COLOUR & SPACE IN CULTURAL HERITAGE

Acquisition, Calibration and the Processing of Hyperspectral Data: Lessons from the Round-Robin Test

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COST is supported by the EU Framework Programme Horizon 2020

Overview

- Camera characterization and calibration
- Key performance parameters
  - Smile
  - Keystone
  - SNR/NER
- Round-robin test errors
- Hyperspectral calibration
- Practical strategies to improve acquisition & data quality

Spectrometer Calibration and Characterization

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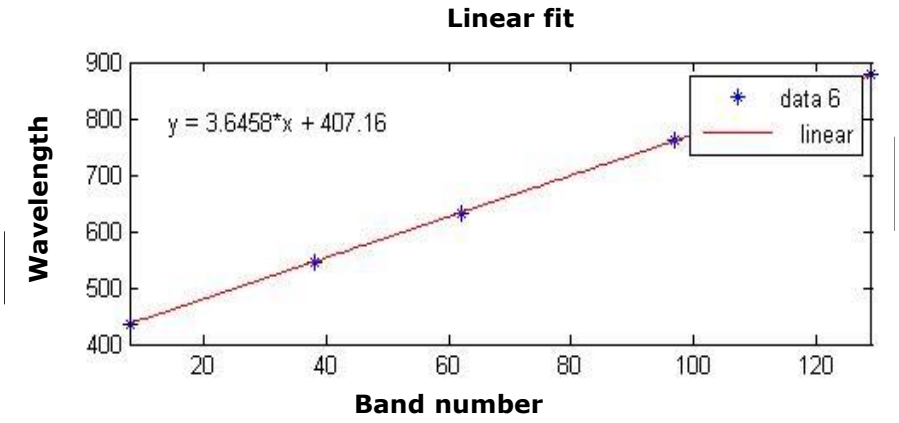
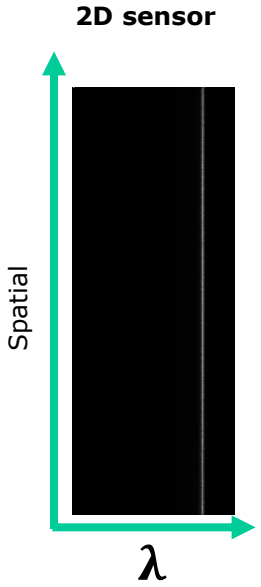
Instrument calibration:
Radiometric/sensor: -Dark signal (automatic shutter) -Bad pixels -**Pixel responsivity, nonuniformity** -**Absolute radiance** Spectral: -**Wavelength as a function of sensor row number (band number)** Geometric: -FOV pr pixel (for georeferencing) Calibration data needed for image calibration. **Essential!**

Instrument characterization:
Radiometric/sensor: -Linearity -**Noise, SNR, NER** -Dynamic range -Stray light Spectral: -Spectral resolution -**Spectral misregistration (smile)** Geometric: -FOV pr pixel (sensor model) -Total FOV -Spatial resolution, -**Spatial misregistration (keystone)** Detailed documentation of system performance **Very nice to have!**

Spectral Calibration of HSI cameras

- ~20 different narrow-band light sources (gas excitation lamps, laser sources) are used to illuminate the FOV of the camera, one at a time
- Fitting of data to spectral bands
- Output: Vector with center band wavelengths (for each band)





Radiometric Calibration of HSI cameras

The raw data output (Digital Number - DN) from the camera and its relationship with the incoming light can be expressed as:

$$DN[i,j] = Np[i,j] \cdot QE[i] \cdot RE[i,j] \cdot SF + BG[i,j]$$

- *i* = spectral band number; j = spatial pixel number.
- *QE(i)* = total quantum efficiency of the whole system.
- *SF* = scaling factor expressing the DN/photoelectron ratio.
- *RE(i,j)* = relative responsivity for each detector element
- *BG(i,j)* = background signal
- *Np* = number of incoming photons at a pixel during the integration time *t*

Relationship with sensor parameters and incoming Radiance (*L*) can be expressed as:

$$Np[i,j] = \frac{L[i,j] \cdot t \cdot A \cdot \Omega \cdot \Delta\lambda[i] \cdot \lambda[i]}{h \cdot c}$$

- *t* is the integration time
- *A* the entrance aperture area
- *Ω* is the solid angle of a pixel
- *Δλ* is the spectral sampling of the camera
- *λ* is the wavelength

Radiance for each spatial pixel and spectral band can be expressed as:

$$L[i,j] = \frac{(DN[i,j] - BG[i,j]) \cdot h \cdot c}{QE[i] \cdot RE[i,j] \cdot SF \cdot t \cdot A \cdot \Omega \cdot \Delta\lambda[i] \cdot \lambda[i]}$$

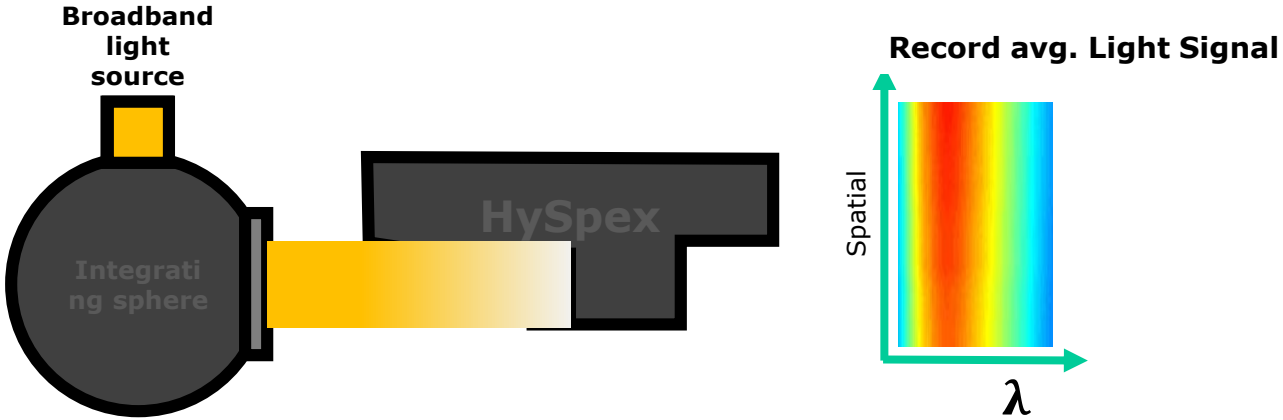
The **DN(i,j) matrix** is the image data.

The **BG(i,j) matrix** is is the background matrix for each image (dependent on the integration time and FPA temperature)

The ultimate goal of the radiometric calibration procedure is thus to generate the **RE(i,j) matrix** and the **QE(i) vector** for the particular instrument, in order to convert raw image data to absolute radiance data **L (in W/m^2 nm sr)**.

Radiometric calibration

Using a calibrated integrating sphere of known spectral radiance output *L(i,j)* whole FOV of the HySpex camera is illuminated uniformly from a fixed distance. This allows to establish the relationship between the DN levels and the radiance for each camera

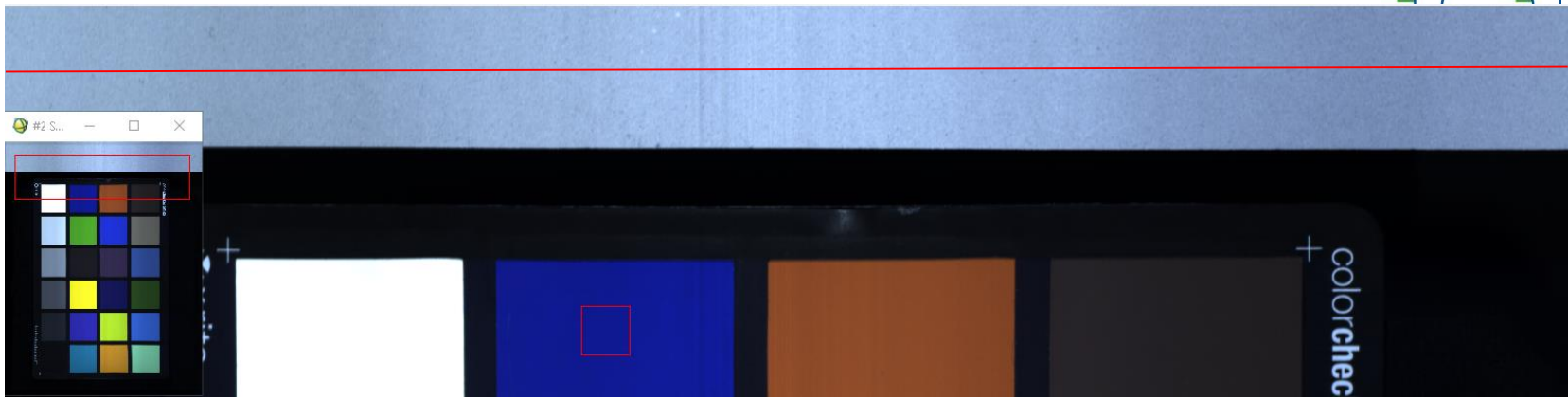


- The measurement is an average of a large number (e.g. 10000) of image frames to reduce noise.
- The spectral calibration is performed before the radiometric calibration.
- Output:
  - QE vector (system quantum efficiency)
  - RE matrix (relative sensitivity of each pixel)
  - Scaled to convert raw data directly to radiance (L) in SI units (W/m^2 nm sr)

Image Correction (RAW)

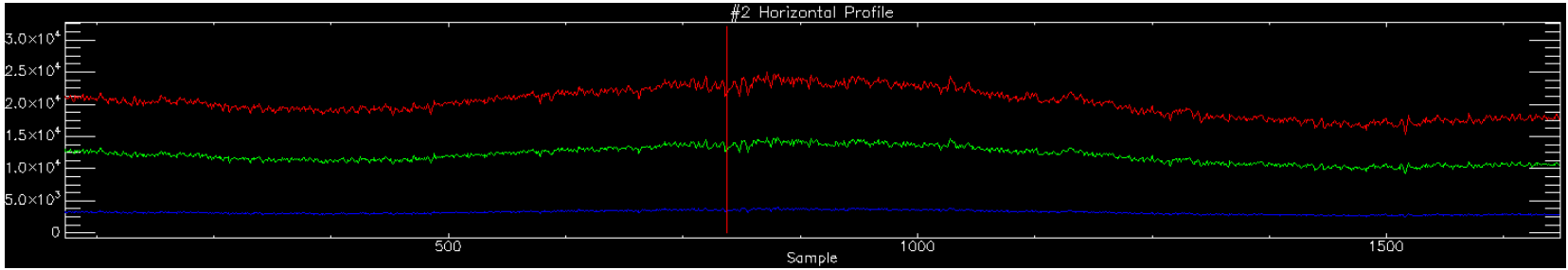
RAW uncalibrated image:

(raw Digital Numbers)



Horizontal profile:

