Analysis of Advanced Baseline Imager Out-of-Band Spectral Response

Aaron Pearlman[1,2] and Changyong Cao[2]
1 Earth Resources Technology, Inc.
2 NOAA/NESDIS/STAR

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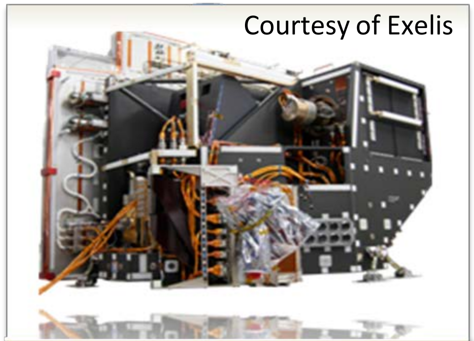
CALCON

Outline

- Advanced Baseline Imager (ABI)
- Spectral Response Functions – Measurements and Validation Efforts
- Background on Out-of Band Response
- ABI Spectral Response Functions
- Results:
  - » Typical Scenes
  - » Out-of-Band Effects
- Conclusion

GOES-R Advanced Baseline Imager

- The NOAA's next generation geostationary imager, the Advanced Baseline Imager (ABI), has increased capability to monitor the surface and atmosphere over current GOES imagers using its sixteen channels.
- Thorough pre-launch radiometric, spatial, and spectral characterization required to meet user needs post-launch.



NOAA: GOES-R ABI

16 Band Imager	
Spectral Region	Spatial Resolution
6 VNIR/SWIR	0.5,1 & 2 km
10 Infrared	2 km

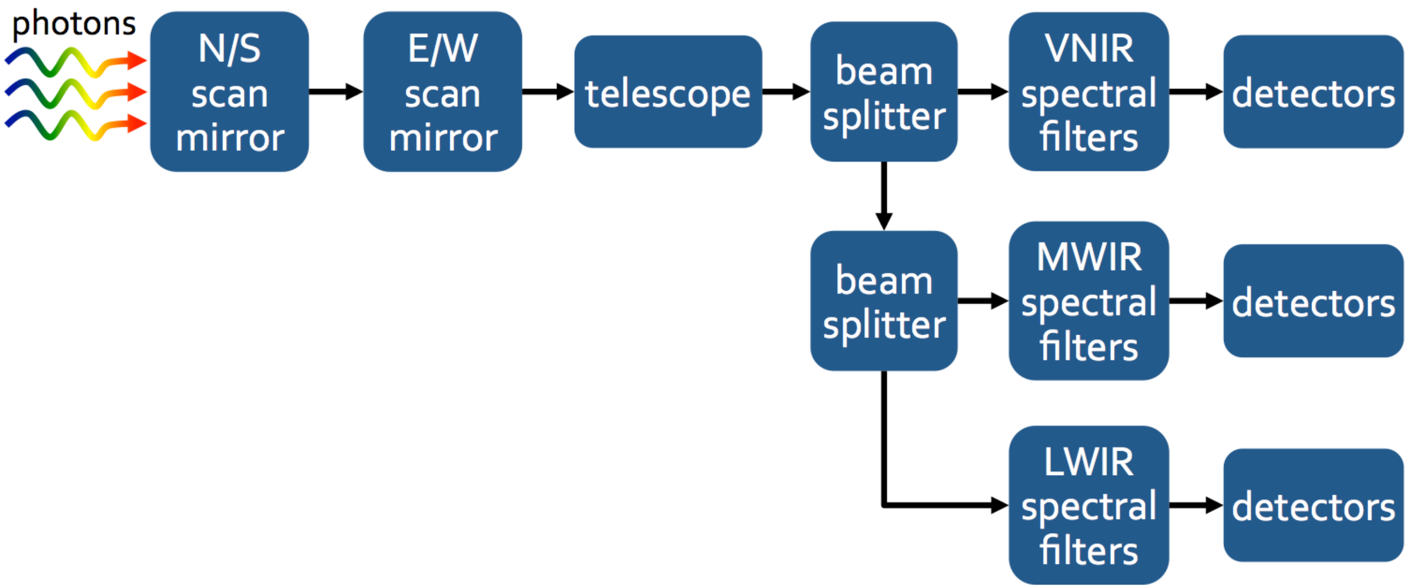
Table 1. Summary of the wavelengths, resolution, and sample use and heritage instrument(s) of the ABI bands. The minimum and maximum wavelength range represent the full width at half maximum (FWHM or 50%) points. [The Instantaneous Geometric Field Of View (IGFOV).]

Future GOES imager (ABI) band	Wavelength range (μm)	Central wavelength (μm)	Nominal subsatellite IGFOV (km)	Sample use	Heritage instrument(s)
1	0.45–0.49	0.47	1	Daytime aerosol over land, coastal water mapping	MODIS
2	0.59–0.69	0.64	0.5	Daytime clouds fog, insolation, winds	Current GOES imager/ sounder
3	0.846–0.885	0.865	1	Daytime vegetation/burn scar and aerosol over water, winds	VIIRS, spectrally modified AVHRR
4	1.371–1.386	1.378	2	Daytime cirrus cloud	VIIRS, MODIS
5	1.58–1.64	1.61	1	Daytime cloud-top phase and particle size, snow	VIIRS, spectrally modified AVHRR
6	2.225–2.275	2.25	2	Daytime land/cloud properties, particle size, vegetation, snow	VIIRS, similar to MODIS
7	3.80–4.00	3.90	2	Surface and cloud, fog at night, fire, winds	Current GOES imager
8	5.77–6.6	6.19	2	High-level atmospheric water vapor, winds, rainfall	Current GOES imager
9	6.75–7.15	6.95	2	Midlevel atmospheric water vapor, winds, rainfall	Current GOES sounder
10	7.24–7.44	7.34	2	Lower-level water vapor, winds, and SO_2	Spectrally modified current GOES sounder
11	8.3–8.7	8.5	2	Total water for stability, cloud phase, dust, SO_2 rainfall	MAS
12	9.42–9.8	9.61	2	Total ozone, turbulence, and winds	Spectrally modified current sounder
13	10.1–10.6	10.35	2	Surface and cloud	MAS
14	10.8–11.6	11.2	2	Imagery, SST, clouds, rainfall	Current GOES sounder
15	11.8–12.8	12.3	2	Total water, ash, and SST	Current GOES sounder
16	13.0–13.6	13.3	2	Air temperature, cloud heights and amounts	Current GOES sounder/ *GOES-12+* imager

www.goes-r.gov

ABI Spectral Response Functions

- Pre-launch characterization of spectral response:
  - » Piece part measurements combined through entire ABI optical train to obtain spectral response functions
    - o Spectral response functions are publicly available – baseline operational https://cs.star.nesdis.noaa.gov/GOESRCWG/ABISRF



Validation Efforts for Spectral Response Functions

- » NIST Deployment of Spectral Irradiance and Radiance Responsivity Calibrations Using Uniform Sources (SIRCUS)
- » Witness filter measurements performed at NIST
  - o Derived uncertainties of in-band filter transmittances and characterized effects of angle of incidence and temperature sensitivity.

Uncertainty in Wavelength (nm)

	Channels 1-3	Channel 4	Channel 5	Channel 6
Instrument Wavelength Error	0.05	0.1	0.2	0.2
Temperature	0.03	0.19	0.03	0.31
Angle of Incidence	0.15	0.3	0.3	0.3
Focusing Geometry	0.05	0.4	0.4	0.4
Nonlinearity	0.01	0.02	0.02	0.02
Quadrature Sum	*0.17*	*0.54*	*0.54*	*0.62*
Expanded Uncertainty	**0.34**	**1.08**	**1.08**	**1.24**

