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Standardization in hyperspectral imaging:
The IEEE P4001 working group, and some examples of ongoing work

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"P4001 - Standard for Characterization and Calibration of Ultraviolet through Shortwave Infrared (250 nm to 2500 nm) Hyperspectral Imaging Devices"

"The standard defines terminology, device classes, laboratory tests, characterization and calibration methodologies, and recommended practices for application-specific tasks. Initial work is limited to devices that cover the the 0.25-2.50um spectral region."

- Sponsored by IEEE Geoscience and Remote Sensing Society / Standards Committee
- Started a 4-year working term in May 2018

Why do we need a standard?

- No formal standards addressing hyperspectral imaging specifically
- Hyperspectral imaging is a fast growing market
- Existing standards for imaging not always applicable or sufficient for hyperspectral
- Specifications given for commercial cameras are surprisingly inadequate today
- Technical peculiarities of hyperspectral:
  - hyperspectral imaging emphasizes spectroscopy in each pixel
  - pushbroom imaging geometries widely used (and emphasized in P4001)

Work in the P4001 group

- Over 50 members from industry, user communities, research, and academia
  (Voting membership establilshed simply by attending two consecutive meetings.)
- Standard will be formalized by voting by the full group
- Voting right established by attending 2 consecutive meetings
- Most meetings held by teleconference. Also physical meetings at relevant conferences, with online participation option.
- Work currently divided into 3 subgroups:
  - C1 - characterization and specification of cameras
  - D1 - data formats
  - T1 - terminology
- About 2 meetings per month, including subgroup meetings

Examples of issues addressed

- How do we define and characterize spatial and spectral resolution?
- How do we specify radiometric accuracy and noise?
- How do we define and characterize coregistration?
- What do we mean by "hyperspectral"?
- How should hyperspectral images be stored? What metadata are needed?

How do we characterize a hyperspectral camera??

Spectral Performance

- spectral range (usable)
- spectral resolution (acceptance angle of a pixel; not FOV divided by number of pixels)
- spectral sampling interval (SSI) (distance of center wavelengths)
- spectral sampling ratio (resolution divided by SSI)
- spectral misregistration (Smile, in pixel and spectral units)
- SRF uniformity (How stable is a SRF within a band)
- spectral calibration accuracy and stability

Geometric Performance

- field of view (along- and cross-track)
- angular resolution (along- and cross-track; acceptance angle of a pixel; Not FOV divided by number of pixels)
- angular sampling interval (ASI) (distance of center angles)
- angular sampling ratio (resolution divided by ASI; measure for sharpness)
- geometric misregistration (Keystone, in pixel and angle units)
- angular response function (ARF) uniformity (How stable is a SRF within a geometric pixel)
- focus range / working distance
- geometric calibration accuracy and stability
- location of each pixel on the scene (precision, stability)

Radiometric Performance

- noise / SNR / NESR (signal dependent)
- read noise
- SNR vs. spectral radiance at specified operating conditions, unbinned (not binned peak SNR!)
- Well depth
- dynamic range / resolution
- ADC characteristics (bit depth, gain (DN/e-))
- sensitivity
  - wavelength and angle dependent (vignetting)
  - F/#
- polarization sensitivity
- non-linearity
- Detector QE/spectral response
- pixel pitch
- dark current
- operability?
- uniformity (DSNU?, PRNU)
- radiometric calibration accuracy and stability
- dynamic range and noise performance on a standard light source

How do we characterize a hyperspectral camera??

Stray light

From our experience, stray light is usually not separable in spectral and geometric components.

However, we distinguish between two kinds of stray light:

- diffuse stray light

  In general, the far tail, low frequency component of pixel response functions or PSFs which can distinguished in

  - in-band diffuse stray light (correctable to a certain extent)
  - out-of-band diffuse stray light (not correctable)

- ghosts

  In general, high frequency component in the tails of a pixel response functions or PSFs.