(Across the FOV on grey reference, along the red line)

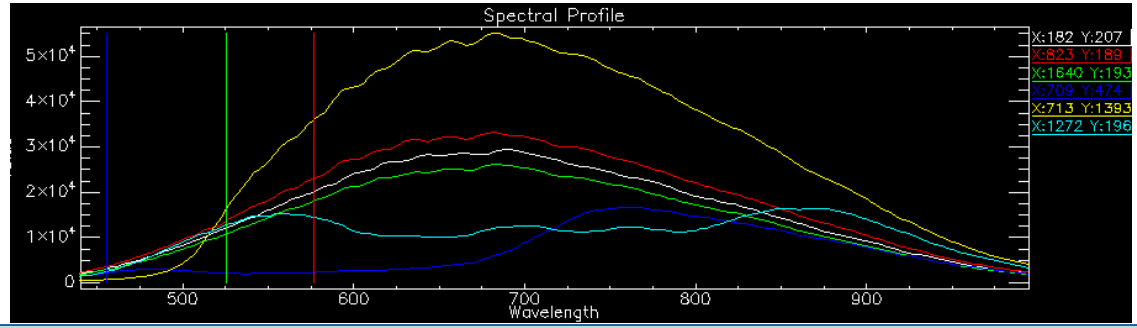


Spectral profile:

Grey reference: White, red green lines

Colur patches:

Corresponing colours



HySpex VNIR-1800
RRT X-Rite CC data

Image Correction (RADIANCE)

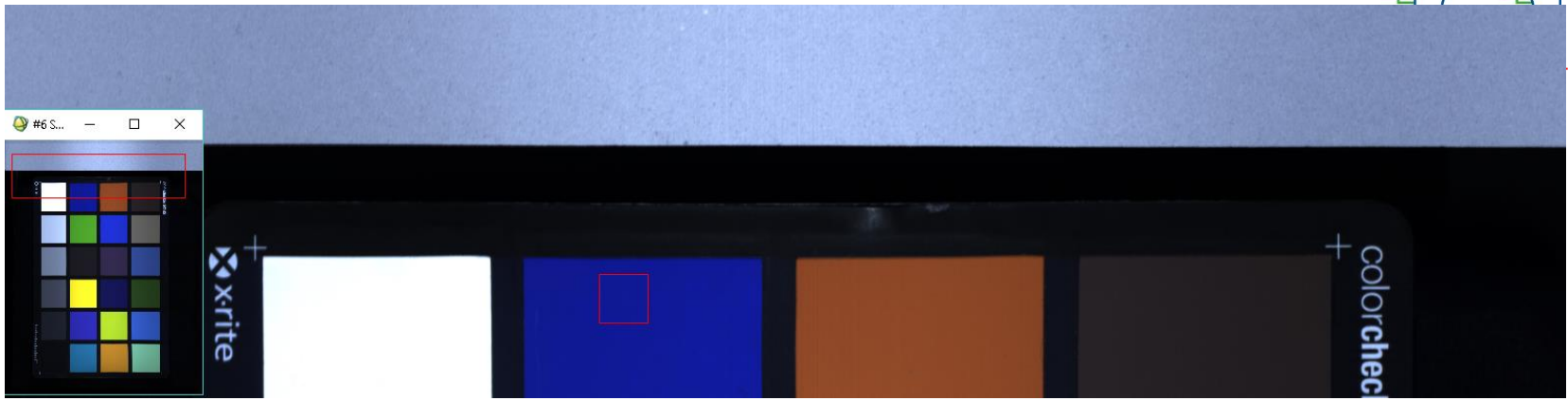
RADIANCE image:

(SI Unit (W/m^s nm sr)

Input to processing

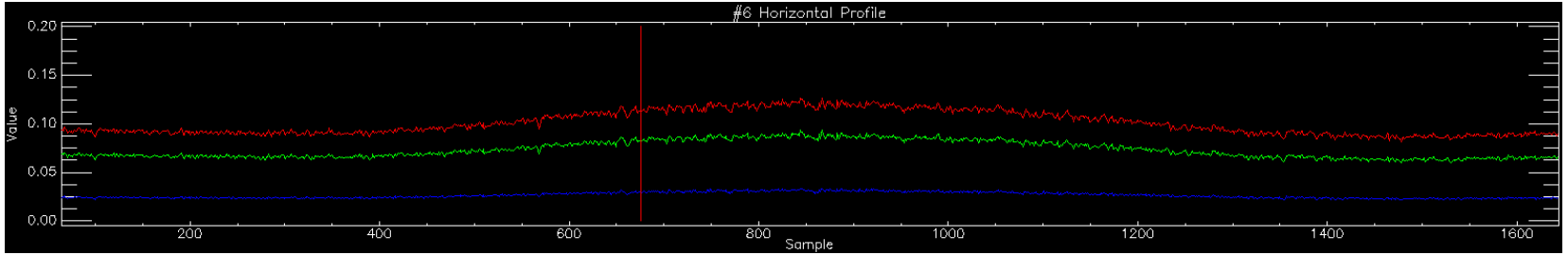
Procedure:

RE vector and QE matrix



Horizontal profile:

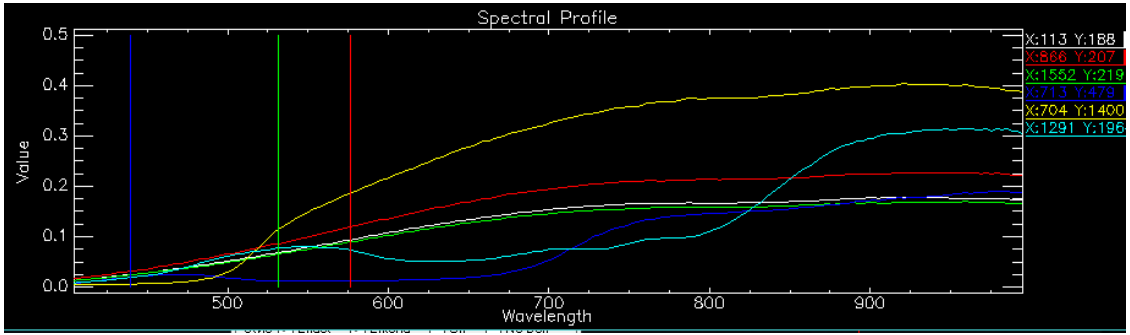
(Across the FOV on grey reference, along the red line)



Spectral profile:

Grey reference: White, red green lines

Colour patches: Corresponding graph colours



Software: HySpex RAD

(Transparent, Sample Code available)

Image Correction (REFLECTANCE)

REFLECTANCE image:

(0-100%)

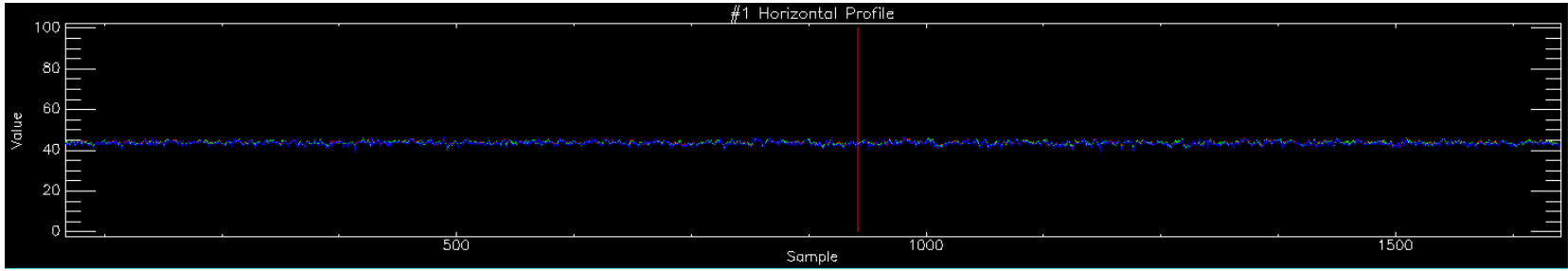
Input: Calibrated spectrum of grey reference.

Normalized spatially inside green area

Horizontal profile:

(Across the FOV on grey reference, along the red line)

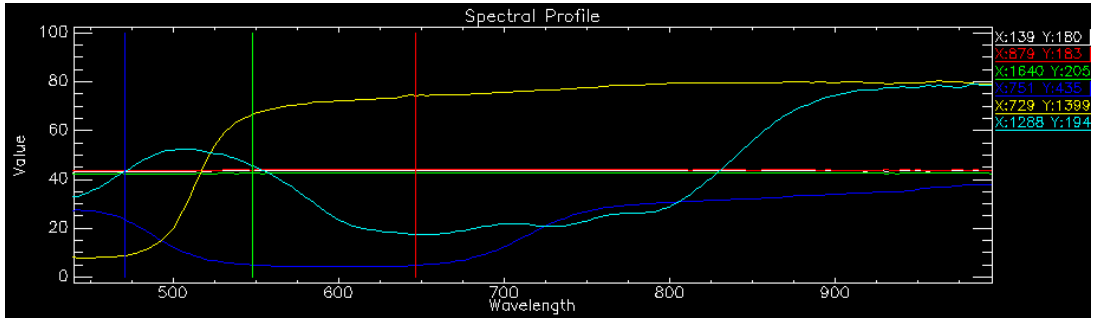
Note graininess of grey reference.



Spectral profile:

Grey reference: White, red green lines

Colour patches: Corresponding graph colours



Software: HySpex REF

(Transparent, Sample Code available)

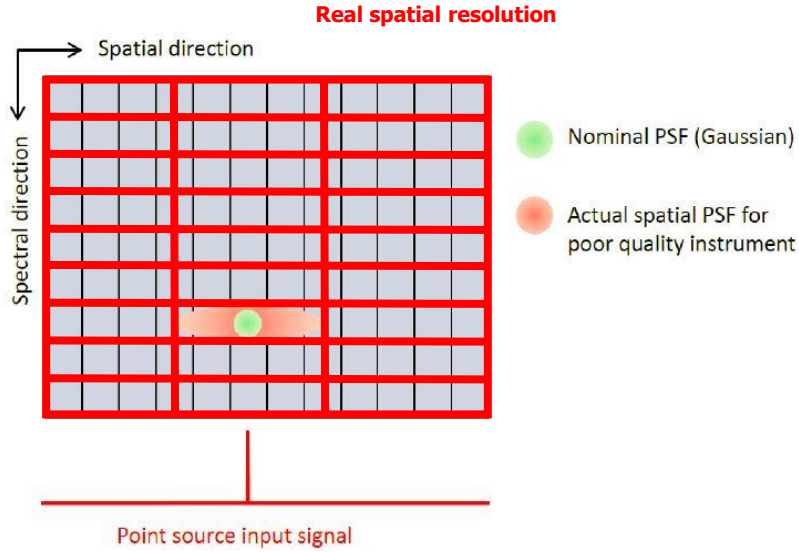
Spatial Resolution

The spatial resolution is limited by the resolution of the optical system.