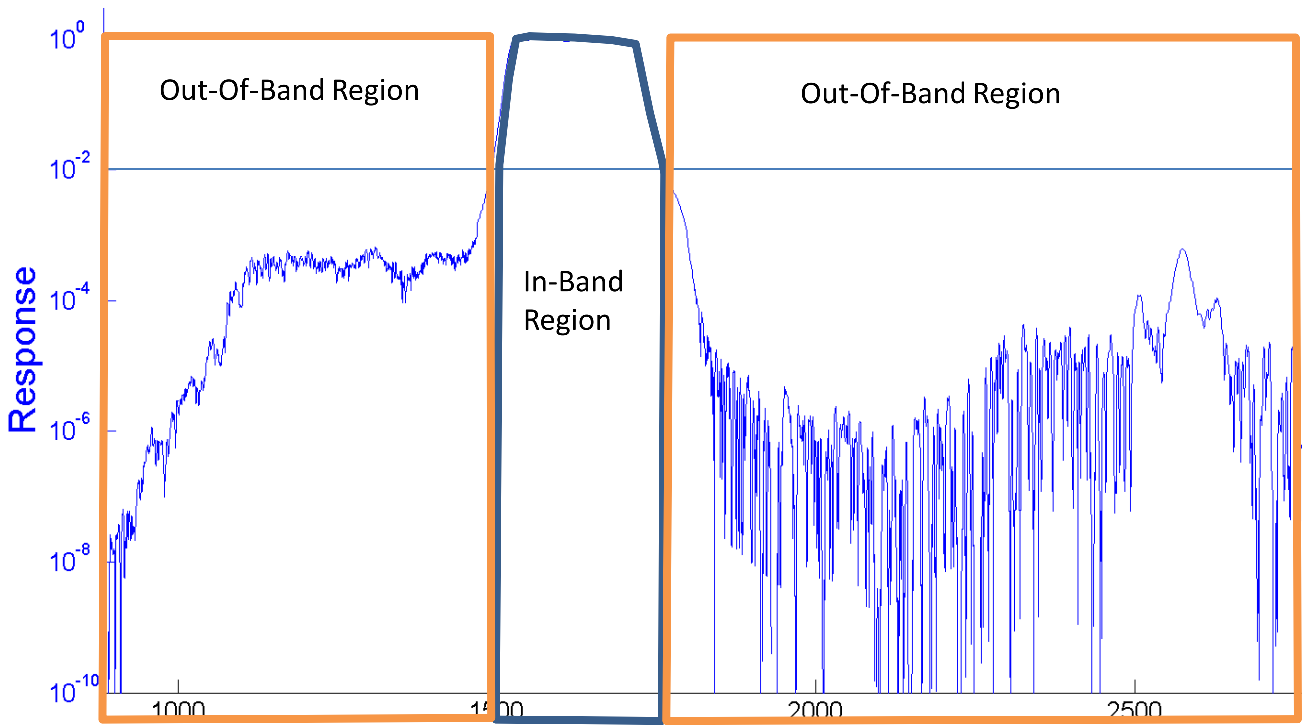
Uncertainty in Wavenumber (cm^{-1})

	Channel 7	Channels 8-9	Channels 10-12	Channels 13-16
Instrument Wavenum-ber Error	0.03	0.02	0.01	0.01
Temperature	0.06	0.04	0.03	0.02
Angle of Incidence	0.4	0.3	0.2	0.15
Focusing Geometry	0.7	0.5	0.35	0.25
Nonlinearity	0.02	0.02	0.02	0.02
Self-emission	0.00	0.00	0.01	0.02
Quadrature Sum	*0.81*	*0.59*	*0.40*	*0.29*
Expanded Uncertainty	**1.6**	**1.2**	**0.8**	**0.6**

Courtesy of S. Kaplan

Spectral Response Functions In-Band/Out-Of-Band

- Out-of-Band spectral response is defined as the spectral response outside the 1% of peak response points (W. Chen Appl. Optics 2012)
- In this work, in-band is defined by the SRF range on the public version.



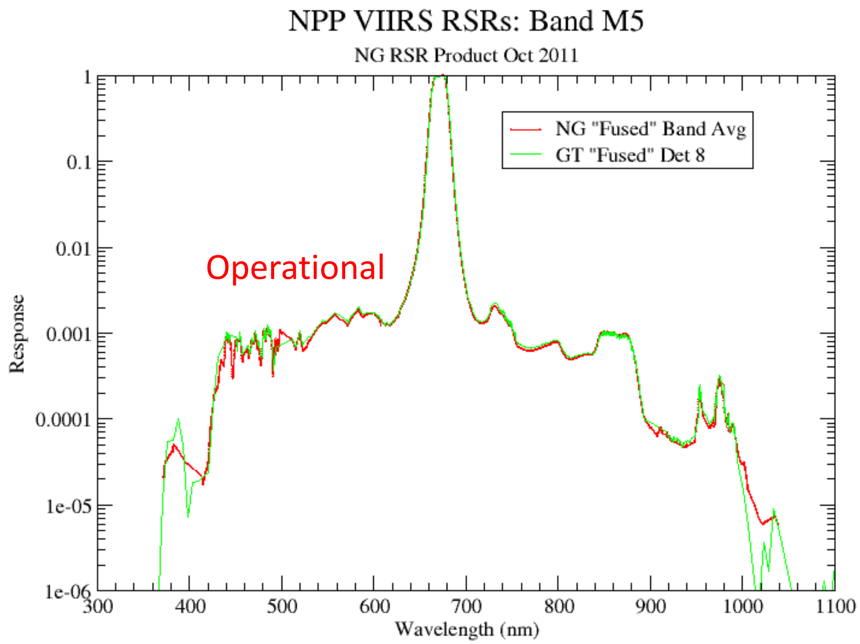
Legacy Issues
Out-of Band Spectral Response

- Sea-Viewing Wide-Field-of-View Sensor (SeaWiFS) :
  - » Corrections applied for out-of-band response.

Gordon *Applied Optics* (1995)
Wang et al. *Applied Optics* (2001)

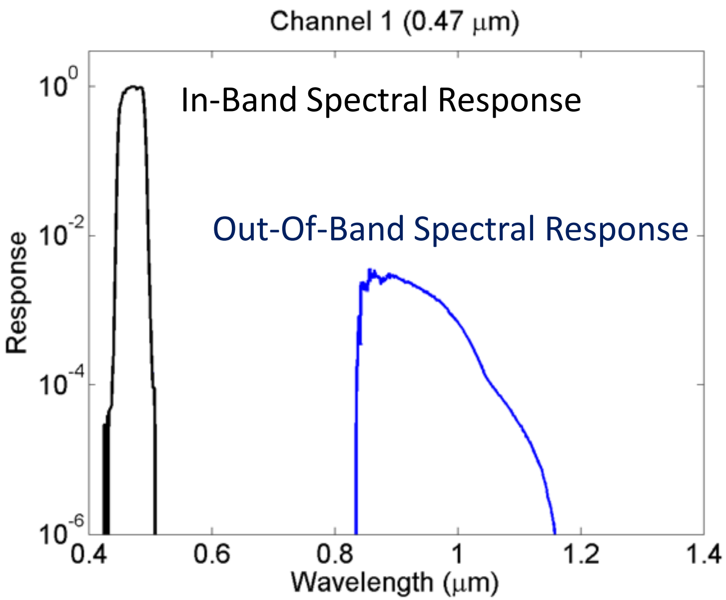
- Visible Infrared Imaging Radiometer Suite (VIIRS) on Suomi NPP:
  - » In-band and Out-of-band response thoroughly characterized pre-launch.
  - » NOAA uses out-of-band response operationally.

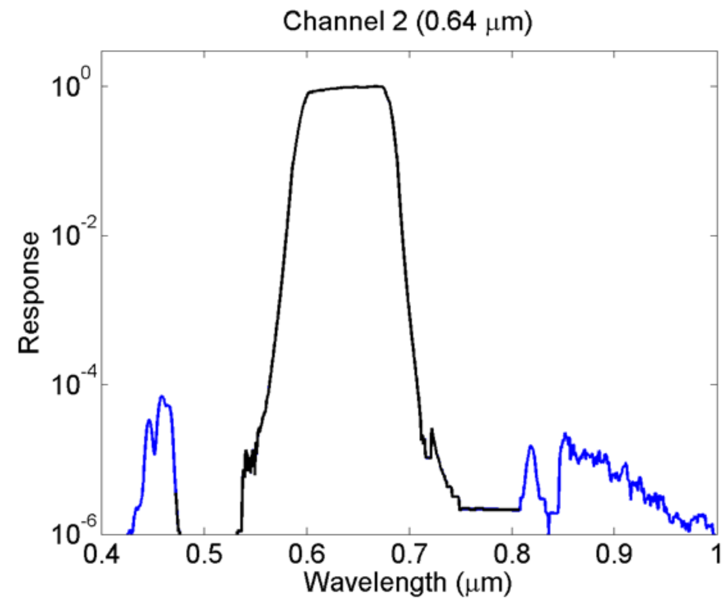
Moeller et al. *SPIE* (2012)