  - in-band ghosts (correctable)
  - out-of-band ghosts (not correctable)

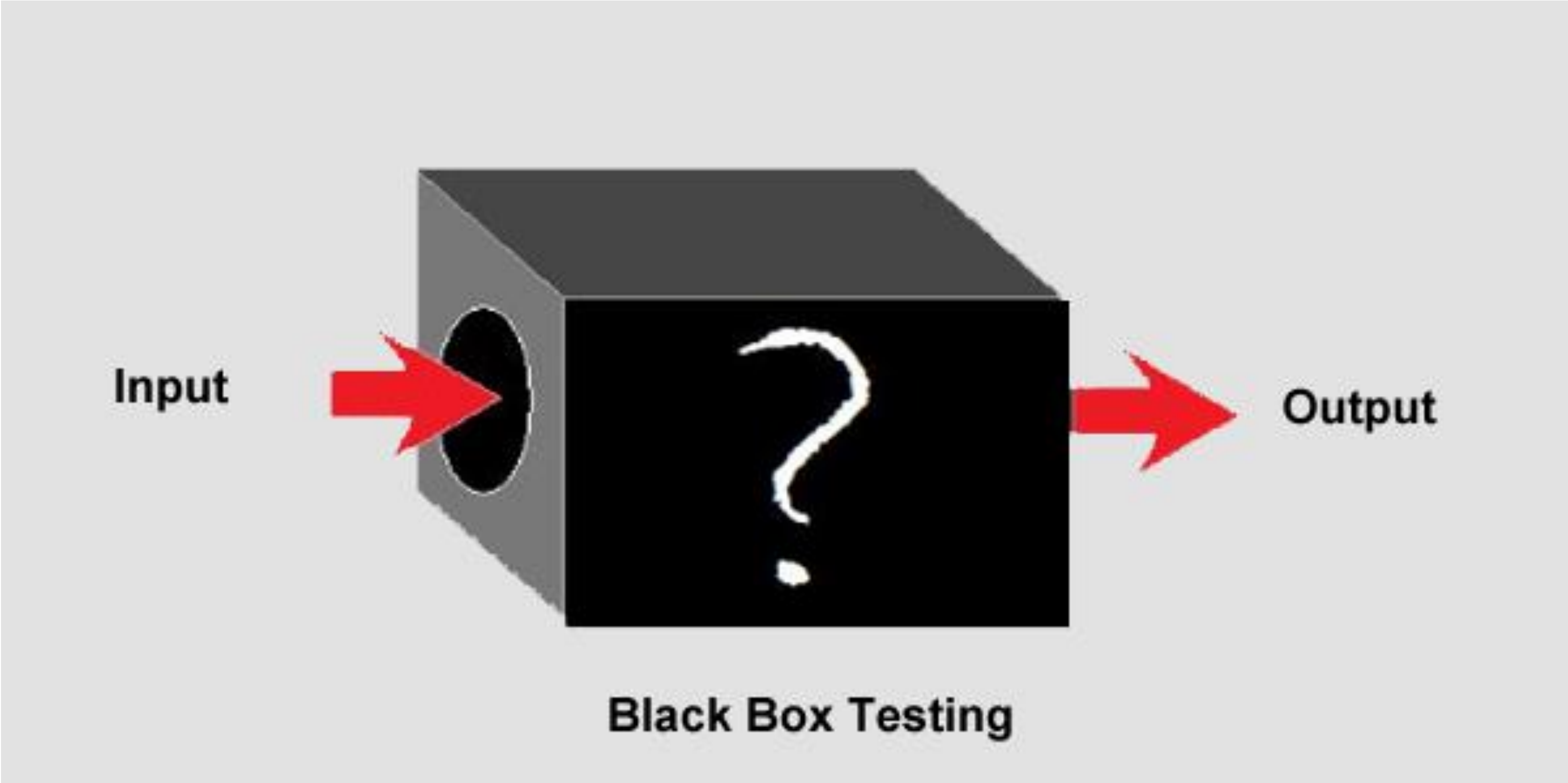
Other

- min / max frame rate / readout rate / data rate
- min / max integrating time
- dead time?
- instrument stability
- focal length
- number of pixels (spectral and spatial) (usable)
- detector stabilized (yes / no, temperature, stability)
- number of bad pixels
- Fill-factor (spatial and temporal)

Physical Specs

- instrument dimensions, instrument mass, power consumption (V, A or W, peak, nominal) of system (including computer and cables if separate)
- valid range of temperature, humidity, (pressure?) (storage and operation)
- instrument stability (maybe hardest to measure and specify)
- computer interface (USB, CameraLink, GigE, standalone; remote control?)
- MTBF
- lens mount (if appropriate)
- mechanical interface (mounting)

