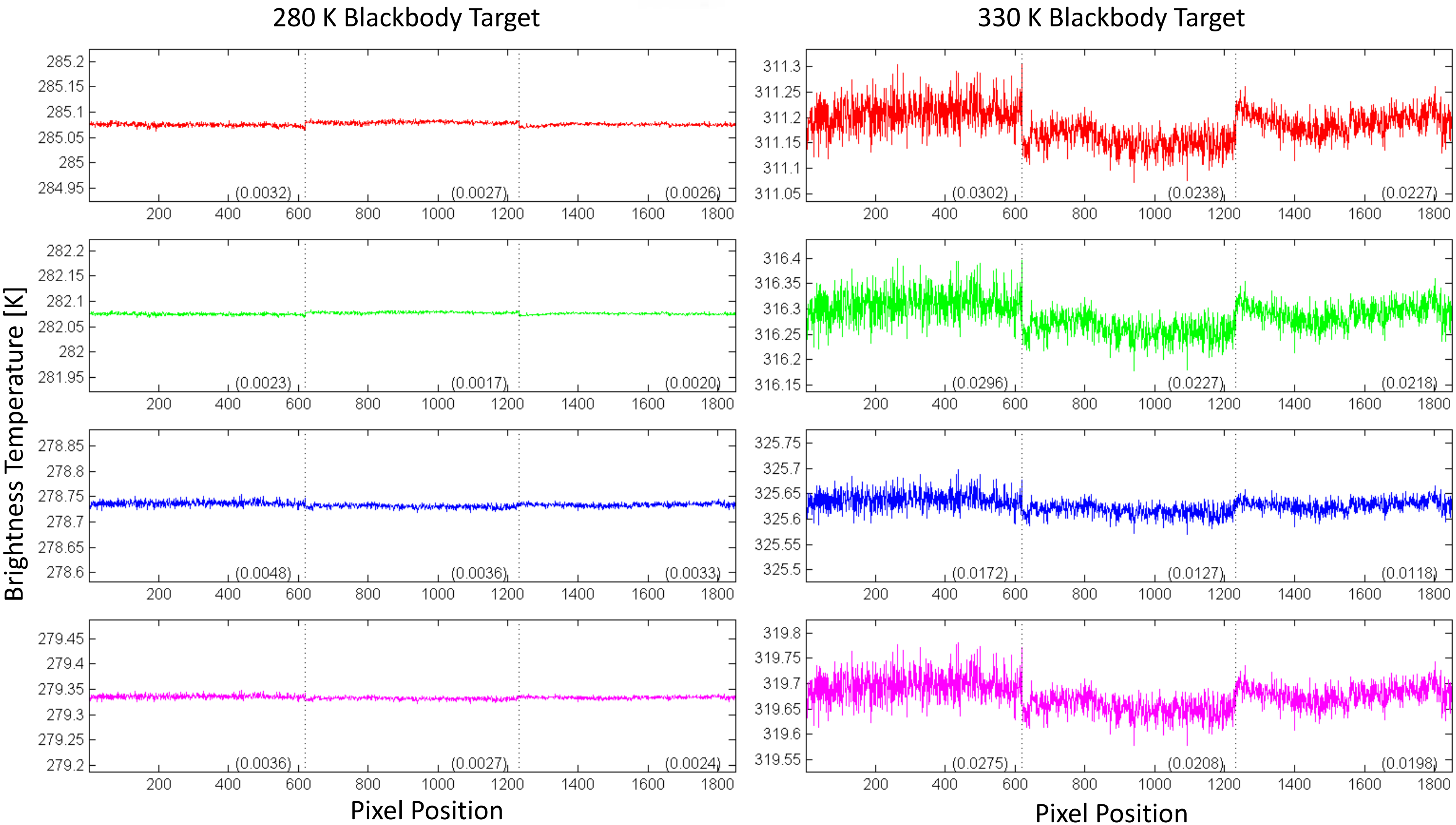
Calibrate



$$S_i = \frac{\int B(T,\lambda)\cdot R_i(\lambda)\cdot d\lambda}{\int R_i(\lambda)\cdot d\lambda}$$

Residual Striping?