The PSF describes the distribution of energy in the image plane when a point source is imaged through the optical system, i.e. the sharpness of the image.

For example, a sensor with 2000 **nominal spatial pixels** and with a the PSF width of 4 pixels has an **effective spatial resolution** of only 2000/4 = 500 pixels.

Can vary a with position in FOV and wavelength, providing an "average" value for FWHM or MTF can be very misleading



NUMBER SPATIAL PIXELS IS NOT THE SAME AS SPATIAL RESOLUTION!

Spectral Resolution

The **true spectral resolution** does not only depend on the number sensor rows over which the spectral range is imaged, but also on the true optical resolution of the instrument.

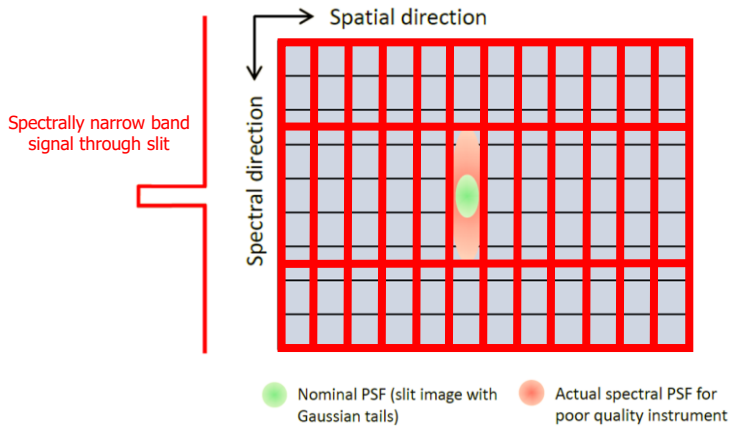
The PSF in the spectral direction or the spectral response function (SRF) describes the distribution of energy in the image plane when a narrow spectral signal is imaged through the optical system.

For example, consider a VNIR instrument that is specified to have 200 spectral bands over the 600nm wide spectral range from 400 to 1000nm. This gives a **nominal spectral sampling** interval of 600nm/200bands = 3nm per band, which *would* correspond to the spectral resolution *if* all the energy is contained within one sensor row.

However, if the image of a narrow band laser source is distributed over e.g. four sensor rows rather than one, the **true spectral resolution** is 3nm x 4 = 12nm.

Can vary a with position in FOV and wavelength, providing an "average" value for FWHM or MTF can be very misleading

Real spectral resolution

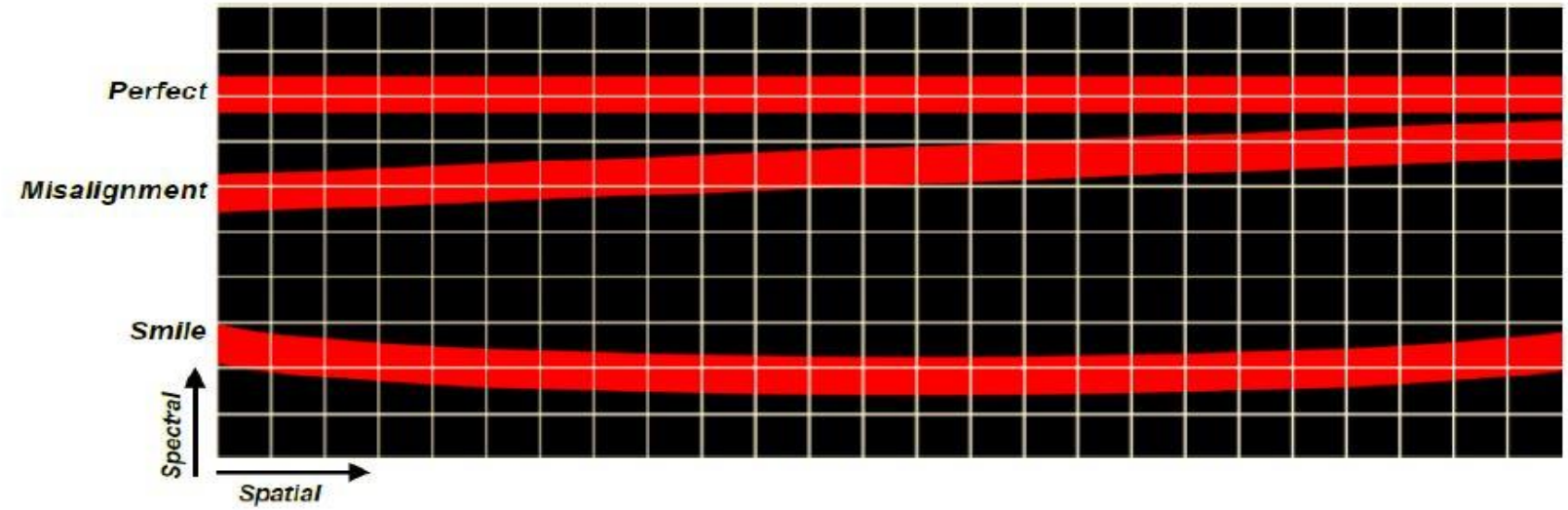


NUMBER SPECTRAL BANDS IS NOT THE SAME AS SPECTRAL RESOLUTION!

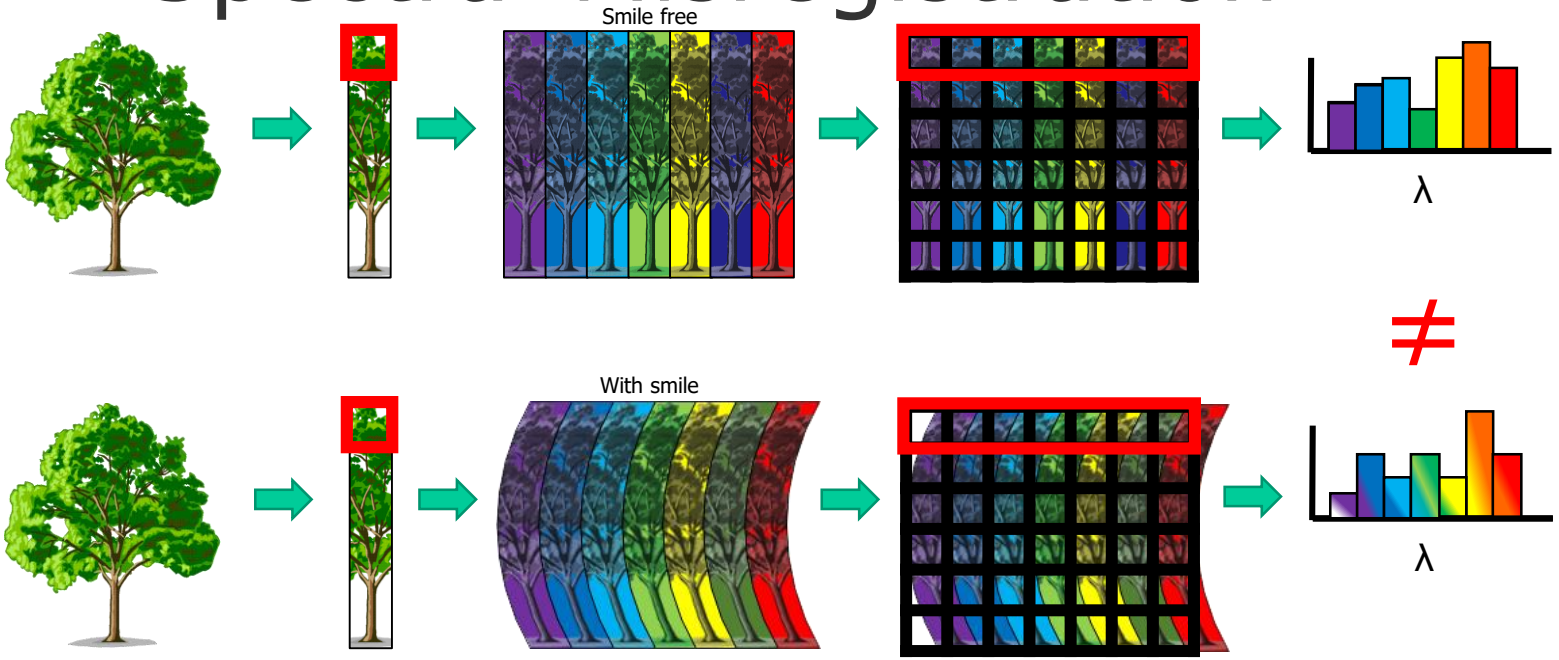
Spectral Misregistration
(Smile Effect)

- Spectral misregistration can be defined as a variation in the band center wavelengths measured by the instrument as a function of position (spatial pixel). The effect is typically seen as a bending or a tilt of a narrow spectral line (e.g. a laser line) across the field of view in the image plane of the instrument
- As illustrated in the figure, there are two main causes of spectral misregistration.
- The first is the so called smile effect, shown as bending or curving of a spectral line across the field of view due to distortions caused by the optics or the dispersive element.
- The second is misalignment between the slit and sensor, shown as a tilt of the spectral line across the field of view.

Schematic of 2D sensor array illuminated by laser source, illustrating spectral misregistration.



Spectral Misregistration



How will smile affect your processing result?

- Smile will shift your spectrum in the spectral direction depending on where you are in the scene.
- If you are looking for narrow features in your spectra, even a small smile can cause objects not to be detected/classified correctly