Tentative Characterization approach: “Black Box” testing

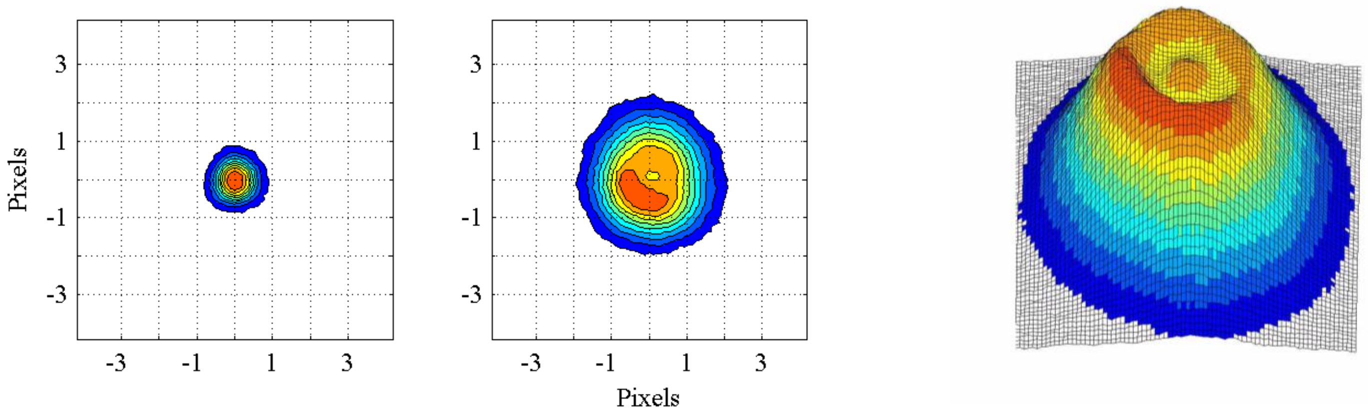


- Avoids the need to specify inner quantities such as f-number or pixel pitch
- Enables verification of specifications by independent testing

Characteristic for spatial resolution

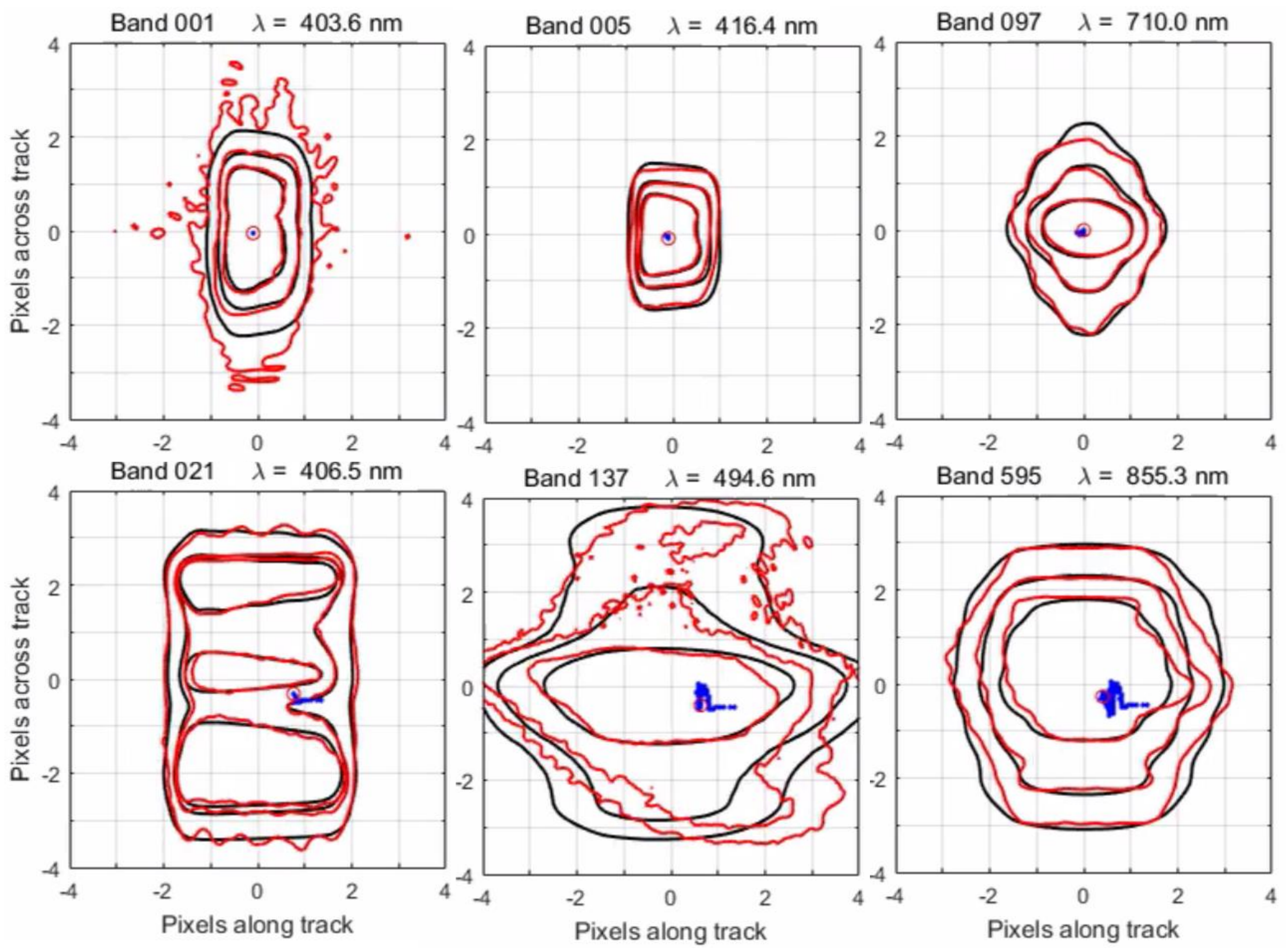
- Current consensus for specifying spatial resolution:
  - nominal pixel sampling distance
  - fraction of spatial point spread function within nominal pixel area