Study 1 Results – 10.8 Band

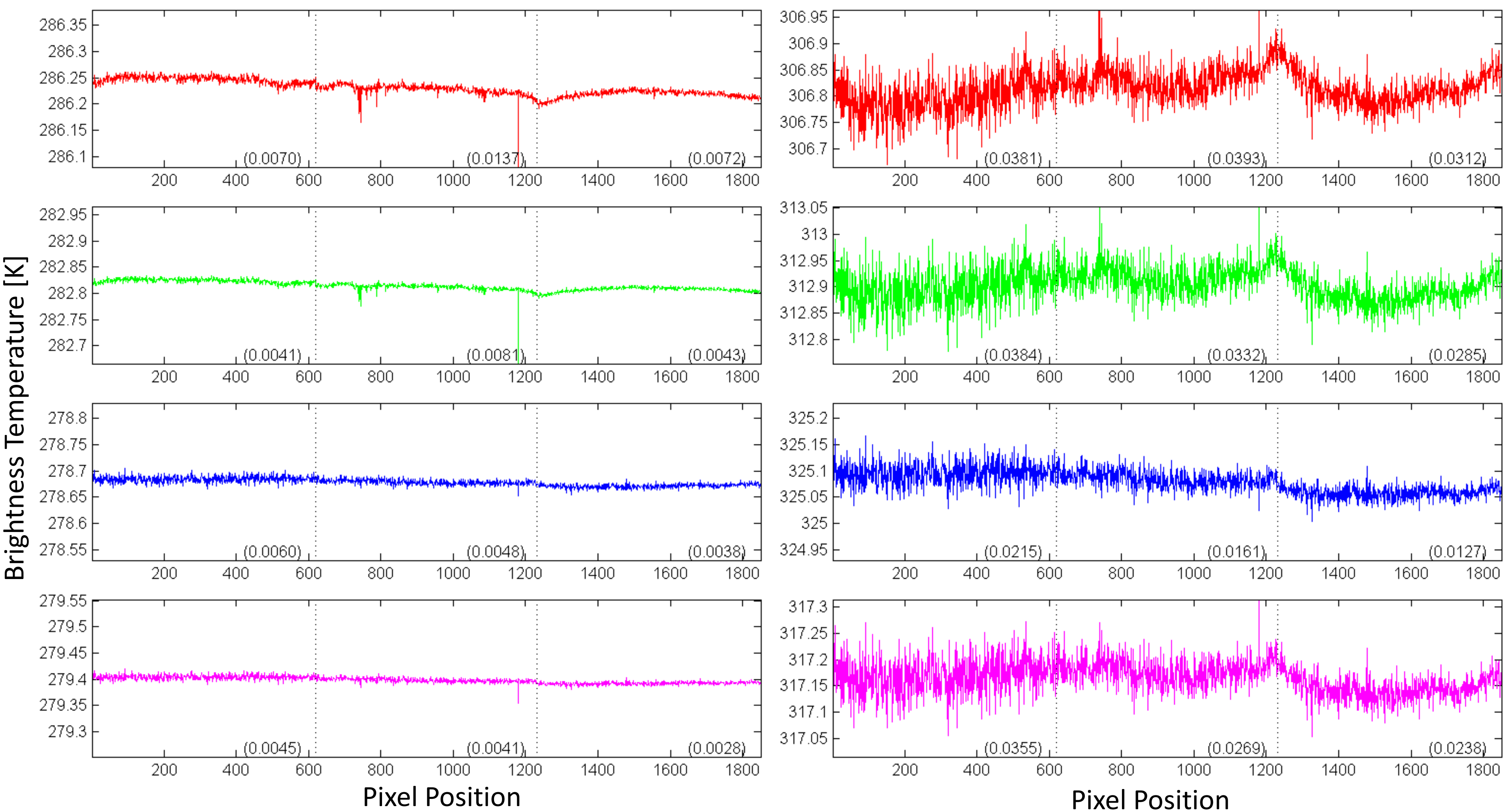


MODTRAN Standard Atmospheres:

Tropical — Mid-Latitude Summer — Mid-Latitude Winter — Sub-Arctic Summer

Study 1 Results – 12.0 Band

280 K Blackbody Target | 330 K Blackbody Target



MODTRAN Standard Atmospheres:

Tropical — Mid-Latitude Summer — Mid-Latitude Winter — Sub-Arctic Summer

Study 1 Observations

- Striping even after radiometric calibration of the detectors

  -Calibration based on a smooth blackbody radiance

  - Atmospheric spectral variations = different integrated signal for a particular detector.

- Minimum for mid-latitude winter atmospheres and maximum for tropical atmospheres

  - Tropical atmosphere: higher transmission and path radiance effects = magnify striping artifacts

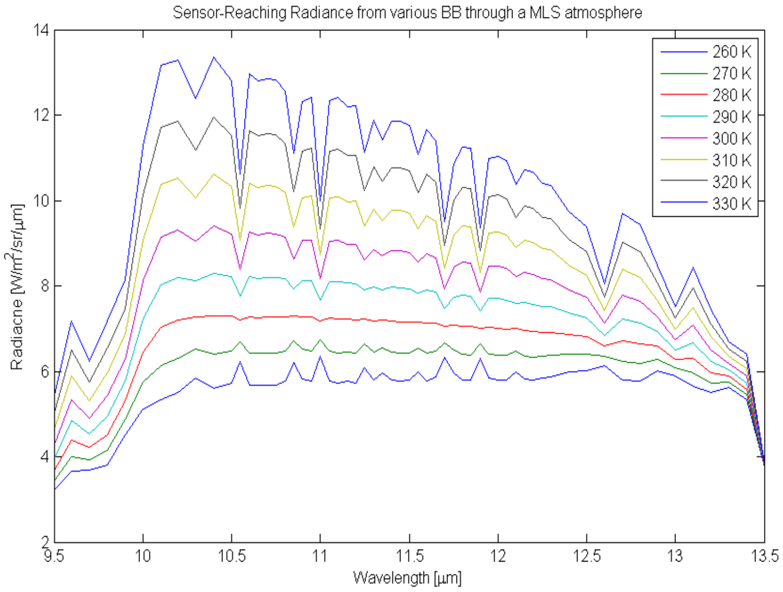
- Striping minimized for temperatures of 270 - 280 K

  -contrast between the target temperature and effective atmospheric temperature.

  - transmission losses compensated by path radiance

- Striping is generally greater in 12.0 micron channel

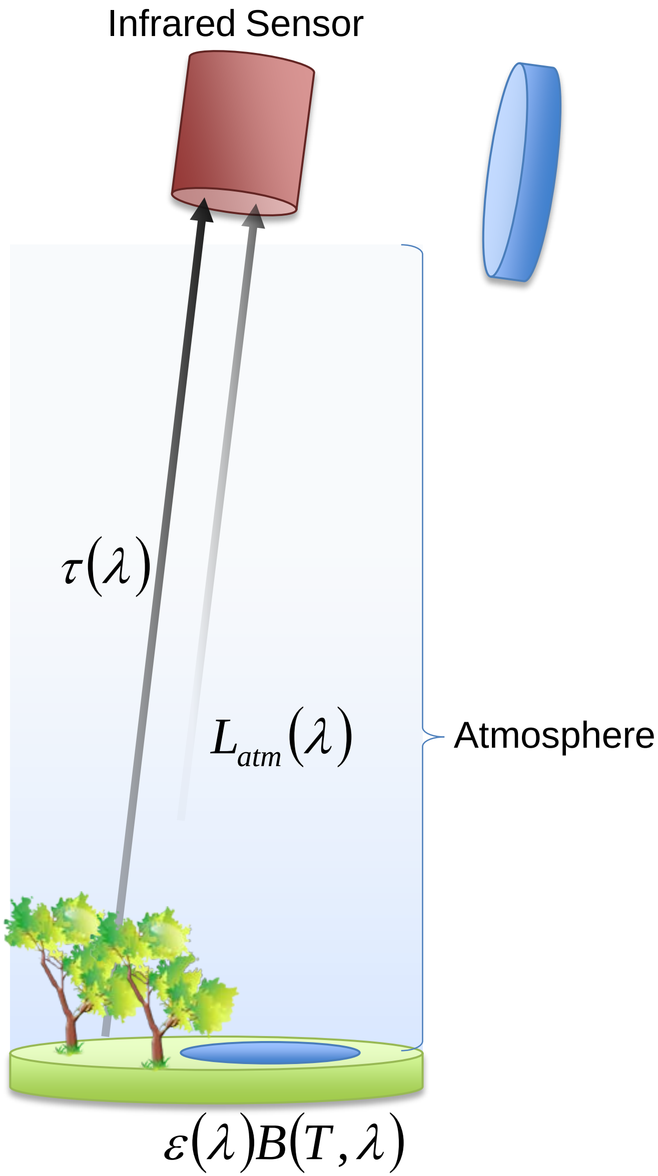
  - wider bandwidth more susceptible to spectral variations