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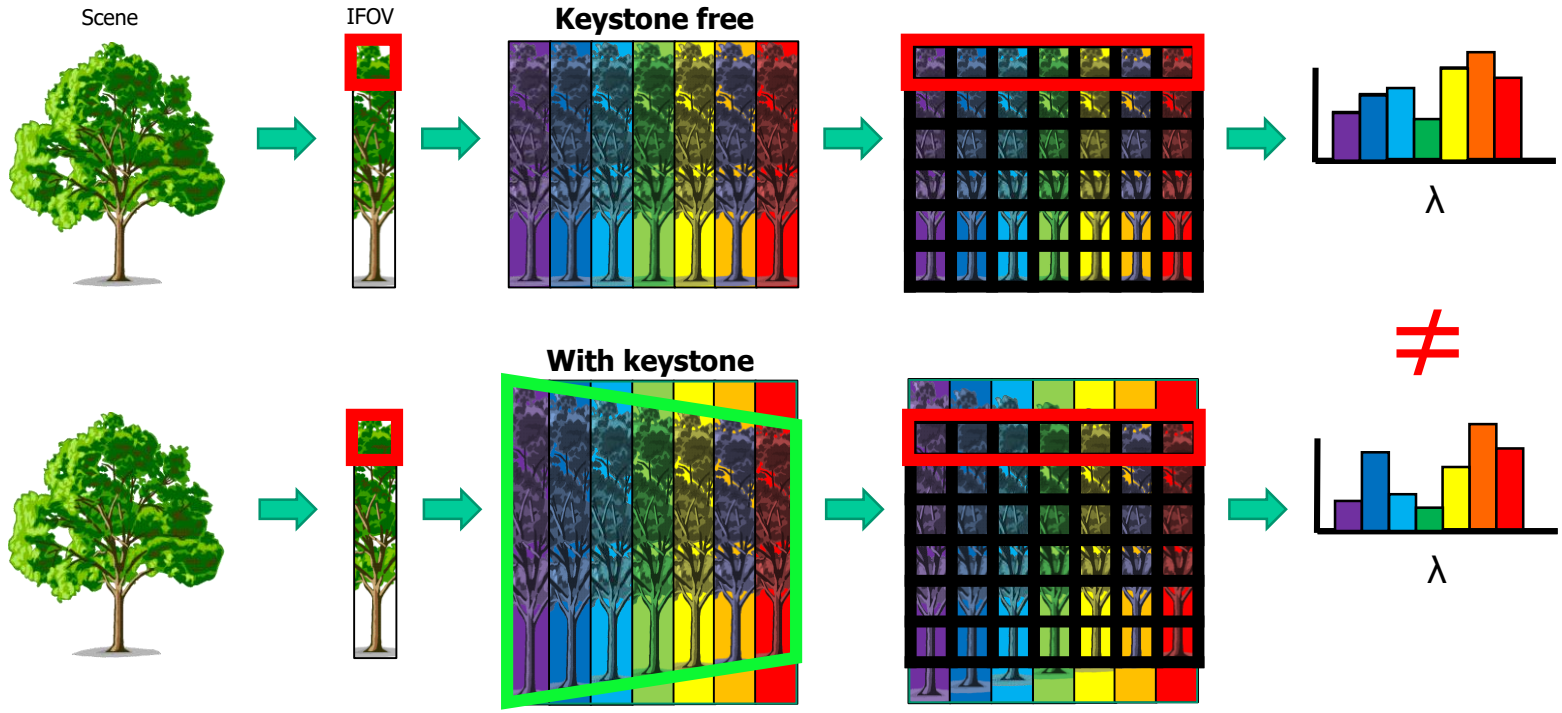
Spatial Misregistration

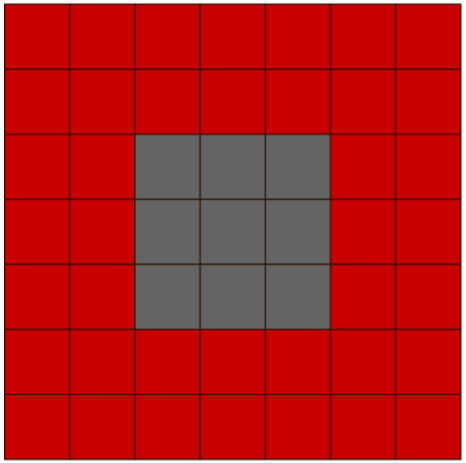
Spatial misregistration can be defined as a variation in spatial position as a function of wavelength.



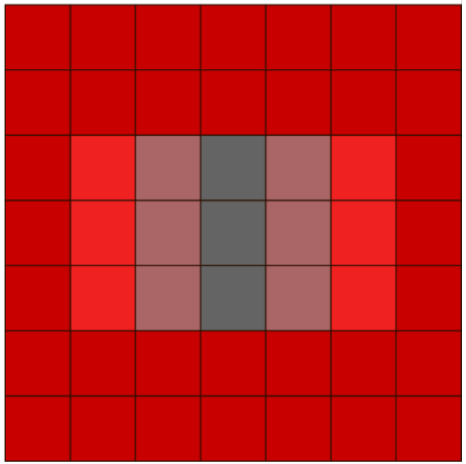
Red signal and blue signal are from two different positions in the scene!

How will keystone affect your processing results?

3x3 pixel object hitting perfectly in both x and y directions with no keystone in the



3x3 pixel object hitting perfectly in both x and y directions with 50 % keystone in the data

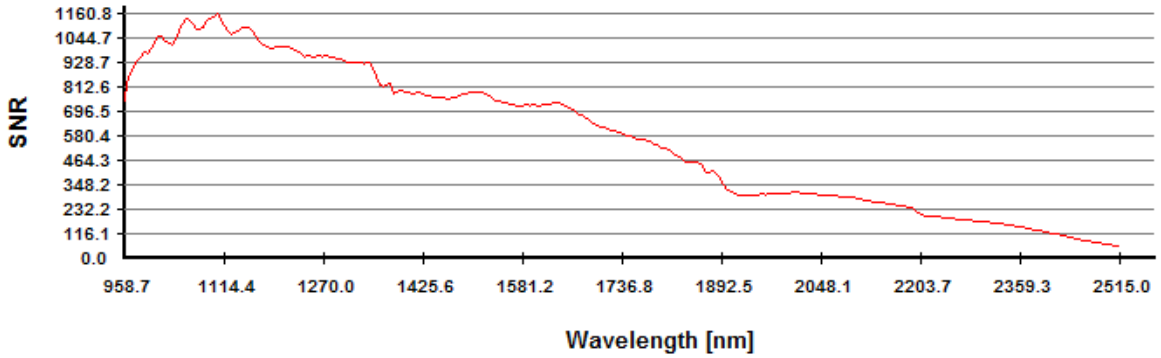


- Keystone in your data will give you unphysical spectral signatures that will not be detected/classified correctly
- Keystone in your data will effectively reduce your spatial resolution, meaning that you would need a lot larger object to get one pure pixel

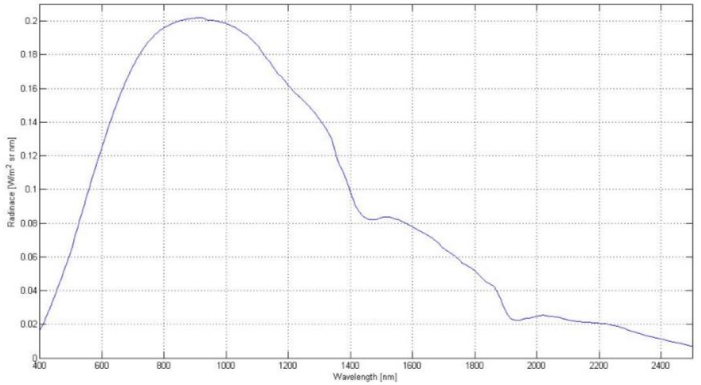
Signal to Noise Ratio (SNR)

SNR curve: Signal to noise ratio as a function of wavelength for a given input spectrum and integration time.

Signal to Noise Ratio (SNR) 6ms int. time



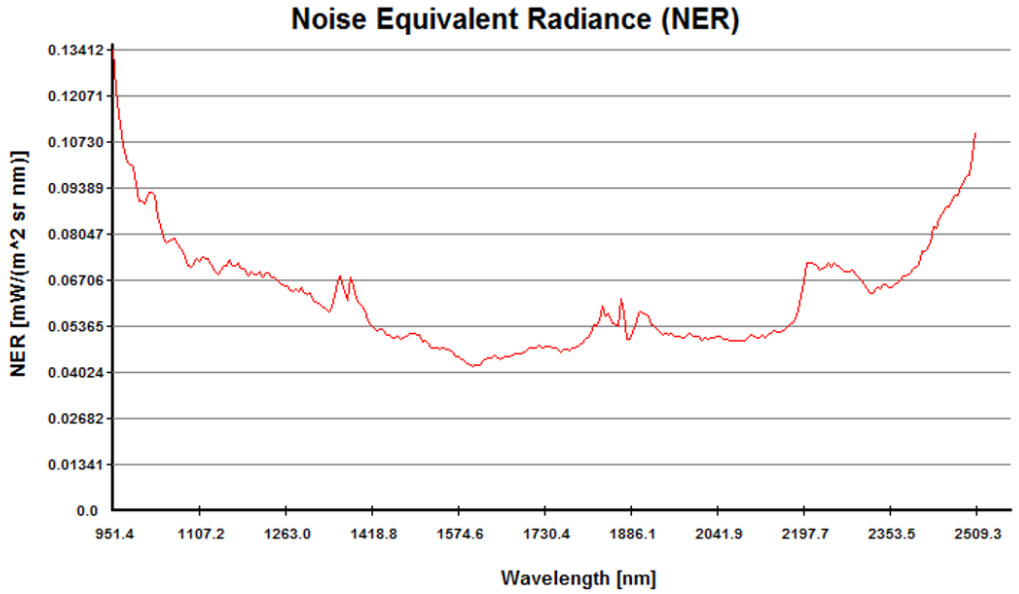
Input radiance



- A high SNR is essential in all scientific applications of hyperspectral imaging systems.
- The SNR will always vary with wavelength due to spectral variations in sensor response, coatings and grating efficiency, etc. and should always be specified as a function of wavelength.
- While defining and measuring SNR is trivial, it is not very sufficient to simply state that a sensor has an SNR of e.g. 1100 without providing additional information about the measurement procedure
- The SNR curve should be accompanied by the input radiance curve and information about the integration time used for measuring the SNR, as well as information about spatial or spectral binning or averaging factors used to calculate the given SNR function.
- If you know the radiance levels from your source and typical reflectance levels in your scene, this info will enable you to evaluate the acquisition parameters (e.g. integration times) for your operational scenario and the SNR you can expect from your data for the whole wavelength range.

Noise Equivalent Radiance (NER)

- NER curve: Shows the input radiance required to reach an SNR of 1 for each band.
- Essential info for any sensor, since it is independent on the input signal, depends on the sensor noise and system QE.
- The NER curve should always be accompanied by information about which integration time the curve is valid for.



NER at 5ms integration time (SWIR-384)

If you know the radiance levels from your source and typical reflectance levels in your scene, this info will enable you to evaluate the acquisition parameters (e.g. integration times) for your operational scenario and the SNR you can expect from your data for the whole wavelength range.

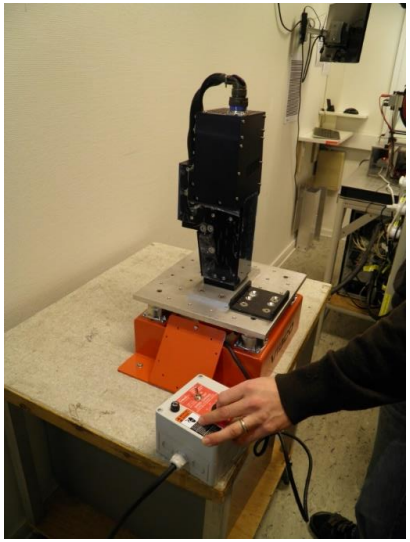
Environmental Tests
(Vibration and Shock)

No point in going through all this hassle if it is invalidated by UPS during shipment!

Factory vibration test on every camera:

- 0 – 100 Hz in 5 minutes sweep
- Vibration sequence performed with camera oriented both horizontally and vertically

- Check the spectral and radiometric calibration before and after the vibration test
- Pass: The camera is stable and the calibration will remain valid also after transportation and during operation.