- Now, how to define and measure point spread function?

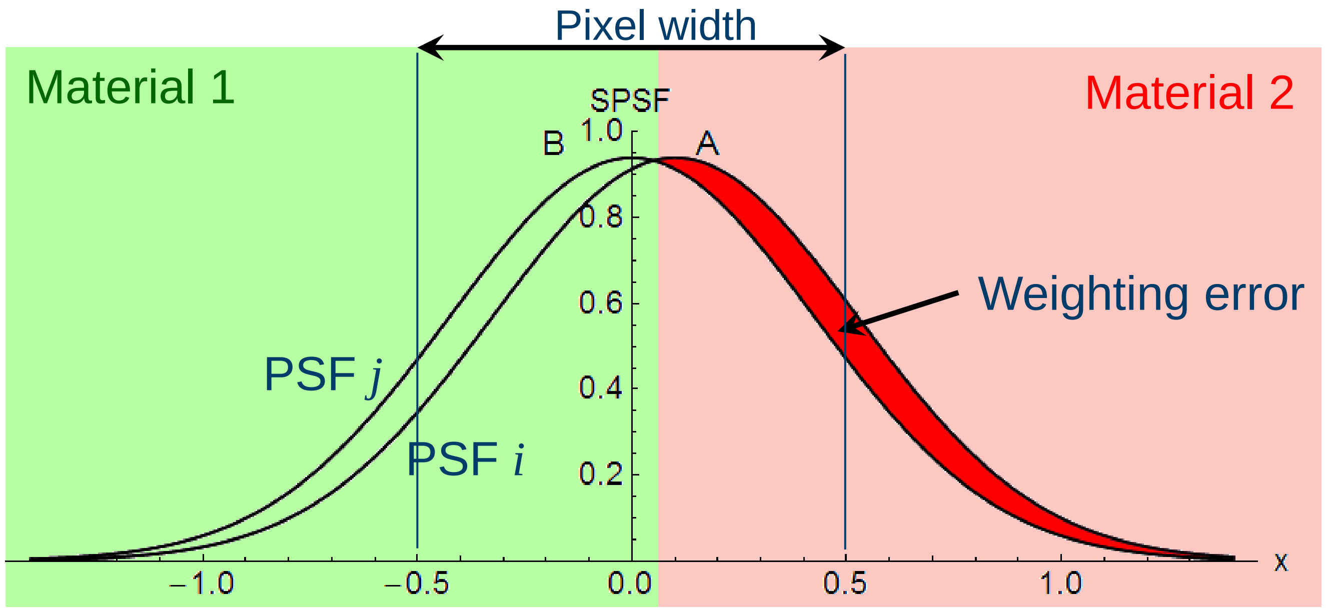


Simplified PSF measurement: example results

- Measured PSF for two pushbroom hyperspectral cameras
- Contours for 50, 75 and 90% enclosed energy
- Red: full 2D PSF reconstructed from 48 scans
- Black: separable PSF from 2 scans, x and y directions
- Good PSF accuracy obtained from two orthogonal LSF scans