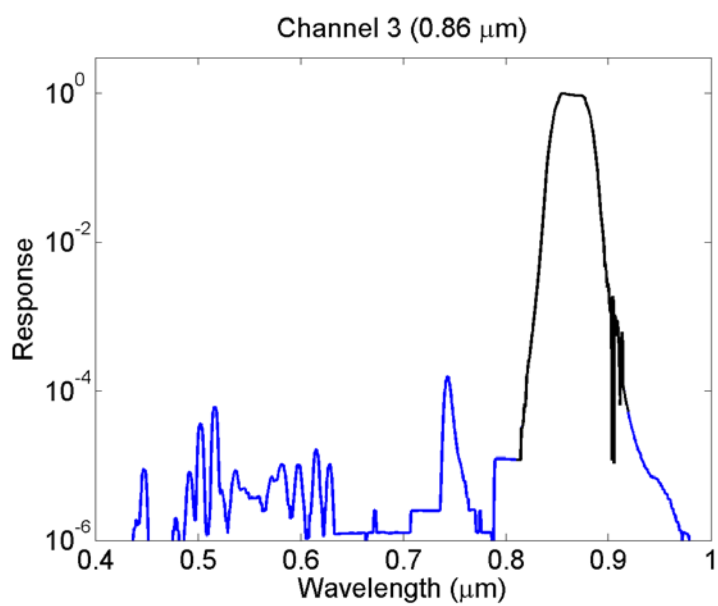


Increased need to study out-of-response is evaluated for ABI, since it will have increased performance over currently operational geostationary imagers

ABI Spectral Response Functions Reflective Solar Bands (1 of 2)

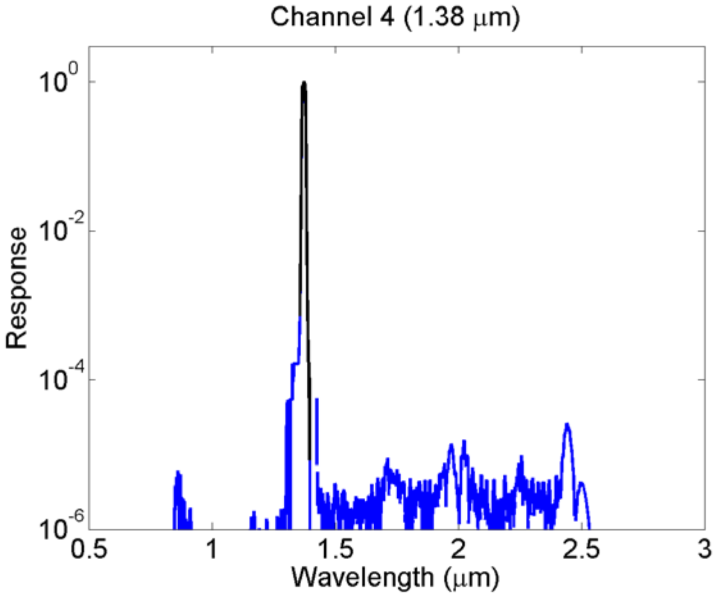


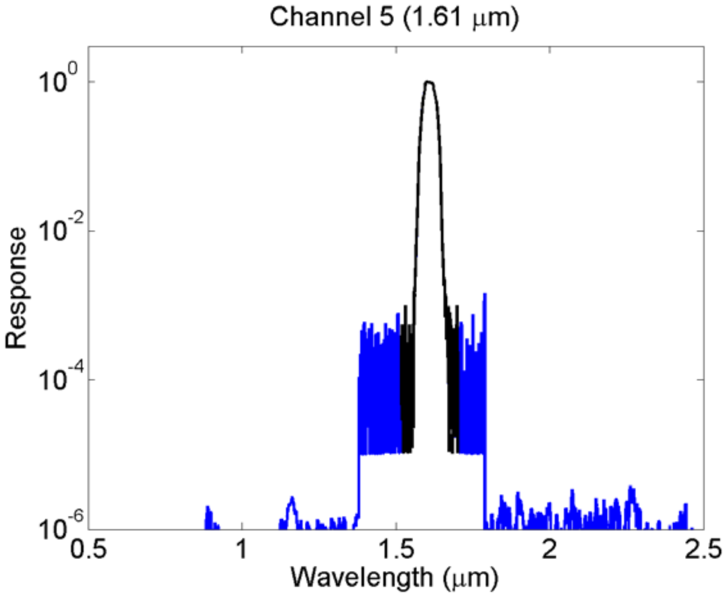


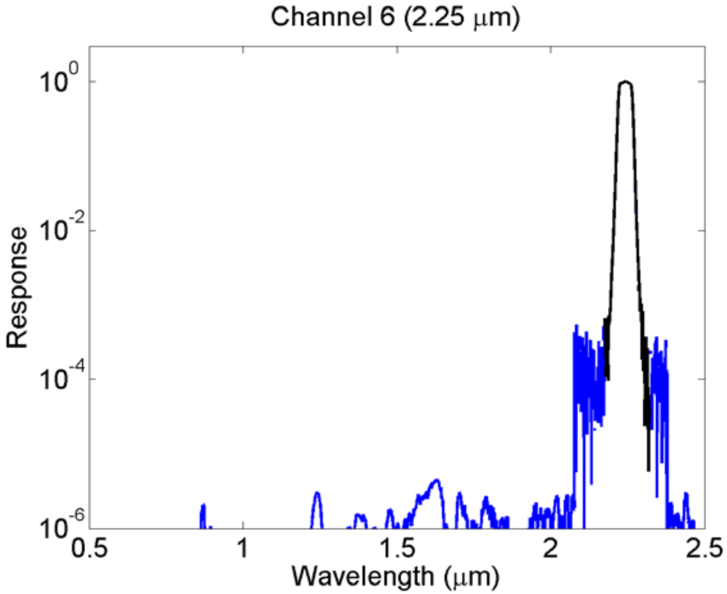


Responses $<10^{-6}$ have negligible impact

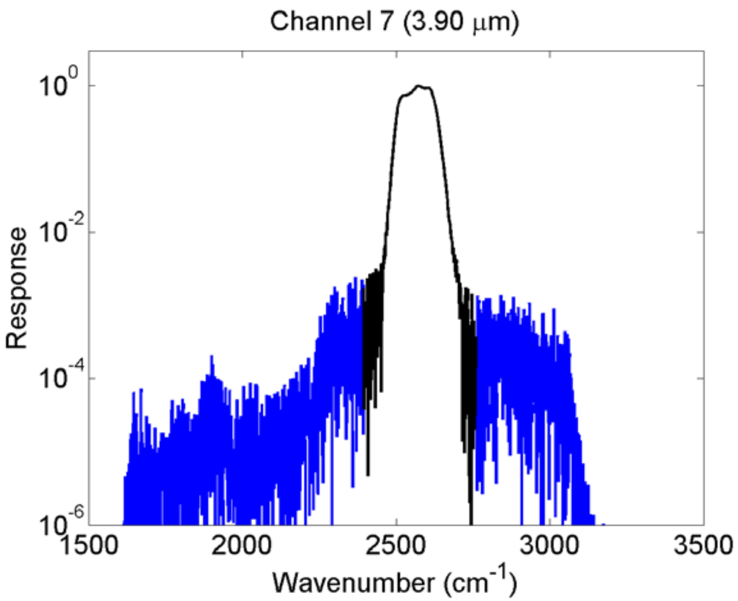
ABI Spectral Response Functions Reflective Solar Bands (2 of 2)