The residual artifacts expected to be small (max standard deviations 35 mK and 57 mK)

Study 2: Realistic Scenes

Realistic Scene



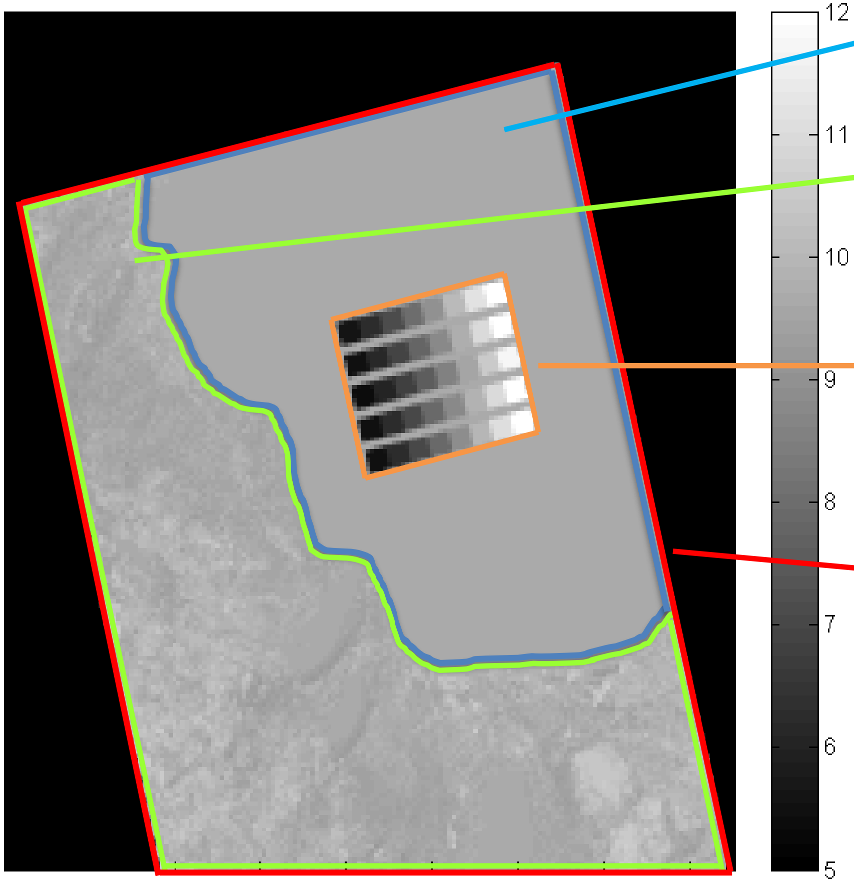
$$S_i = \frac{\int [\varepsilon(\lambda)B(T,\lambda)\cdot\tau_{atm}(\lambda) + L_{atm}(\lambda)]\cdot R_i(\lambda)\cdot d\lambda}{\int R_i(\lambda)\cdot d\lambda}$$

- Replace uniform scene with realistic scene
  - Various emissivities
- Group pixel responses into classes
  - Representative spectral shapes

How do different band shapes affect the brightness temperature in a realistic scene?

DIRSIG Lake Tahoe Image

DIRSIG Thermal Radiance image [W/m2/sr/um]



Lake:
- Water, sea-level

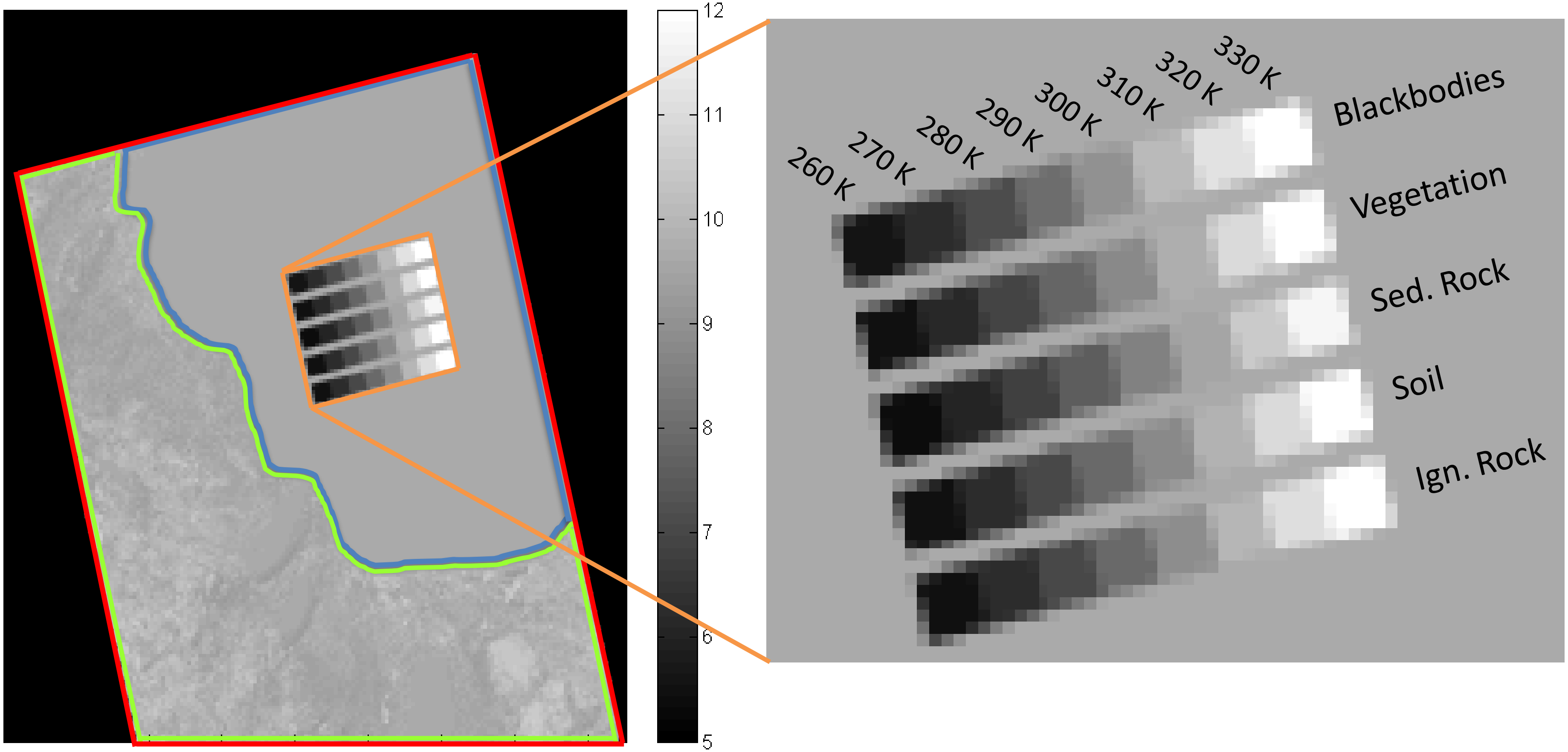
Terrain:
- Various land cover types
- Relief via DEM