Characterizing spatial coregistration by volume between PSFs



PSFs for two bands, in a scene containing red and green materials

- Integrated difference between PSFs is a natural metric for coregistration error:

$$\varepsilon_{s,ij} \stackrel{def}{=} \frac{1}{2}\iint_{x,y} \left|\mathrm{PSF}_j(x,y) - \mathrm{PSF}_i(x,y)\right| dxdy = \Delta w_{\max}$$

- Generalizes "keystone" coregistration metric (when PSF height and width ≈1)
- Mathematical upper bound on spectral weighting error

Sharpness and misregistration specifications

Spatial across track

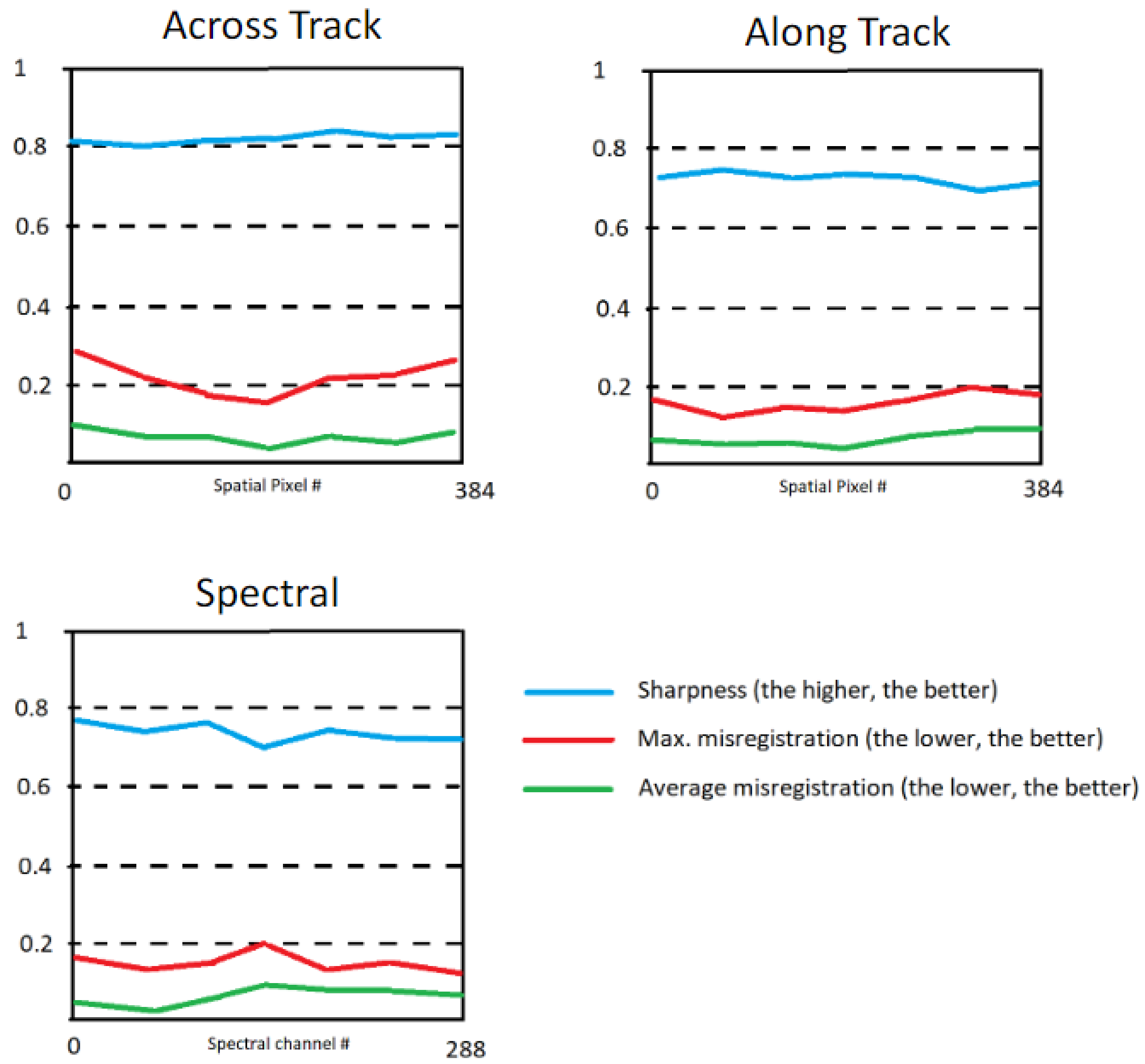
Sharpness	more than 0.8
Pixel count	384
Effective pixel count	312
Misregistration (max.)	less than 0.3
Misregistration (average)	less than 0.1