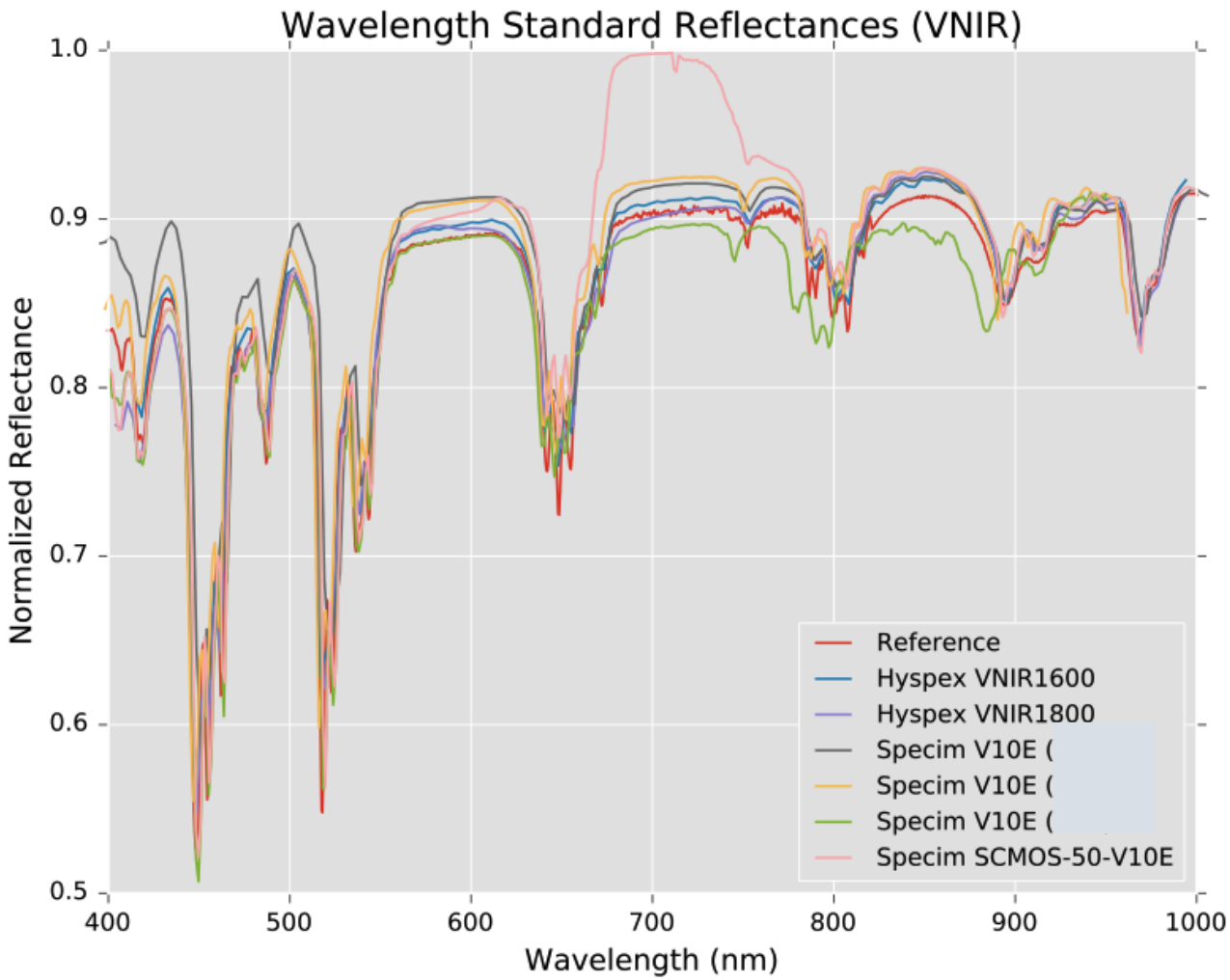


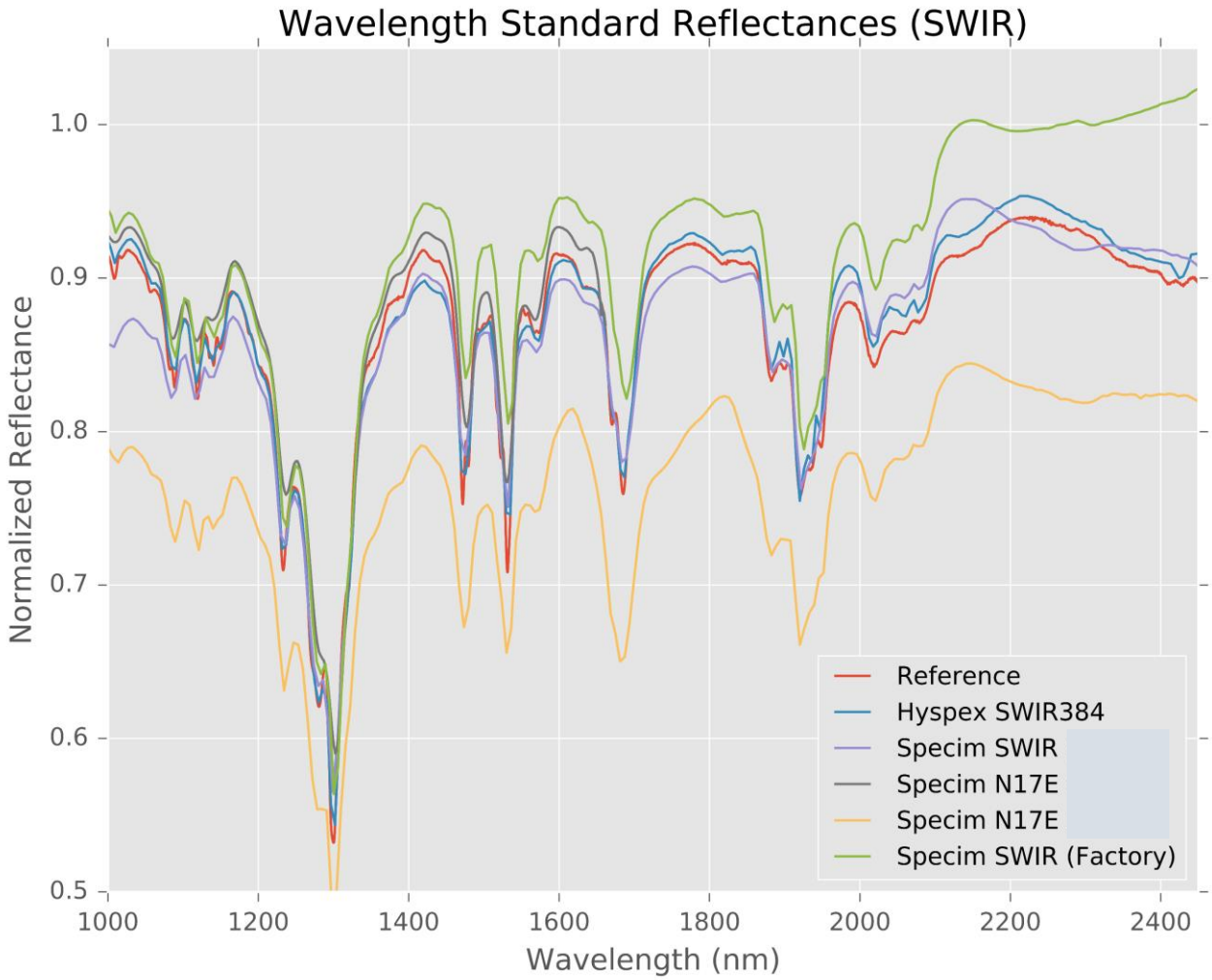
Round Robin Tests

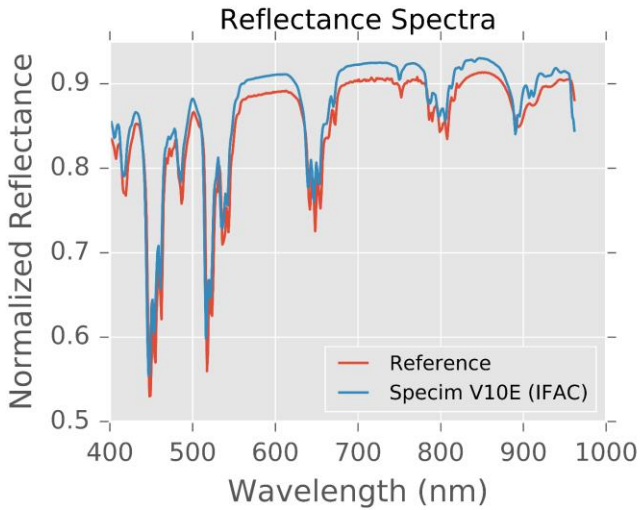
- The test results were very variable
- Sources of variability
  - Equipment (Multispectral, hyperspectral, manufacturers, specifications, ...)
  - Users (Museums, universities, manufacturers, ...)
  - Data Processing (ENVI, manufacturer software, custom software, ...)

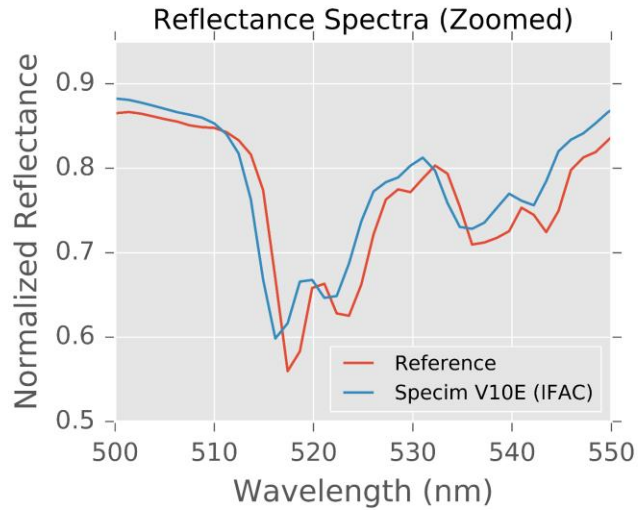
Test Target Results

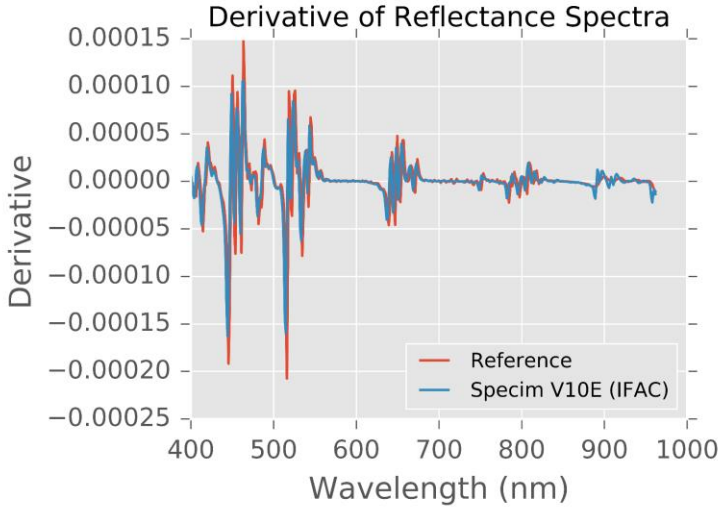
- Sphere Optics Rare Earth Wavelength Standard
- Diffuse lambertian reflectance standard composed of PTFE doped with the oxides of the rare earth elements Holmium, Erbium and Dysprosium