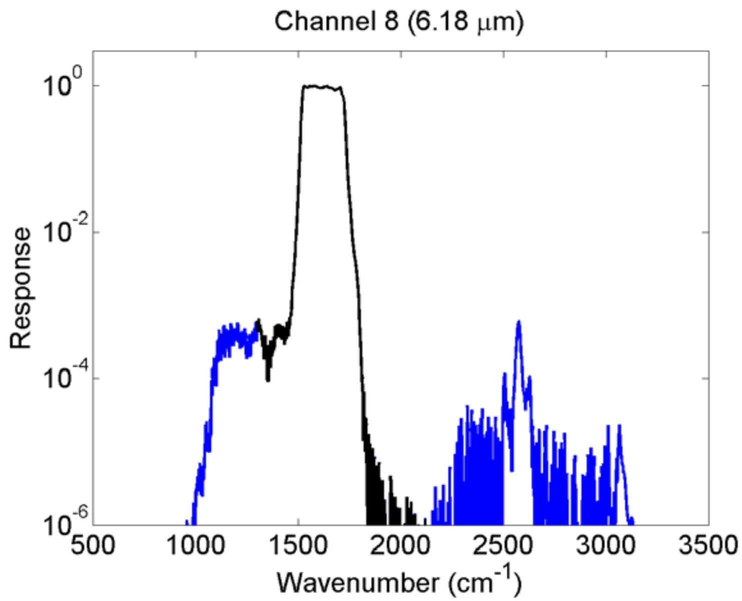


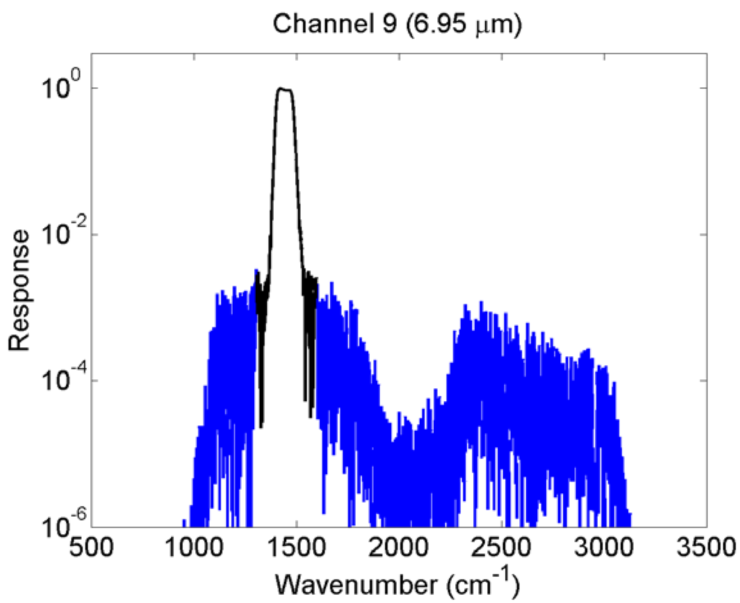




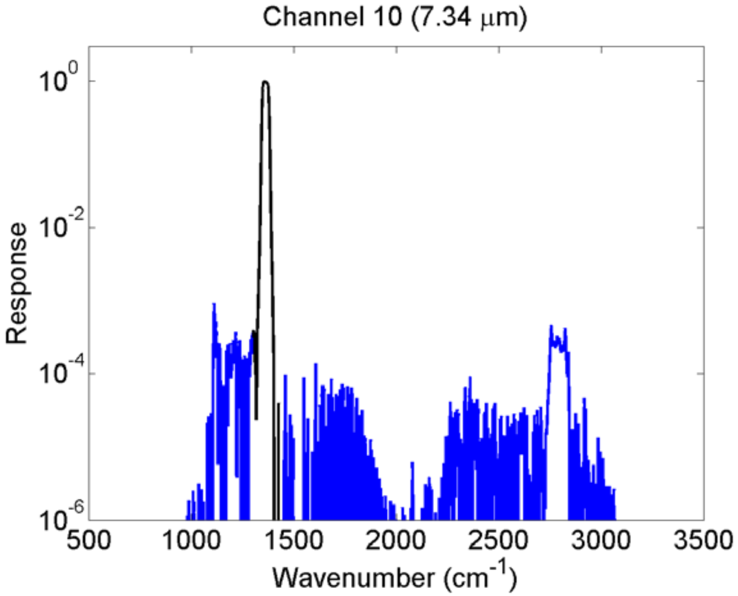
ABI Spectral Response Functions Thermal Emissive Bands (1 of 3)

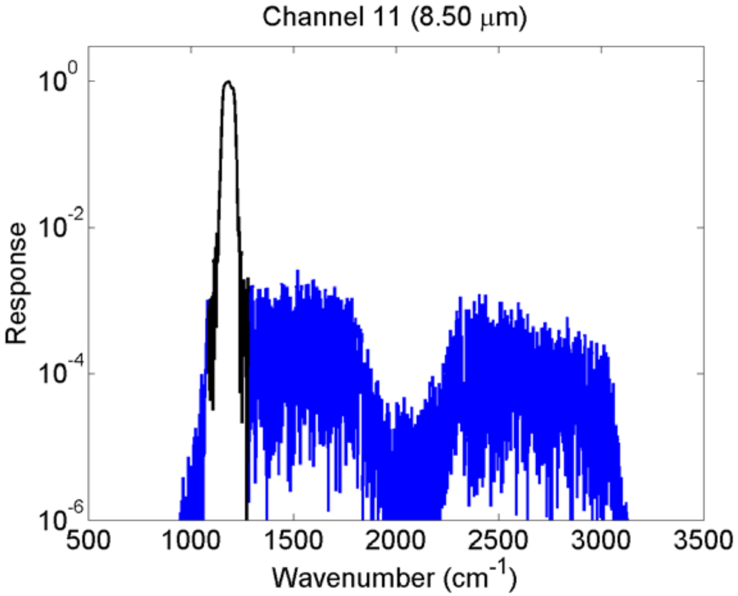


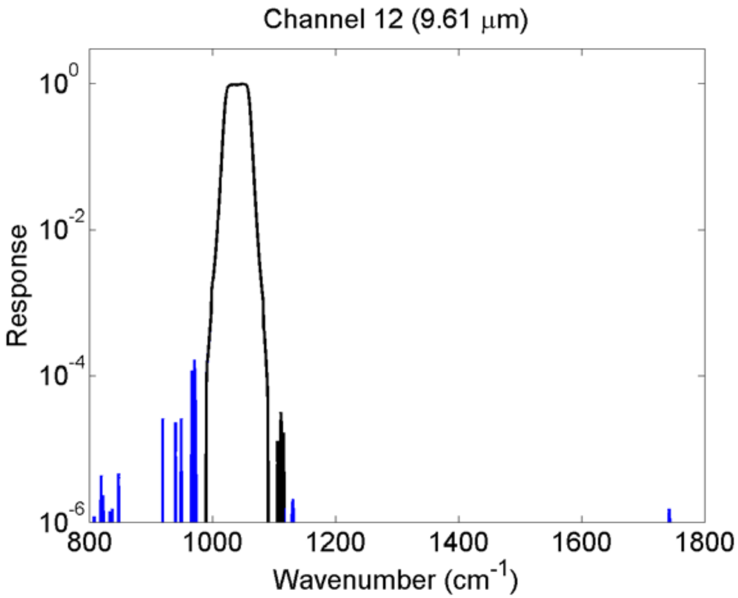




ABI Spectral Response Functions Thermal Emissive Bands (2 of 3)

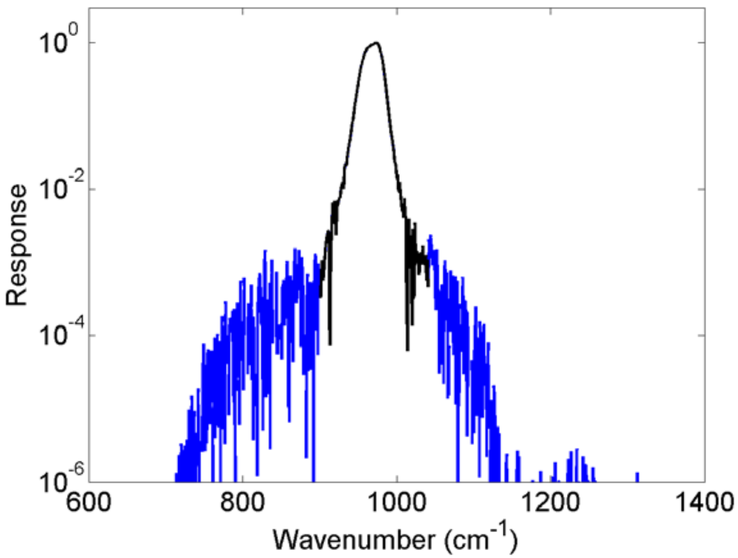




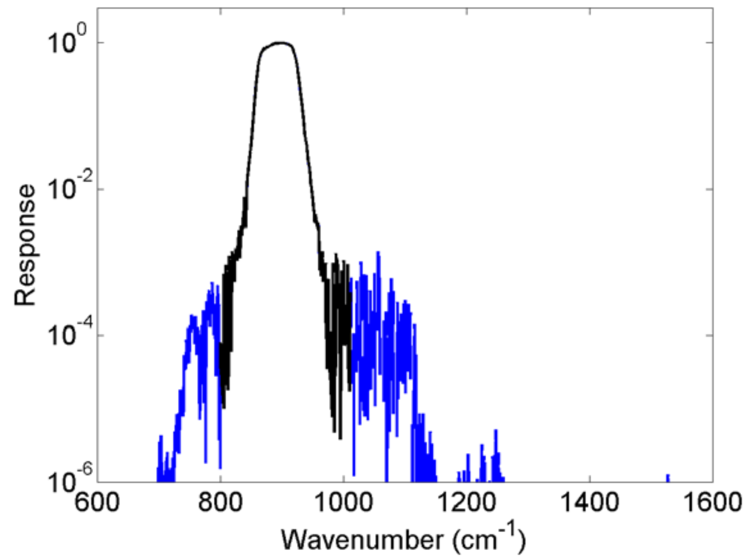


ABI Spectral Response Functions Thermal Emissive Bands (3 of 3)