Spatial along track

Sharpness	more than 0.7
Misregistration (max.)	less than 0.2
Misregistration (average)	less than 0.1

Spectral

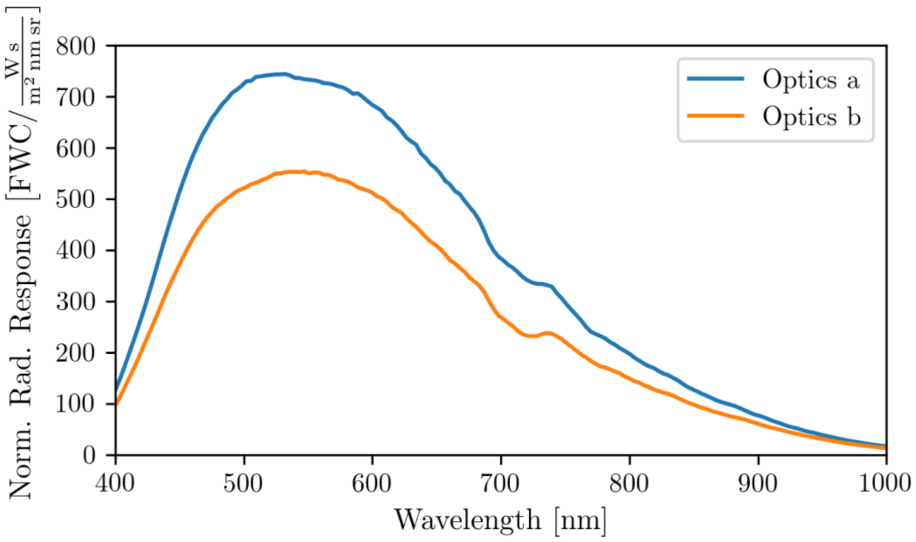
Sharpness	more than 0.7
Spectral channel count	288
Eff. spectral channel count	219
Misregistration (max.)	less than 0.2
Misregistration (average)	less than 0.1



SNR, Saturation and Radiometric Response

- "Peak SNR", used on many commercial camera specification sheets is meaningless
- Ongoing work: What is a necessary and sufficient set of characteristics for radiometric performance?
- Proposed concepts include
  - "Full well per spectral radiance exposure"?
  - Specify noise via photon transfer characteristic?
  - "Noise equivalent radiance dose" (NERD)?

$$K_{\mathrm{FWC},i} = \frac{S_i/S_{\mathrm{FWC}}}{L_i t}$$



$$NERD(\lambda, t_i) = \frac{\delta n(t_i)}{A_{\mathrm{det}}\Omega_{\mathrm{det}}T(\lambda)\eta(\lambda)}$$

How do we define "hyperspectral"?

- Goal is to replace existing qualitative descriptions with one having measurable thresholds.

- Two proposed definitions are currently being discussed:
  - "A hyperspectral imaging system is one which is capable of collecting distinct, yet contiguous bands across the instrument’s spectral range, with a mean spectral sampling interval (SSI) to minimum spectral range (SR) coverage ratio of 1:50 (SSI/SR ≤ 0.02)"

  - "A system with the spectral range at least 0.7 octaves, which is sampled without gaps by at least 40 spectral bands. Sampling interval for each band should be smaller than 1/30th of the spectral range."

- Options will be voted on by the full P4001 working group.

Joining the IEEE P4001 group

- New participants are welcome.
- Contact chair Chris Durell at Labsphere (cdurell@labsphere.com)