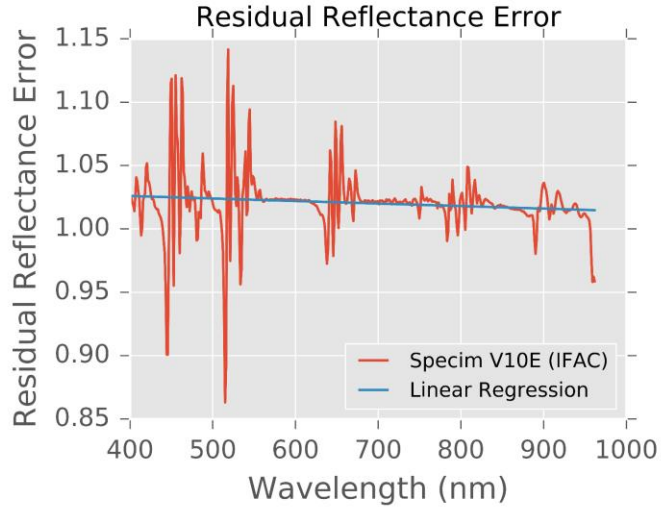

Wavelength Standard Reflectances (VNIR)
Normalized Reflectance
Wavelength (nm)
1.0
0.9
0.8
0.7
0.6
0.5
400
500
600
700
800
900
1000
Reference
Hyspex VNIR1600
Hyspex VNIR1800
Specim V10E (
Specim V10E (
Specim V10E (
Specim SCMOS-50-V10E


Wavelength Standard Reflectances (SWIR)
Normalized Reflectance
1.0
0.9
0.8
0.7
0.6
0.5
1000
1200
1400
1600
1800
2000
2200
2400
Wavelength (nm)
Reference
Hyspex SWIR384
Specim SWIR
Specim N17E
Specim N17E
Specim SWIR (Factory)


Reflectance Spectra
Normalized Reflectance
Wavelength (nm)
Reference
Specim V10E (IFAC)


Reflectance Spectra (Zoomed)
Normalized Reflectance
Wavelength (nm)
Reference
Specim V10E (IFAC)


Derivative of Reflectance Spectra
Derivative
Wavelength (nm)
Reference
Specim V10E (IFAC)


Residual Reflectance Error
Residual Reflectance Error
Wavelength (nm)
Specim V10E (IFAC)
Linear Regression

Radiometric Calibration of HySpex HSI cameras

The raw data output (Digital Number - DN) from the camera and its relationship with the incoming light can be expressed as:

$$DN[i,j] = Np[i,j] \cdot QE[i] \cdot RE[i,j] \cdot SF + BG[i,j]$$

- *i* = spectral band number; j = spatial pixel number.
- *QE(i)* = total quantum efficiency of the whole system.
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- *RE(i,j)* = relative responsivity for each detector element
- *BG(i,j)* = background signal
- *Np* = number of incoming photons at a pixel during the integration time *t*

Relationship with sensor parameters and incoming Radiance (*L*) can be expressed as:

$$Np[i,j] = \frac{L[i,j] \cdot t \cdot A \cdot \Omega \cdot \Delta\lambda[i] \cdot \lambda[i]}{h \cdot c}$$

- *t* is the integration time
- *A* the entrance aperture area
- *Ω* is the solid angle of a pixel
- *Δλ* is the spectral sampling of the camera
- *λ* is the wavelength

Radiance for each spatial pixel and spectral band can be expressed as:

$$L[i,j] = \frac{(DN[i,j] - BG[i,j]) \cdot h \cdot c}{QE[i] \cdot RE[i,j] \cdot SF \cdot t \cdot A \cdot \Omega \cdot \Delta\lambda[i] \cdot \lambda[i]}$$

The **DN(i,j) matrix** is the image data.

The **BG(i,j) matrix** is is the background matrix for each image (dependent on the integration time and FPA temperature)

The ultimate goal of the radiometric calibration procedure is thus to generate the **RE(i,j) matrix** and the **QE(i) vector** for the particular instrument, in order to convert raw image data to absolute radiance data **L (in W/m^2 nm sr)**.

Classic Calibration Workflow

1) Acquisition Steps
    1) Acquire Dark Current using identical settings and acquisition time
    2) Acquire scan of spectralon target
2) Processing
    1) Subtract dark current (static noise) from all images
    2) Divide target image by spectralon scan (normalization)

→ Floating point data (0.0→1.0) at reflectance factor

What can go wrong?

Types of Errors Seen in RRT

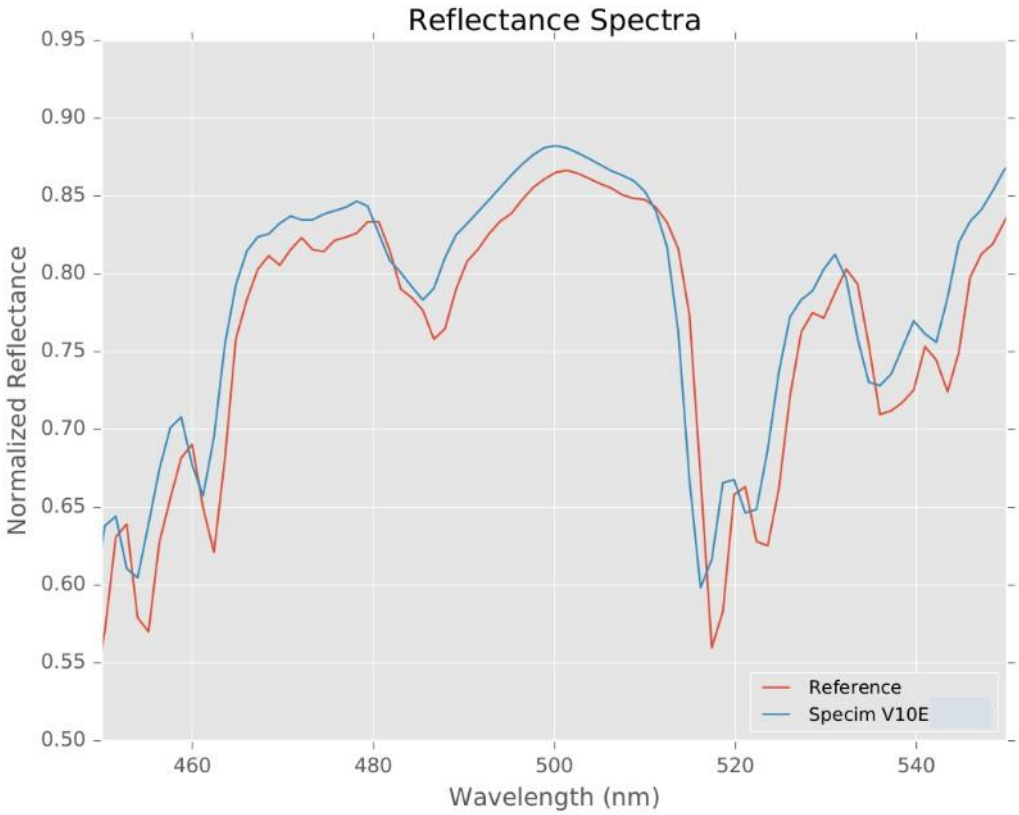
1) Spectral Alignment
2) Noise
3) Amplitude
4) Spatial Distortions

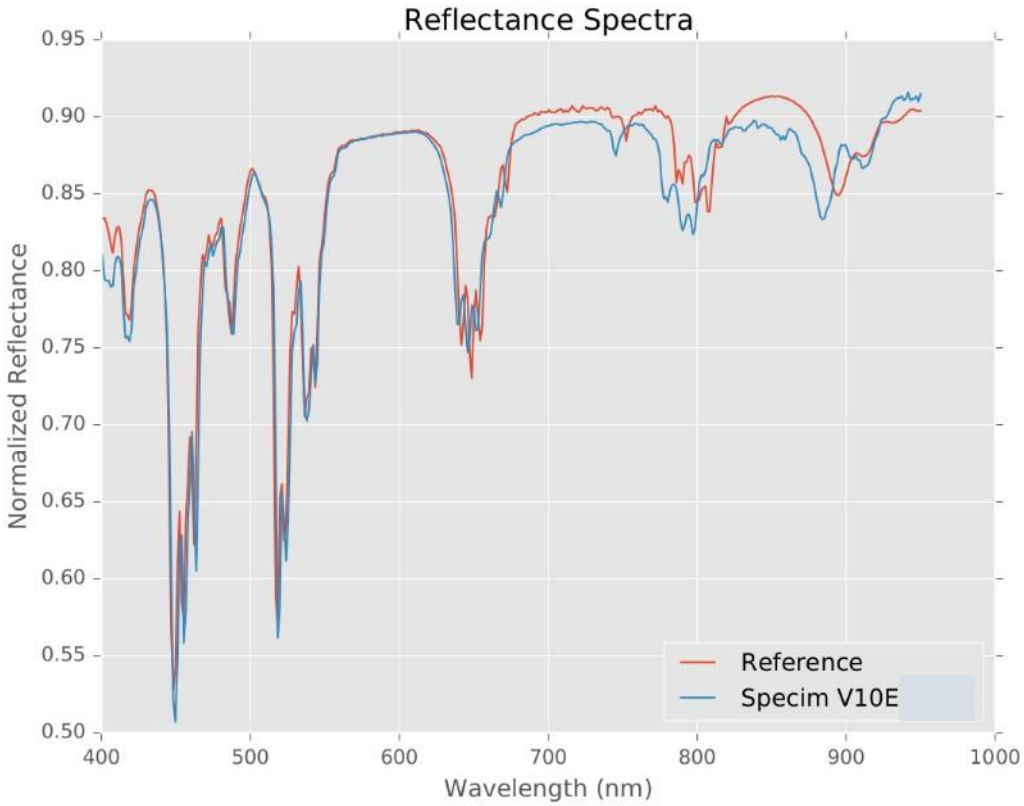
Types of Errors Seen in RRT

1) Spectral Alignment
2) Noise
3) Amplitude
4) Spatial Distortions

Consequences for spectral accuracy, spatial reliability, classification, pigment mapping, change detection and colorimetry etc.