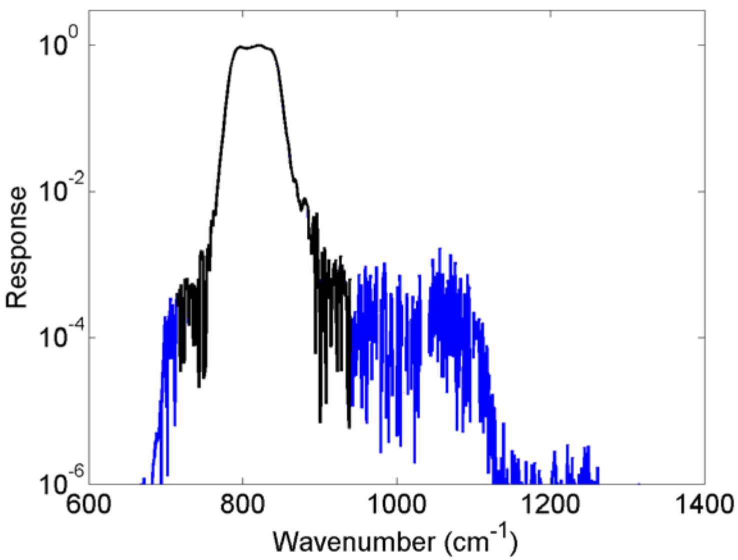
Channel 13 (10.35 μm)



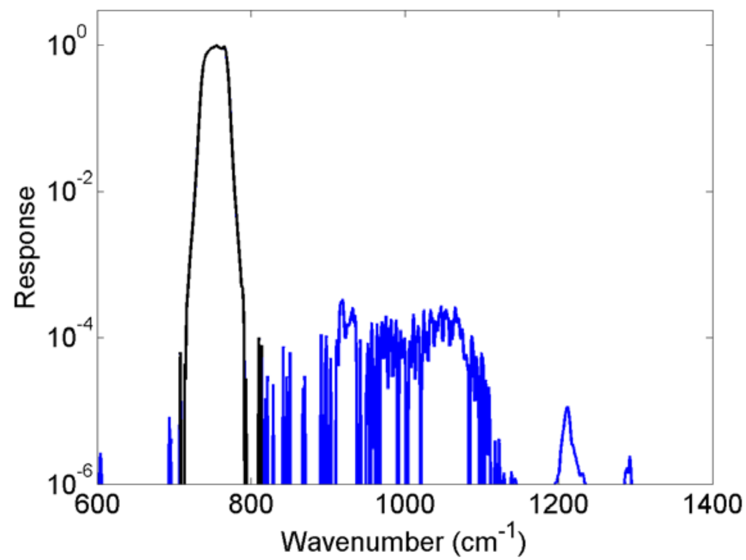
Channel 14 (11.20 μm)



Channel 15 (12.30 μm)



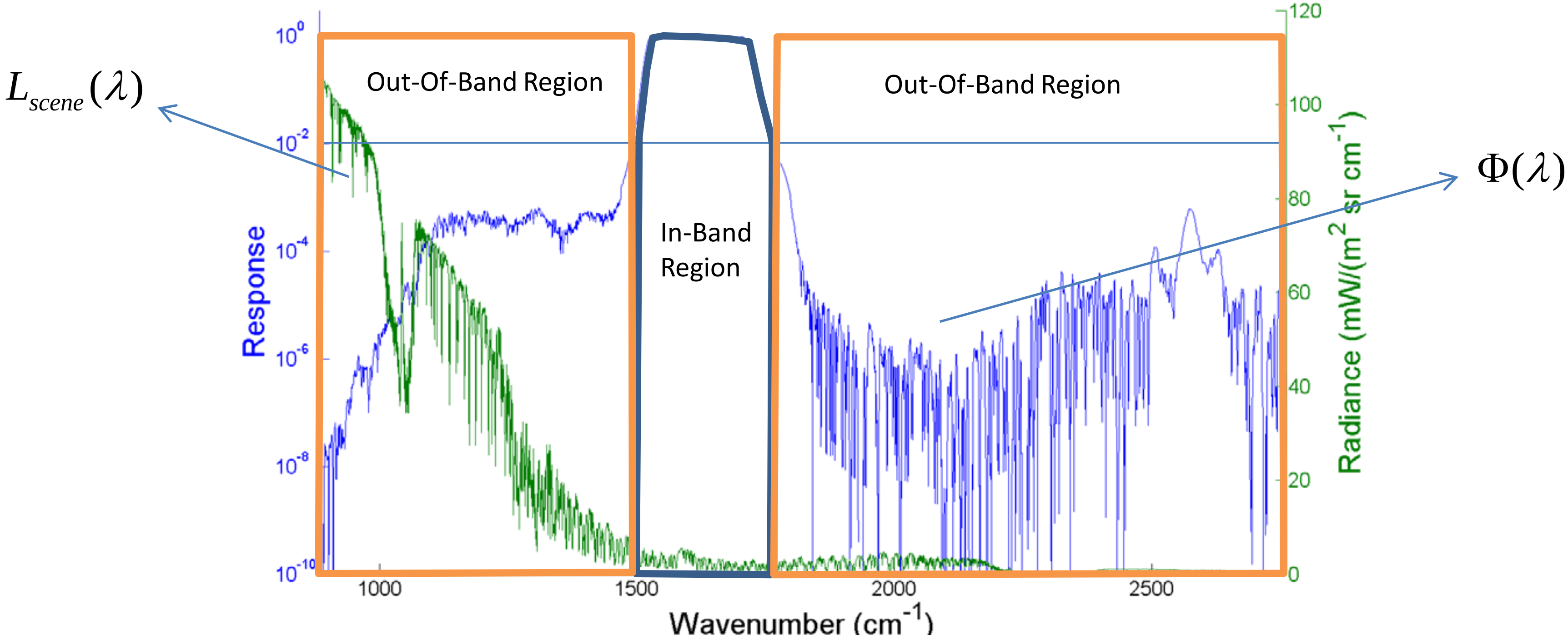
Channel 16 (13.30 μm)



Spectral Response Functions Out-of-Band Effects

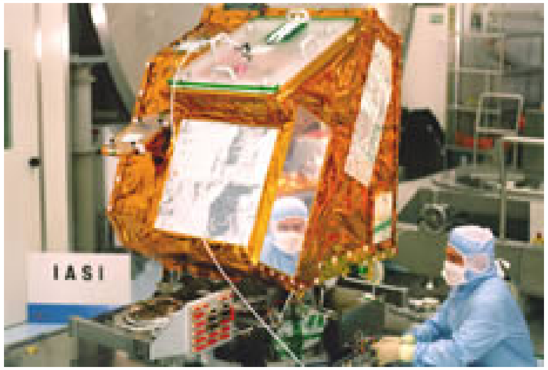
- Calculate effective spectral radiance (L_{eff}) for the desired region
- For out-of-band effects, calculate % difference in spectral radiance (or temperature for thermal emissive channel) between in-band and full spectrum (in-band + out-of-band)

$$L_{eff} = \frac{\int L_{scene}(\lambda)\,\Phi(\lambda)\,d\lambda}{\int \Phi(\lambda)\,d\lambda}$$



Typical Scenes

- Reflective solar bands:
  - » Hyperspectral data from Hyperion aboard EO-1.
  - » Simulated data using both 6SV (Second Simulation of a Satellite Signal in the Solar Spectrum, Vector, version 1) and MODTRAN
- Thermal emissive bands:
  - » Hyperspectral data from IASI (Infrared Atmospheric Sounding Interferometer) aboard METOP



IASI

Hyperspectral Sounder	
Spectral Region	645-2760 cm^{-1}
Spectral Sampling	0.25 cm^{-1} (8460 bands)
Spatial Resolution	~12 km

Hyperion

Hyperspectral Imager	
Spectral Region	0.4-2.5 µm
Number of Bands	220
Spatial Resolution	2 km

GOES-R Advanced Baseline Imager

- For solar reflective bands, match scenes to relevant channels

TABLE 1. Summary of the wavelengths, resolution, and sample use and heritage instrument(s) of the ABI bands. The minimum and maximum wavelength range represent the full width at half maximum (FWHM or 50%) points. [The Instantaneous Geometric Field Of View (IGFOV).]