Panels:
- Various emissivities
- Various temperatures

Atmosphere:
- Uniform atmosphere for entire scene
- Atm. terms generated via MODTRAN

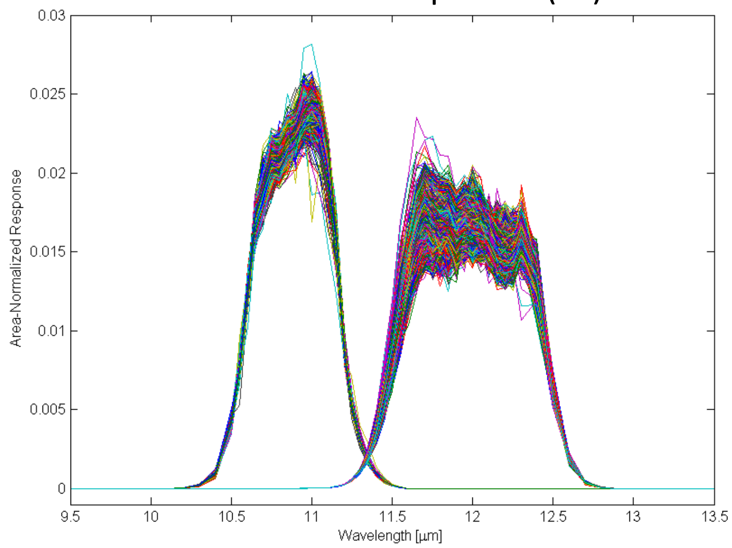
DIRSIG Lake Tahoe Image

DIRSIG Thermal Radiance image [W/m2/sr/um]