Spectral Alignment Problems





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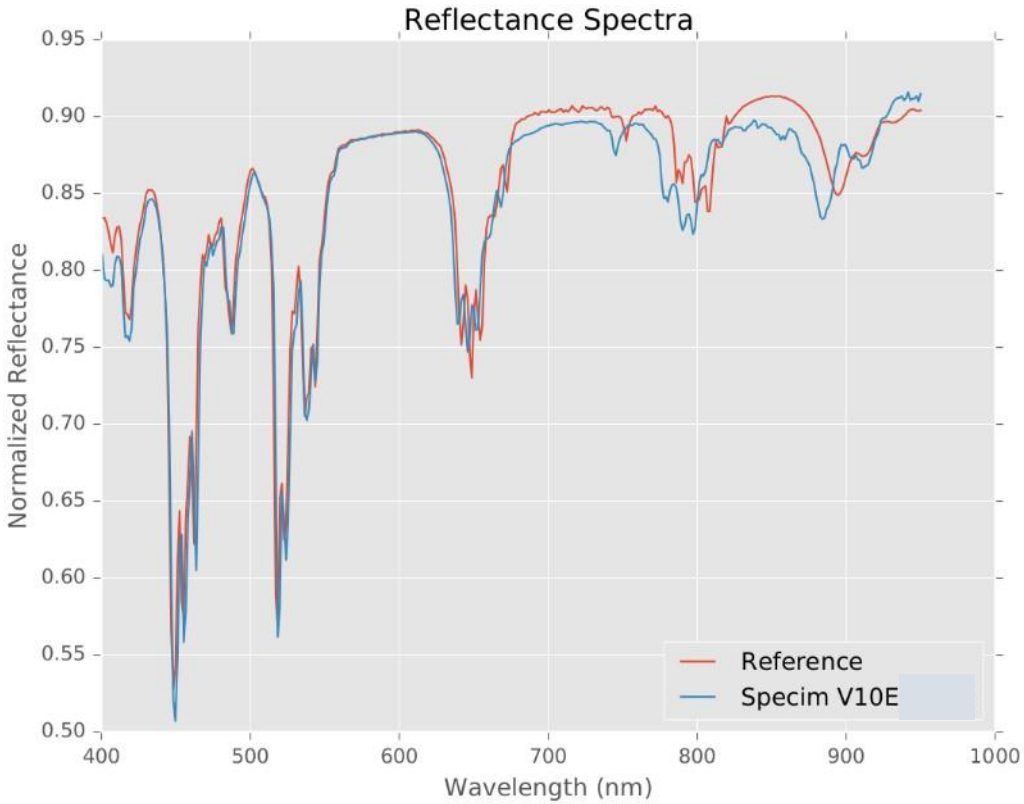

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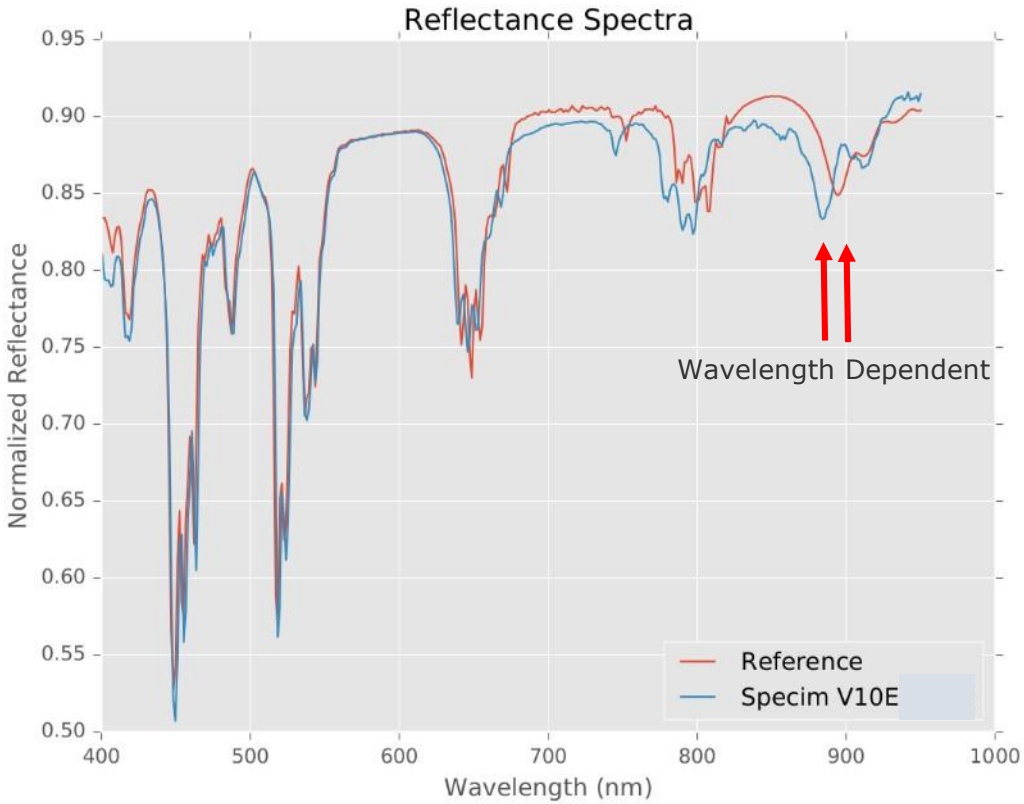
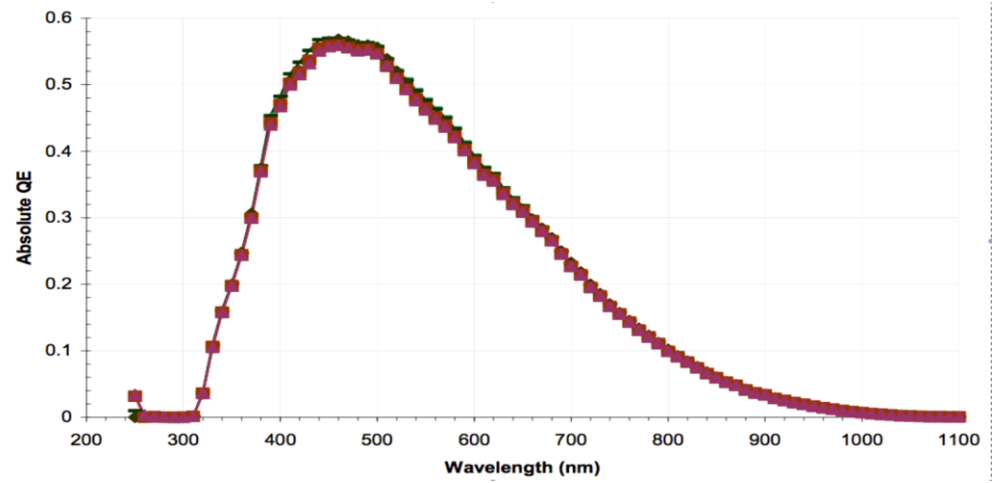


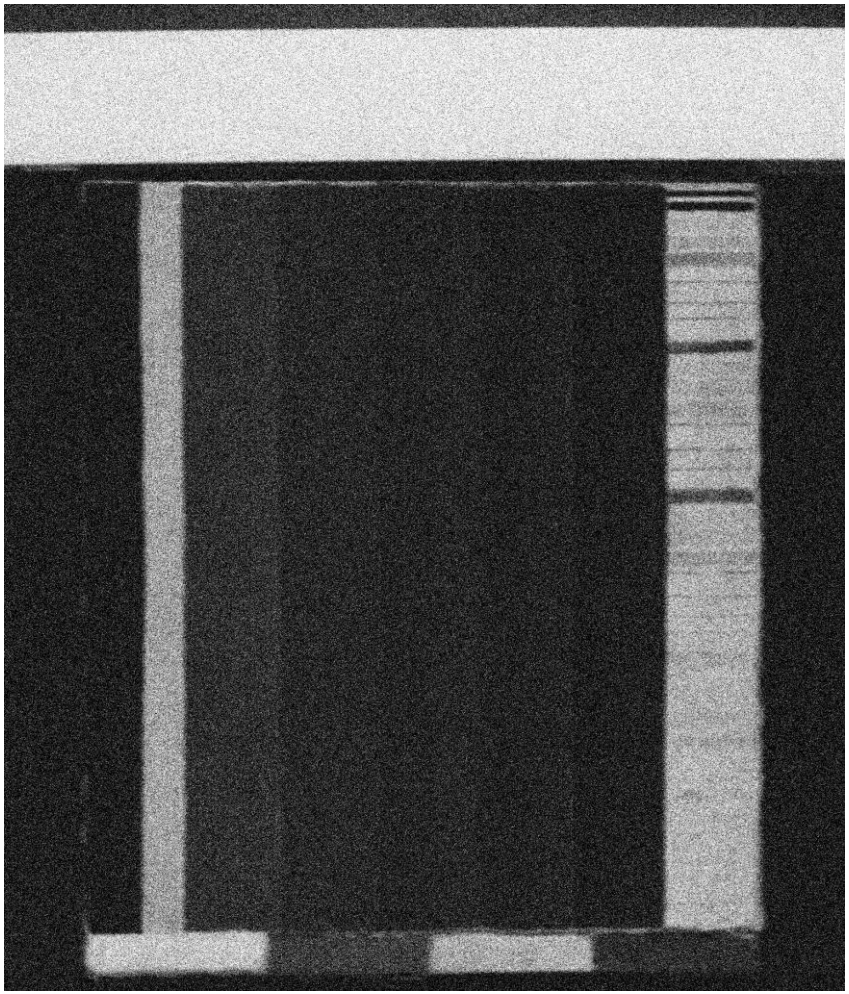
Spectral Alignment Problems

- Incorrect spectral calibration
  - Spectrometer mis-alignment
  - Shock to camera during transport
- Recalibration
  - Factory recalibration
  - Use wavelength standard and fit to a function (polynomial)