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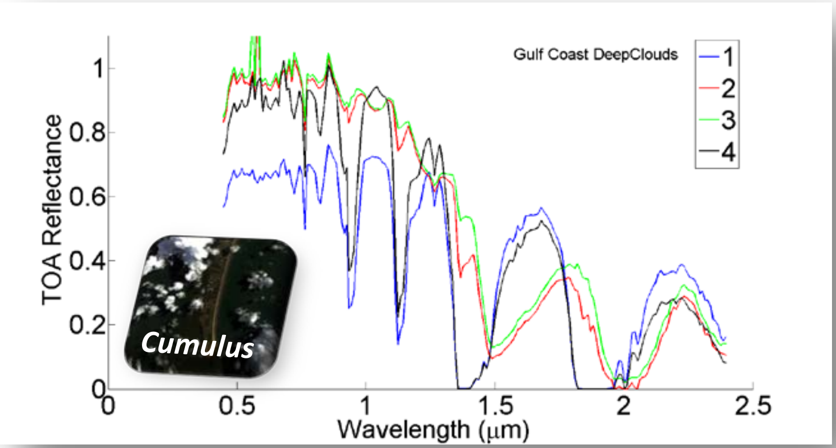
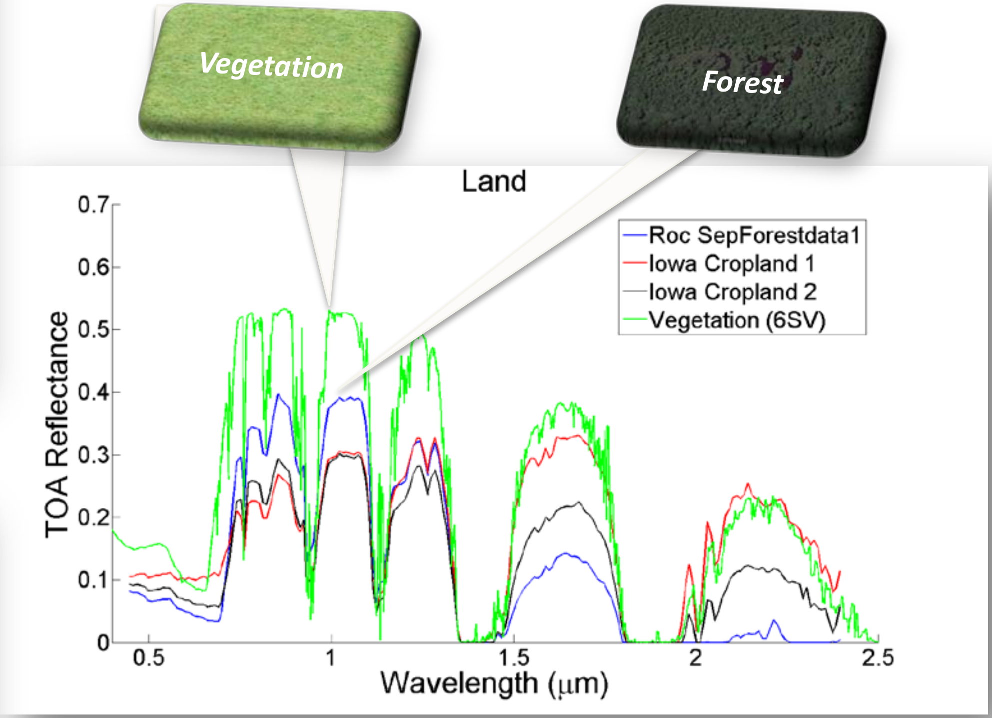
Land	3	0.846–0.885	0.865	1	Daytime vegetation/burn scar and aerosol over water, winds	VIIRS, spectrally modified AVHRR
Cirrus Clouds	4	1.371–1.386	1.378	2	Daytime cirrus cloud	VIIRS, MODIS
Clouds	5	1.58–1.64	1.61	1	Daytime cloud-top phase and particle size, snow	VIIRS, spectrally modified AVHRR
Clouds	6	2.225–2.275	2.25	2	Daytime land/cloud properties, particle size, vegetation, snow	VIIRS, similar to MODIS

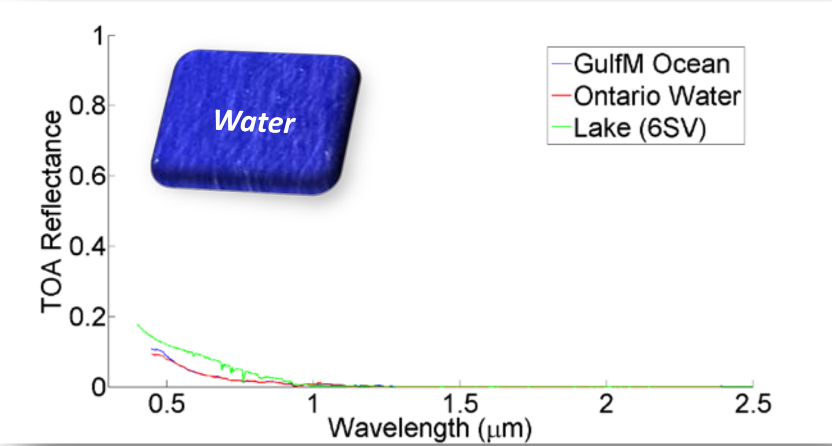
- For thermal emissive bands, used all scenes for all channels