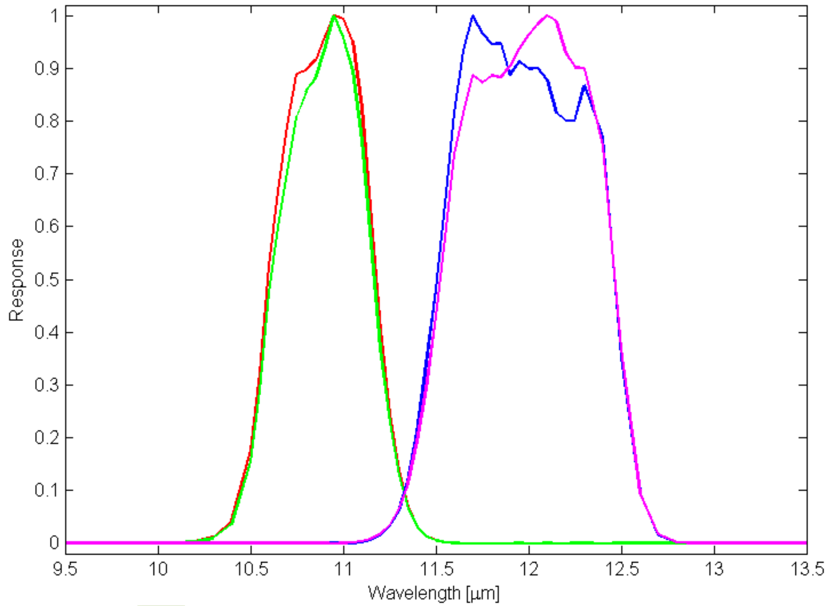
Spectral Response Classes

1850 Pixel Responses (x2)

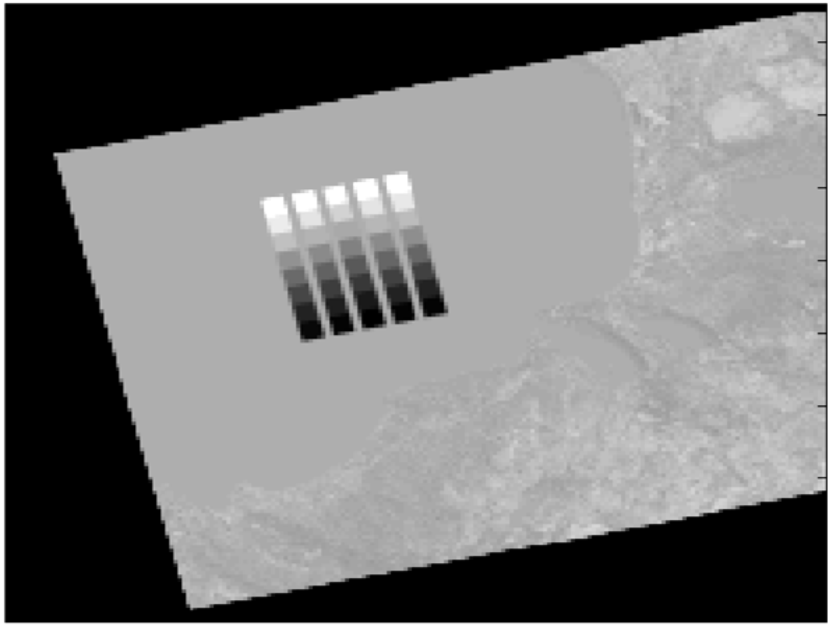


K-means Classifier

2 spectral shapes per band



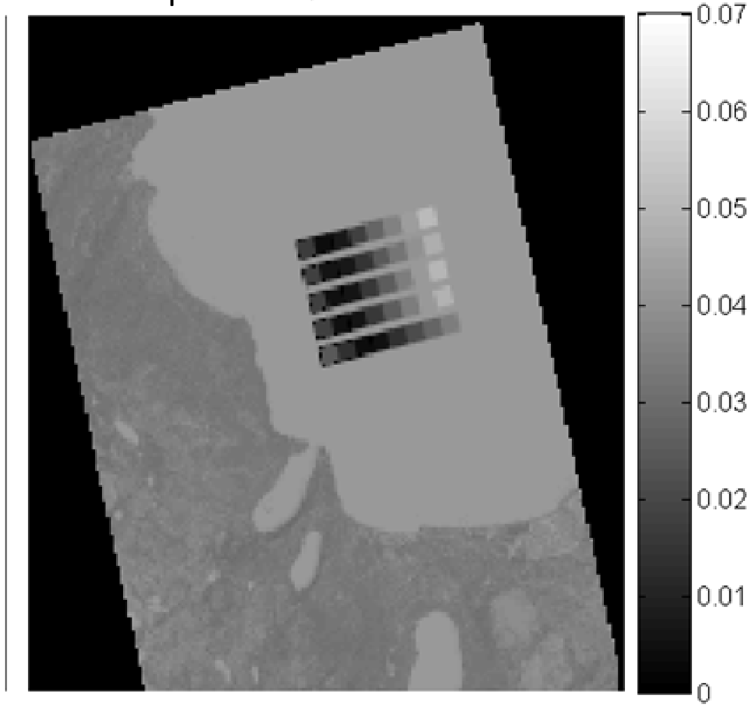
Apply each band shape to the entire DIRSIG scene



DIRSIG Product

- 4 band shapes (2 for each band)
- 4 MODTRAN Standard Atmospheres:
  - Tropical, Mid-Latitude Summer, Mid-Latitude Winter, Sub-Arctic Summer
- 2 TIRS bands * 2 band shapes per band * 4 atmospheres = 16 DIRSIG radiance images

Percent Difference between shape 1 and shape 2 for the 10 micron band

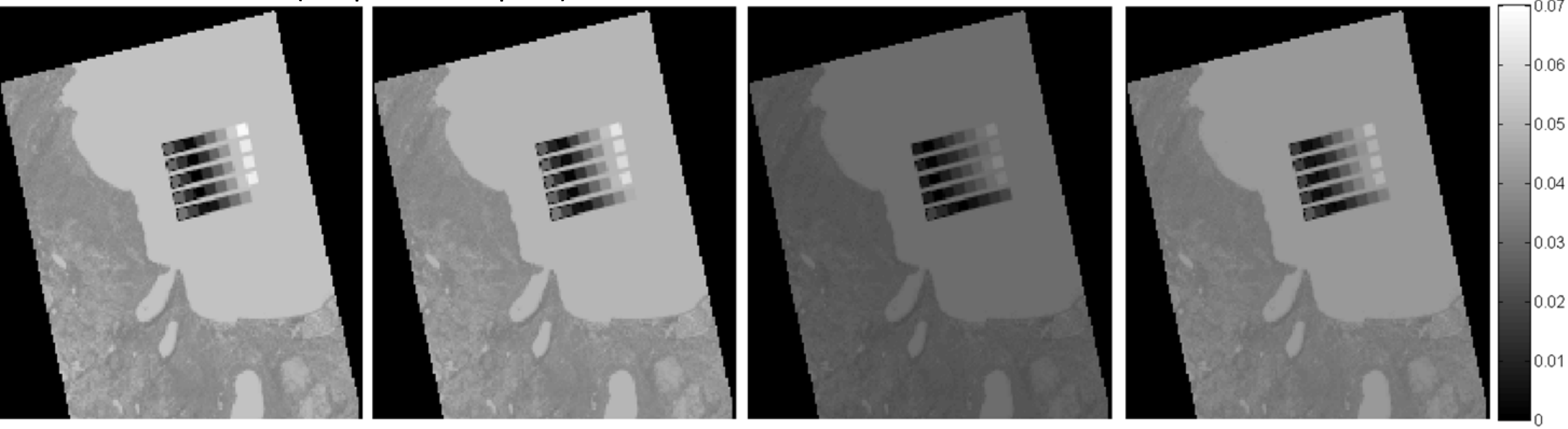


- Express results as % difference images:

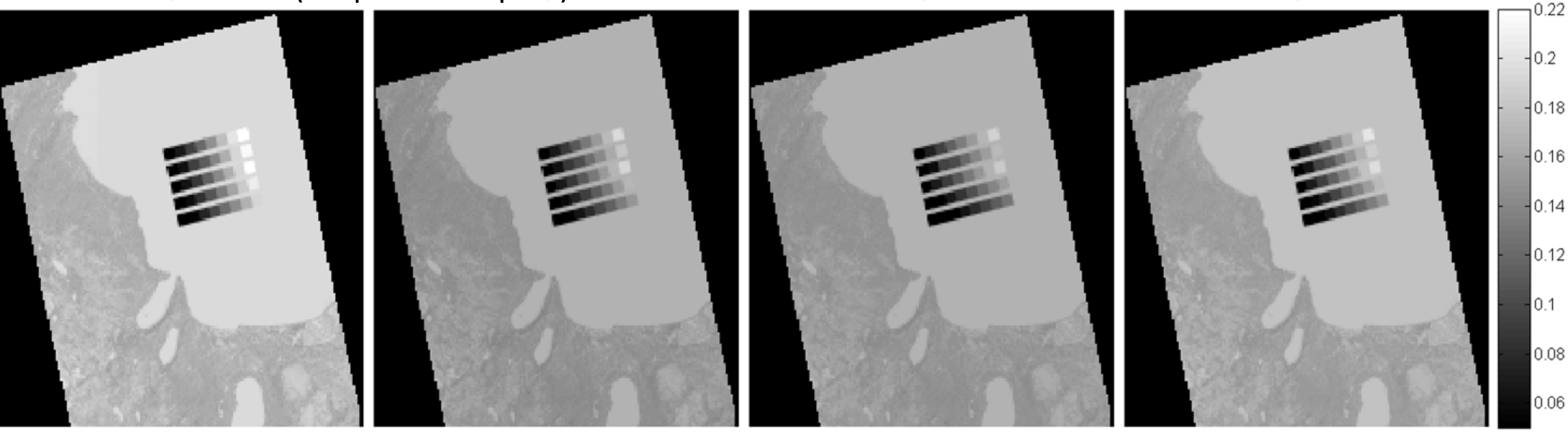
$$\frac{\left|L_{shape1} - L_{shape2}\right|}{mean\left(L_{shape1}, L_{shape2}\right)} \cdot 100\%$$

DIRSIG Product

Percent difference (shape 1 – shape 2) for 10.8 micron band



Percent difference (shape 1 – shape 2) for 12.0 micron band



Tropical | Mid-Latitude Summer | Mid-Latitude Winter | Sub-Arctic Summer

Study 2 Observations

- Temperature differences generally greater in 12.0 micron channel
  - wider bandwidth more susceptible to spectral variations
  - greater variation in 12 micron band shapes

- Temperature differences greatest for tropical atmosphere
  - higher transmission and path radiance effects = increased spectral variation

- Material type affects temperature differences (very subtle)
  - lower emissivity materials less susceptible to band shape
  - lower emissivity = more reflected atmosphere = less contrast between ground and atm.

- Results consistent with previous study

Band shape differences expected to be 0.1% and a 0.2%

Summary

- Spectral requirements analysis to choose best candidates for primary science rows

- Predict residual pixel-to-pixel artifacts for science row candidates:
  - Residual striping when viewing uniform target through atmosphere
    - Very small striping expected (35 mK and 57 mK for the 10.8 and 12.0 micron bands respectively)
  - Band shape influence on brightness temperatures in a realistic scene
    - Temperature differences between band shapes expected to be small (0.1% and 0.2% for the 10.8 and 12.0 micron bands respectively)

- Modeling tools (MODTRAN and DIRSIG) utilized to predict instrument performance before instrument is built

Acknowledgements/References/Contact

LDCM

Acknowledgements

- Detector Characterization Lab at NASA Goddard
  Nicholas Boehm, Chao-Hsi Chang, Roger Foltz, Mike Hickey, Duncan Kahle, Emily Kan, Augustyn Waczynski
- Digital Imaging and Remote Sensing Lab at RIT

References

[1] Jhabvala, M., Reuter, D., Choi, K., Jhabvala, C., and Sundaram, M., "QWIP-based thermal infrared sensor for the landsat data continuity mission," in [*Infrared Physics & Technology], 52, 424–429 (2009).*

[2] "LDCM thermal infrared sensor requirements document," Tech. Rep. GSFC 427-15-02, NASA Goddard Space Flight Center (May 2009).

[3] Schott, J. R., [*Remote Sensing: The Image Chain Approach], Oxford University Press, New York, NY (1997).*

[4] Berk, A., Bernstein, L. S., and Robertson, D. C., "MODTRAN: A moderate resolution model for LOWTRAN 7," Tech. Rep. GL-TR-89-0122, Spectral Sciences, Inc., Burlington, MA (April 1989).

[5] MacQueen, J., "Some methods for classification and analysis of multivariate observations," in [*Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability, Vol. 1], 281–297, Univ. of Calif.* Press (1967).

[6] Schott, J. R., Brown, S. D., Raqueno, R. V., Gross, H. N., and Robinson, G., "An advanced synthetic image generation model and its application to multi/hyperspectral algorithm development," in [*Canadian Journal of Remote Sensing], 25(2), 99–111 (1999).*

[7] Salisbury, J. W. and D'Aria, D. M., "Emissivity of terrestrial materials in the 8-14 *m atmospheric window,"* in [*Remote Sensing Environment], 42, 83–106 (1992).*

Contact Information

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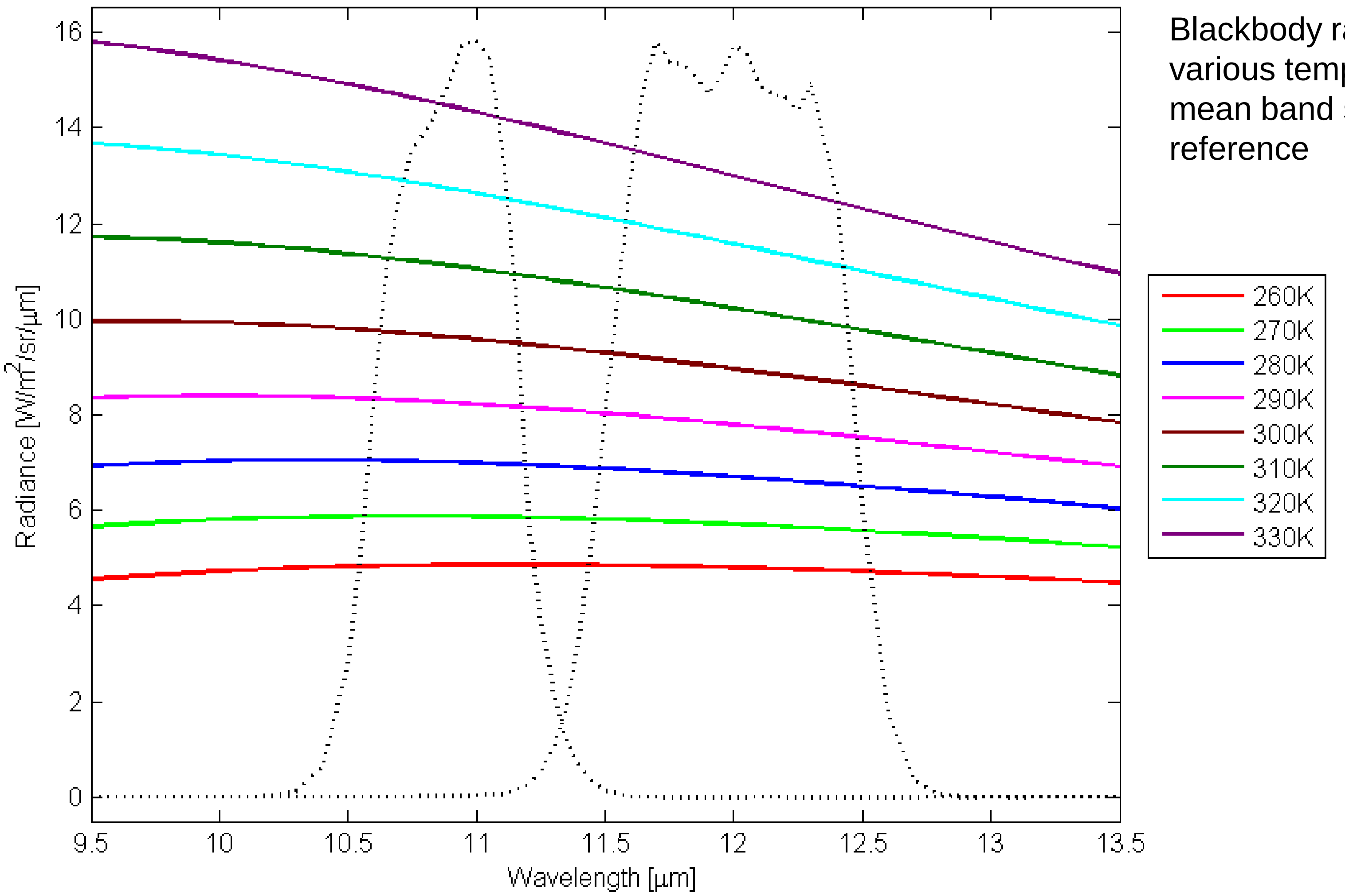
Backup Slides