Typical Scenes
Reflective Solar Bands

- Hyperion and simulated scenes cover major categories of scenes relevant to ABI

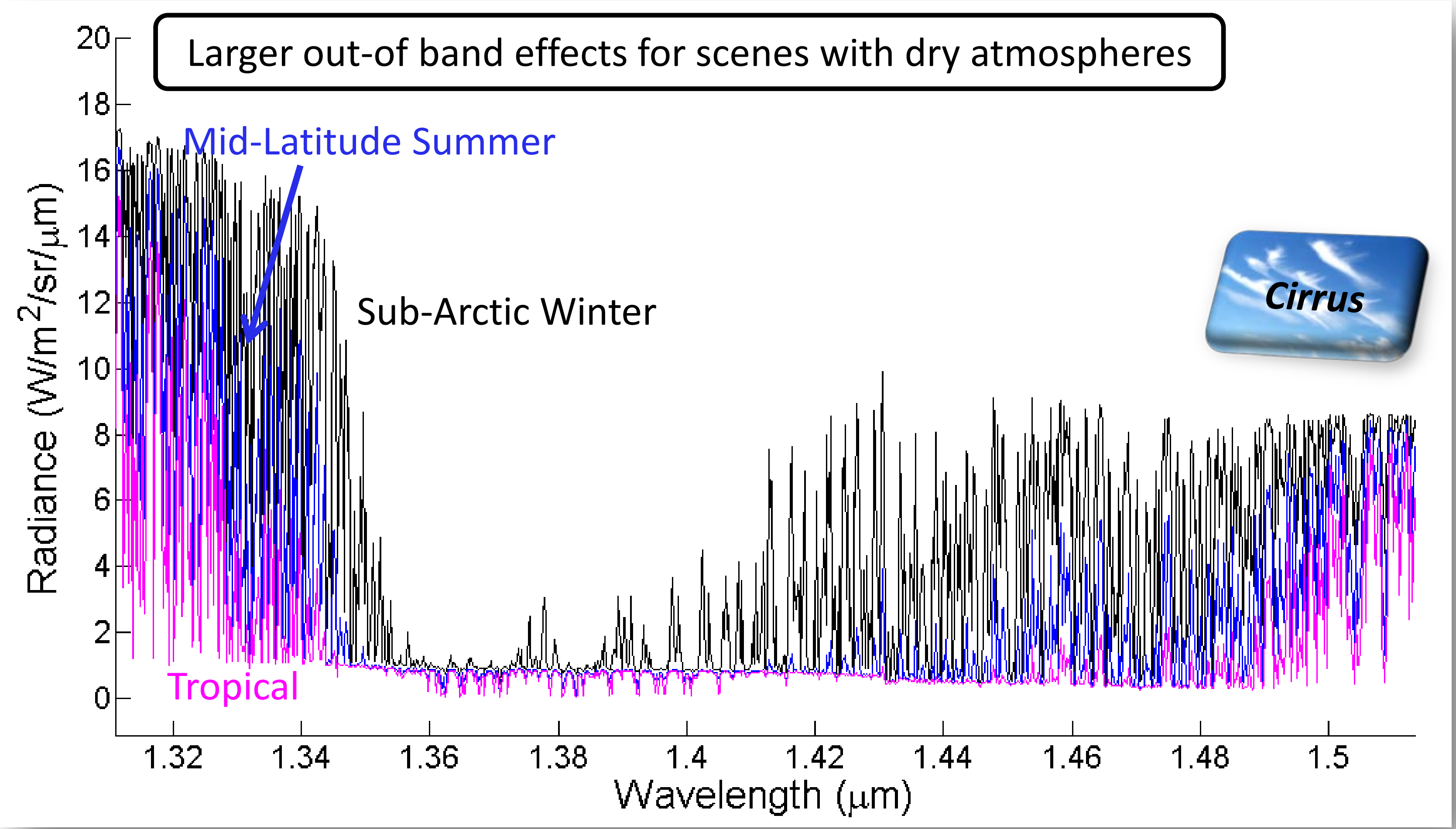






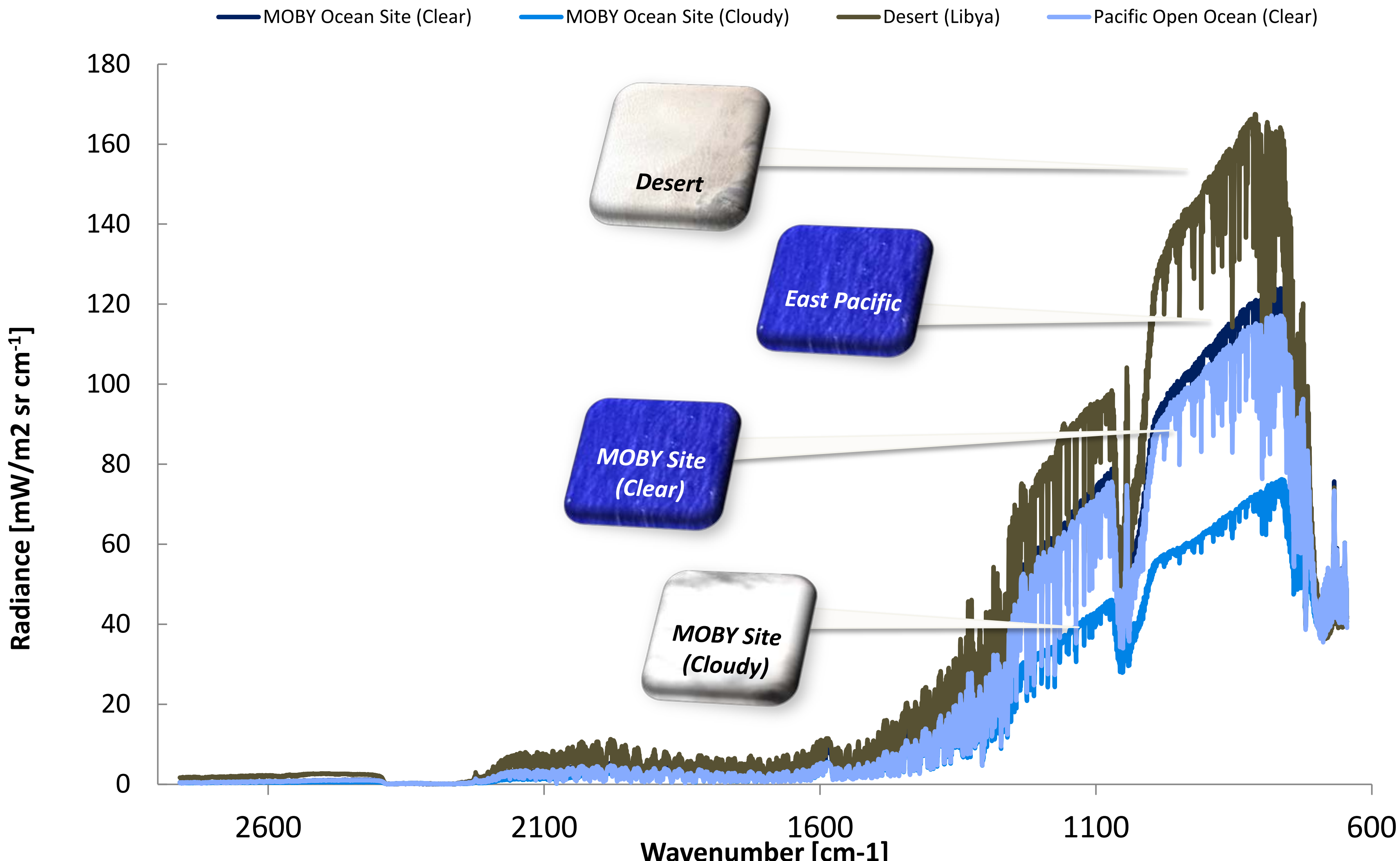
Typical Scenes
Cirrus Cloud Scenes for Channel 4

- Simulated scenes using MODTRAN used for high resolution spectra needed for channel 4 (1.38 µm cirrus detection channel)



2 km cloud thickness, 8 km base altitude

Typical Scenes
Thermal Emissive Bands



Padula et al. AMS 2014

Out-of-Band Effects
Reflective Solar Bands (except channel 4)

- Minor impacts found for cloud and land scenes

		Gulf Coast Deep Clouds			
Channels	**Wavelength (µm)**	**1**	**2**	**3**	**4**
2	0.64	0.00	0.00	0.00	0.00
5	1.61	0.04	0.05	0.05	0.04
6	2.25	0.01	0.01	0.01	0.02

% Difference in Radiance

		Land		
Channels	**Wavelength (µm)**	**Rochester - forest**	**Iowa Cropland #1**	**Vegetation (simulated)**
3	0.86	0.00	0.00	0.00

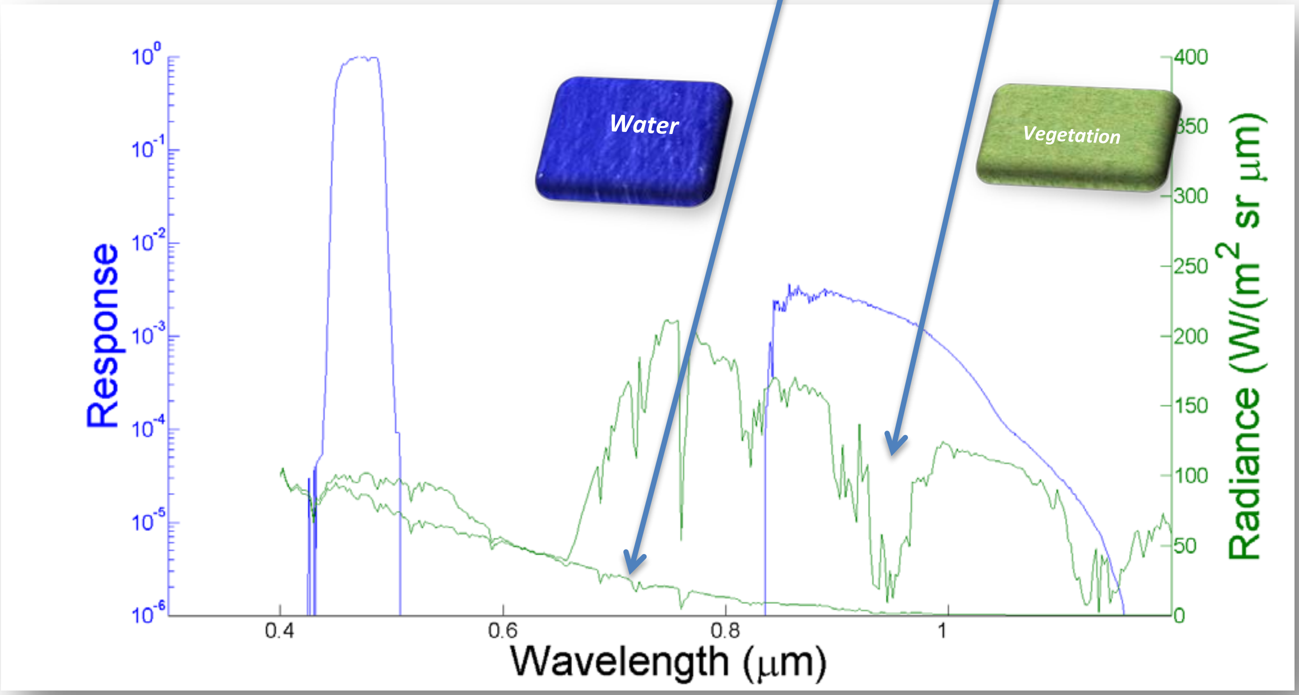
% Difference in Radiance

Out-of-Band Effects
Reflective Solar Bands

- Highest out-of-band effects found for water scenes in 0.47 µm channel
- Out of-band impacts for land scenes were lower than for water scenes