Blackbody Temperatures



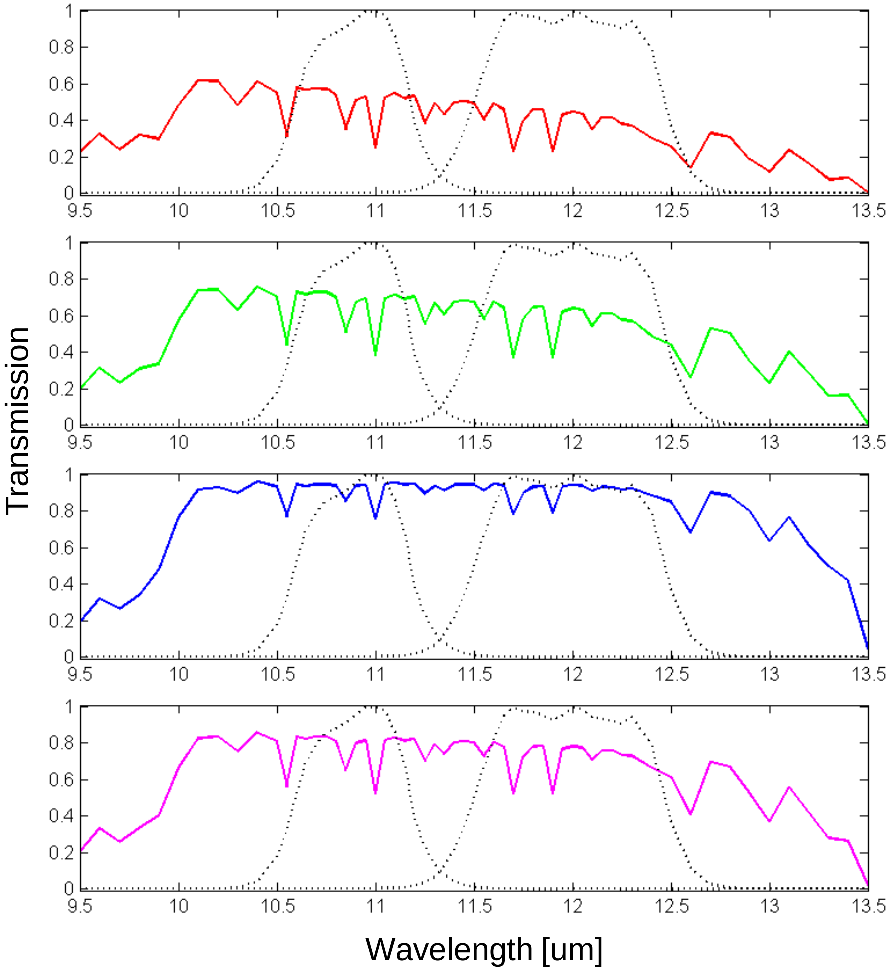
Blackbody radiance curves at various temperatures with the mean band shapes shown for reference

Atmosphere Types

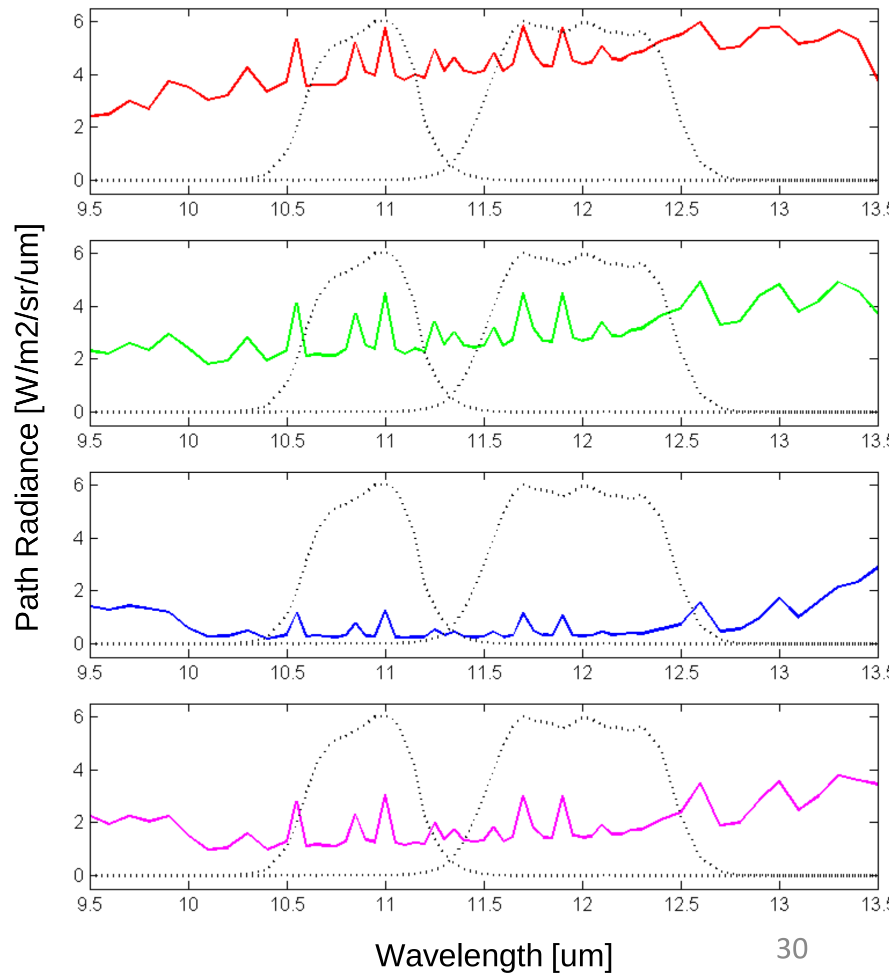
MODTRAN Standard Atmospheres:

Tropical — Mid-Latitude Summer — Mid-Latitude Winter — Sub-Arctic Summer

Atmospheric Transmission



Atmospheric Path Radiance



Pixel-to-Pixel Uniformity Requirements

- Full Field of View: The standard deviation of all pixel radiances across the FOV within a band shall not exceed 0.5% of the average radiance

$$\sqrt{\frac{\sum_{i=1}^{N}\left(L_i - \overline{L}\right)^2}{N-1}} \leq 0.005 \cdot \overline{L}$$

- Banding: (1) The root mean square deviation from the average radiance across the full FOV for any 100 contiguous pixel radiances within a band shall not exceed 0.5% of that average radiance

$$\sqrt{\frac{\sum_{i=n}^{n+99}\left(L_i - \overline{L}\right)^2}{100}} \leq 0.005 \cdot \overline{L}$$

- Banding: (2) The standard deviation of the radiances across any 100 contiguous pixels within a band shall not exceed 0.5% of the average radiance across the full FOV

$$\sqrt{\frac{\sum_{i=n}^{n+99}\left(L_i - \overline{L}\right)^2}{99}} \leq 0.005 \cdot \overline{L}$$

- Streaking: The maximum value of the streaking parameter within a band shall not exceed 0.005

$$\frac{\left|L_i - \frac{1}{2}\left(L_{i-1} + L_{i+1}\right)\right|}{L_i} \leq 0.005$$

* Pixel data has been radiometrically calibrated using on-board blackbody method discussed earlier

Full Field of View

- All pixels meet FOV requirement for all conditions

$$\sqrt{\frac{\sum_{i=1}^{N}\left(L_i - \overline{L}_i\right)^2}{N-1}} \leq 0.005$$

Band 1: 10.8 um

Blackbody Temperature	TRP St. Dev.		TRP 0.5% mean	MLS St. Dev.		MLS 0.5% mean	MLW St. Dev.		MLW 0.5% mean	SAS St. Dev.		SAS 0.5% mean
260	0.0019	≤	0.0328	0.0017	≤	0.0293	0.0001	≤	0.0244	0.0009	≤	0.0264
270	0.0012	≤	0.0353	0.0010	≤	0.0326	0.0002	≤	0.0291	0.0003	≤	0.0303
280	0.0004	≤	0.0381	0.0003	≤	0.0363	0.0006	≤	0.0343	0.0004	≤	0.0346
290	0.0008	≤	0.0412	0.0008	≤	0.0403	0.0010	≤	0.0400	0.0012	≤	0.0395
300	0.0018	≤	0.0446	0.0018	≤	0.0448	0.0015	≤	0.0463	0.0020	≤	0.0447
310	0.0029	≤	0.0483	0.0029	≤	0.0497	0.0020	≤	0.0531	0.0030	≤	0.0505
320	0.0042	≤	0.0522	0.0041	≤	0.0549	0.0025	≤	0.0605	0.0040	≤	0.0567
330	0.0055	≤	0.0565	0.0054	≤	0.0606	0.0031	≤	0.0684	0.0050	≤	0.0633

Band 2: 12.0 um

Blackbody Temperature	TRP St. Dev.		TRP 0.5% mean	MLS St. Dev.		MLS 0.5% mean	MLW St. Dev.		MLW 0.5% mean	SAS St. Dev.		SAS 0.5% mean
260	0.0048	≤	0.0332	0.0030	≤	0.0296	0.0002	≤	0.0242	0.0012	≤	0.0264
270	0.0037	≤	0.0349	0.0022	≤	0.0322	0.0004	≤	0.0283	0.0008	≤	0.0296
280	0.0025	≤	0.0368	0.0014	≤	0.0350	0.0008	≤	0.0328	0.0007	≤	0.0332
290	0.0014	≤	0.0389	0.0010	≤	0.0381	0.0012	≤	0.0378	0.0012	≤	0.0371
300	0.0016	≤	0.0412	0.0017	≤	0.0415	0.0017	≤	0.0431	0.0019	≤	0.0413
310	0.0031	≤	0.0437	0.0029	≤	0.0451	0.0022	≤	0.0488	0.0028	≤	0.0459
320	0.0050	≤	0.0463	0.0044	≤	0.0489	0.0027	≤	0.0549	0.0037	≤	0.0507
330	0.0072	≤	0.0490	0.0060	≤	0.0530	0.0033	≤	0.0614	0.0048	≤	0.0559

Banding (1)

- All pixels meet banding (1) requirement for all conditions

$$\sqrt{\frac{\sum_{i=n}^{n+99}\left(L_i - \overline{L}\right)^2}{100}} \leq 0.005 \cdot \overline{L}$$

Band 1: 10.8 um

Blackbody Temperature	# Pixels Failing Requirement			
	TRP	MLS	MLW	SAS
260	0	0	0	0
270	0	0	0	0
280	0	0	0	0
290	0	0	0	0
300	0	0	0	0
310	0	0	0	0
320	0	0	0	0
330	0	0	0	0

Band 2: 12.0 um

Blackbody Temperature	# Pixels Failing Requirement			
	TRP	MLS	MLW	SAS
260	0	0	0	0
270	0	0	0	0
280	0	0	0	0
290	0	0	0	0
300	0	0	0	0
310	0	0	0	0
320	0	0	0	0
330	0	0	0	0

Banding (2)

- All pixels meet banding (2) requirement for all conditions

$$\sqrt{\frac{\sum_{i=n}^{n+99}\left(L_i-\overline{L}\right)^2}{99}} \leq 0.005 \cdot \overline{L}$$

Band 1: 10.8 um

Blackbody Temperature	# Pixels Failing Requirement			
	TRP	MLS	MLW	SAS
260	0	0	0	0
270	0	0	0	0
280	0	0	0	0
290	0	0	0	0
300	0	0	0	0
310	0	0	0	0
320	0	0	0	0
330	0	0	0	0

Band 2: 12.0 um

Blackbody Temperature	# Pixels Failing Requirement			
	TRP	MLS	MLW	SAS
260	0	0	0	0
270	0	0	0	0
280	0	0	0	0
290	0	0	0	0
300	0	0	0	0
310	0	0	0	0
320	0	0	0	0
330	0	0	0	0

Streaking

- Greater than 99.8% of pixels meet streaking requirement for all conditions

$$\frac{\left|L_i - \frac{1}{2}\left(L_{i-1} + L_{i+1}\right)\right|}{L_i} \leq 0.005$$

Band 1: 10.8 um

Blackbody Temperature	# Pixels Failing Requirement			
	TRP	MLS	MLW	SAS
260	0	0	0	0
270	0	0	0	0
280	0	0	0	0
290	0	0	0	0
300	0	0	0	0
310	0	0	0	0
320	0	0	0	0
330	0	0	0	0

Band 2: 12.0 um

Blackbody Temperature	# Pixels Failing Requirement			
	TRP	MLS	MLW	SAS
260	3	3	0	1
270	3	3	0	0
280	3	1	0	0
290	0	0	0	0
300	0	0	0	0
310	3	1	0	0
320	3	3	0	1
330	3	3	0	1