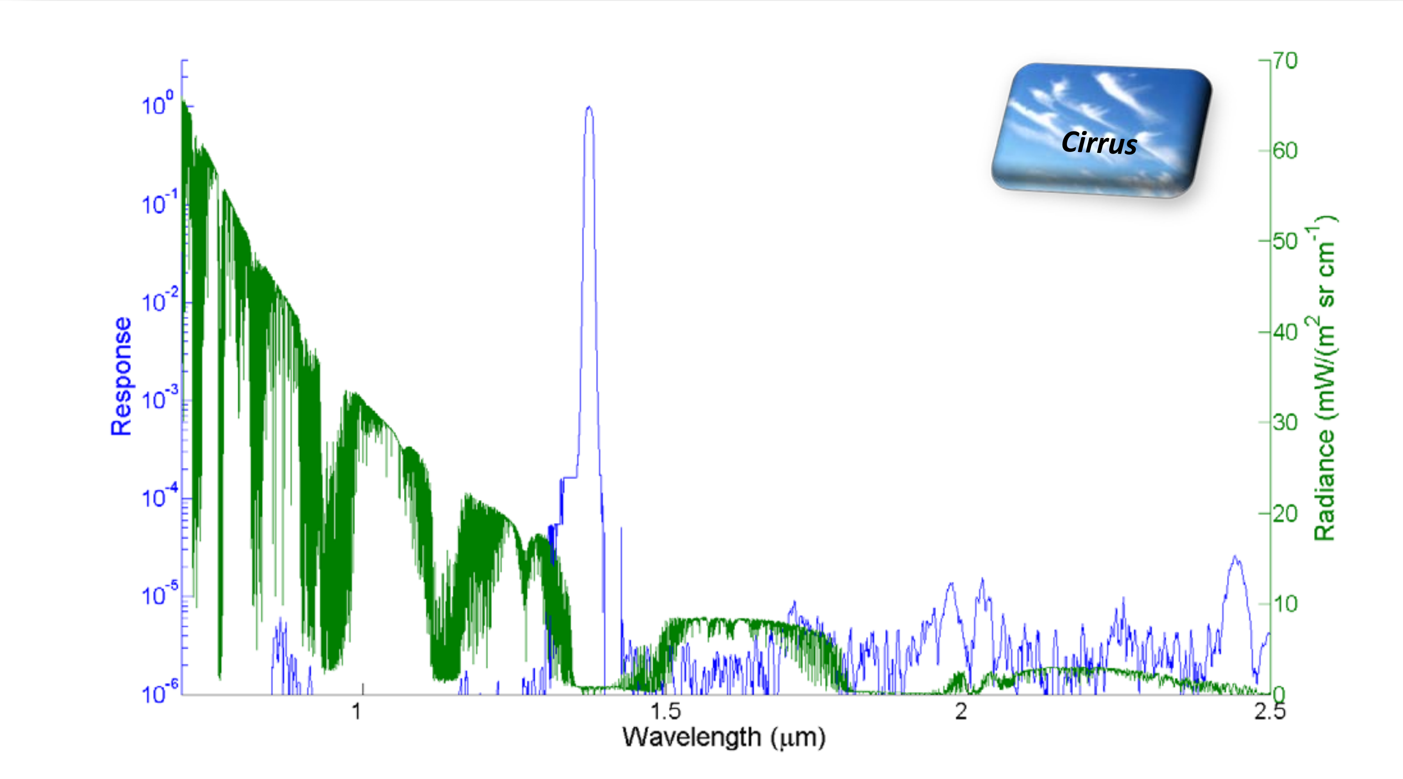
Channel	Wavelength (µm)	Water			Vegetation (simulated)
		Gulf of Mexico - Ocean	Lake Ontario	Lake (simulated)	
1	0.47	-0.89	-0.89	-0.89	0.14

% Difference in Radiance



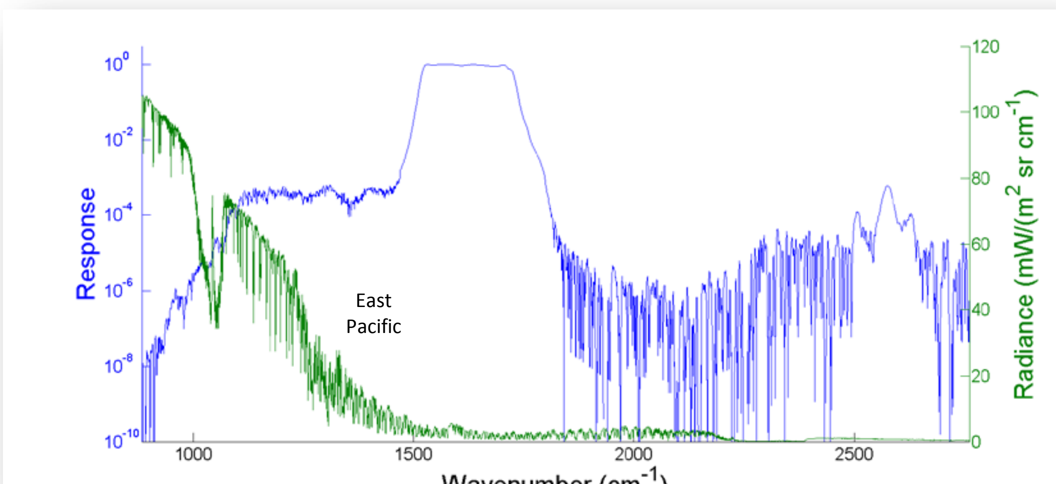
Out-of-Band Effects
Channel 4 (1.38 µm)

	Mid-Latitude Summer	Sub-Arctic Winter	Tropical
In-band SRF Radiance (W/m²/sr/µm)	0.765	1.10	0.672
Full SRF Radiance (W/m²/sr/µm)	0.773	1.11	0.675
% Difference in Radiance	0.43	0.44	0.43



Out-Of-Band Effects: Thermal Emissive Bands Percent Difference in Radiance

		Scenes			
Channel	Wavelength (µm)	Libya	East Pacific	Moby clear Sky	Moby cloudy
7	3.9	-0.02	-0.01	0.00	0.00
8	6.18	0.41	0.63	0.37	0.38
9	6.95	0.22	0.32	0.19	0.18
10	7.34	0.16	0.21	0.13	0.11
11	8.5	-0.17	-0.18	-0.17	-0.17
12	9.61	0.00	0.00	0.00	0.00
13	10.35	-0.02	-0.01	-0.01	-0.01
14	11.2	0.00	0.00	0.00	0.01
15	12.3	-0.01	-0.01	-0.01	-0.01
16	13.3	-0.01	-0.02	-0.02	-0.02



- 6.18 µm channel shows largest out-of-band effects

Out-Of-Band Effects: Thermal Emissive Bands Difference in Temperature

Temperature Difference (K) at Scene Temperature

		Scenes			
Channel	**Wavelength µm)**	**Libya**	**East Pacific**	**Moby clear Sky**	**Moby cloudy**
7	3.90	-0.01	-0.01	-0.01	-0.01
8	6.18	0.11	0.14	0.09	0.09
9	6.95	0.08	0.10	0.06	0.05
10	7.34	0.09	0.10	0.08	0.07
11	8.50	0.07	0.08	0.08	0.09
12	9.61	0.00	0.00	0.00	0.00
13	10.35	-0.02	-0.01	-0.01	-0.01
14	11.20	0.00	0.00	0.00	0.00
15	12.30	0.00	0.00	0.00	0.00
16	13.30	0.01	0.01	0.00	0.01

- % Difference in radiance converted to brightness temperature difference using the Planck function.
- ➢ Impacts at most ~140 mK for eastern Pacific ocean scene (at scene temperature)

Conclusions

- Overall, ABI has strong performance:
  - High out-of-band rejection in all channels (< 1% impact)
  - Highest impacts found for channel 1 (0.47 μm) lake scene – 0.9%
- ABI is expected to meet user needs for weather prediction:
  - Pre-launch characterization of ABI's spectral response plays a key role in understanding its performance.
- Out of band response impacts can be mitigated by using spectral response functions operationally that include both in-band and out-of-band regions.
- Future Work:
  - Work to make full spectral response functions available publicly
  - Consult users about appropriate choice for operational spectral response functions
  - Analyze uncertainty impacts