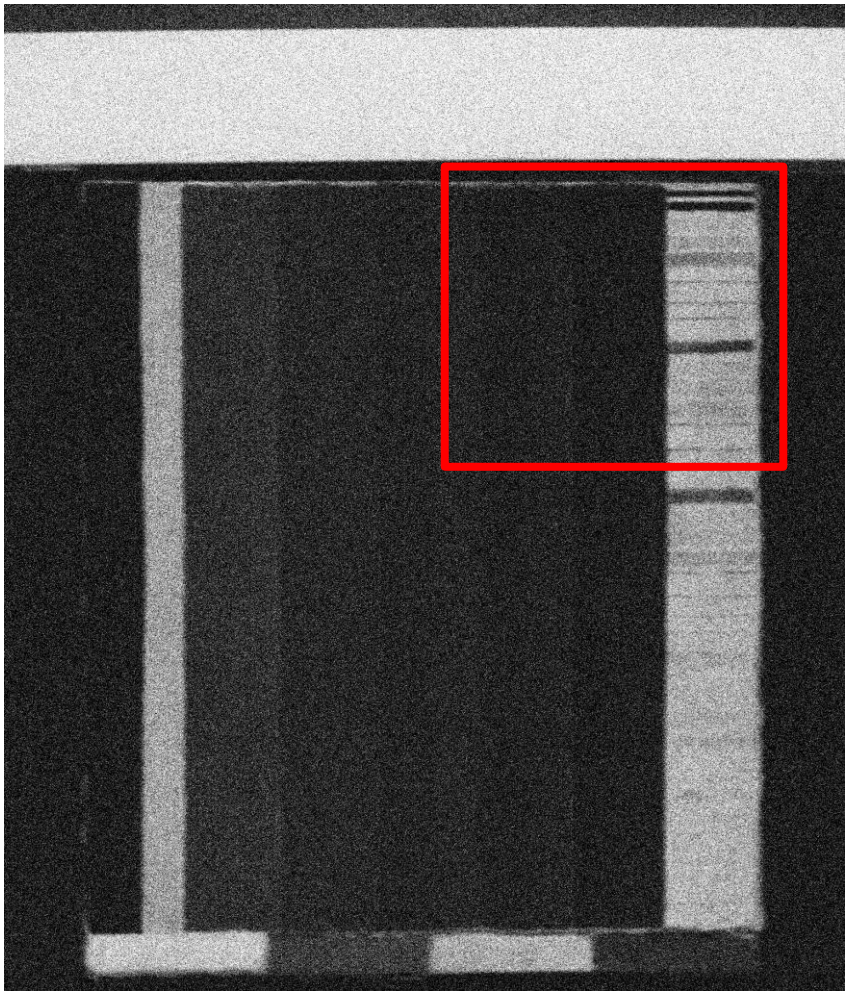
Noise

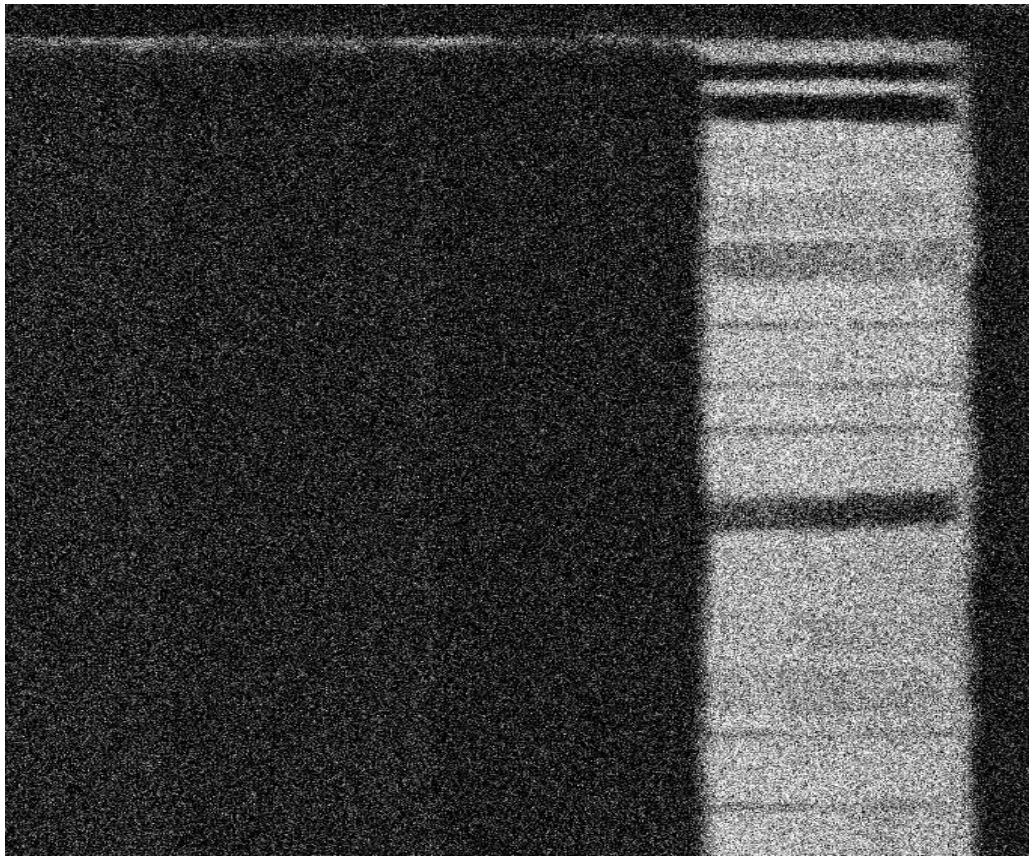
- Noise can be approximated to 2 kinds:
  - Thermal noise: static (varies with temperature)
  - Shot noise: variable (dependent on signal)
- Reduces signal-to-noise
- Quantum Efficiency:
  - Detectors have wavelength-dependent sensitivities





400nm

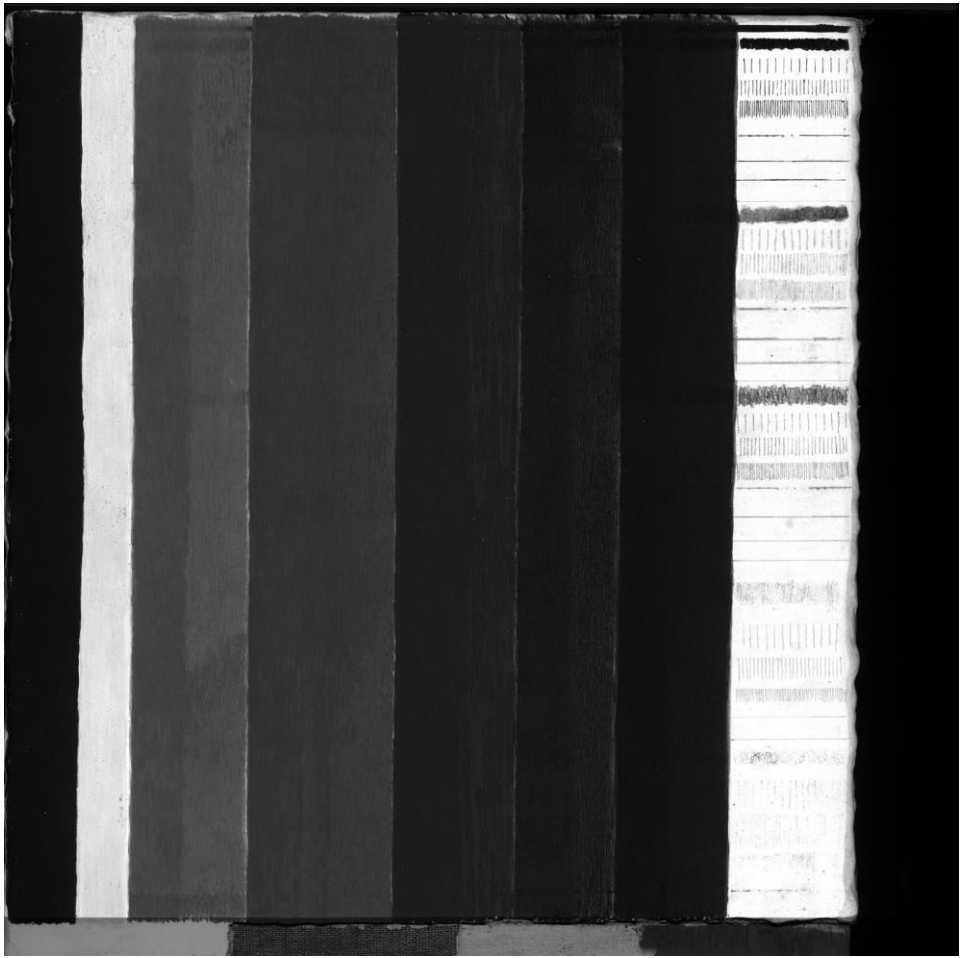


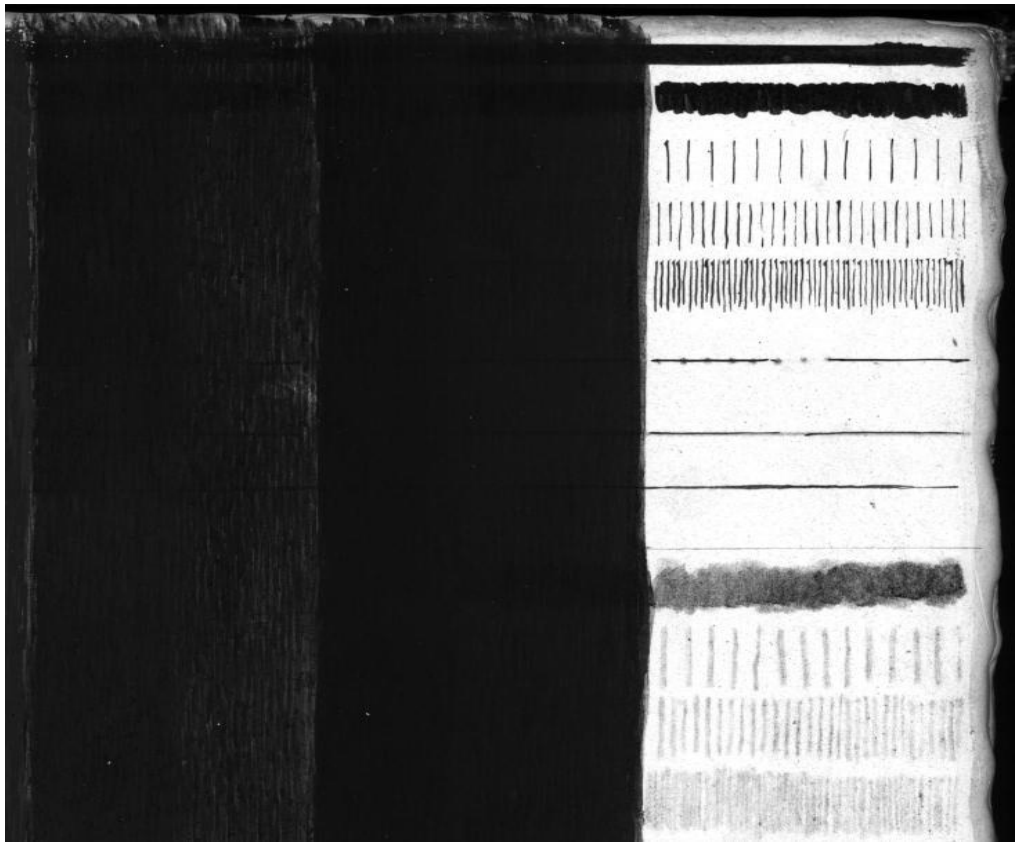


Zoom

Improving Signal-to-Noise

- Binning
  - Spatial / Spectral
- Use full dynamic range of camera
  - Tune acquisition time to target object
  - Use 50% reflectance spectralon
  - Or acquire Spectralon with different acquisition time (cameras are very linear)
- Averaging
  - Multiple line acquisition improves signal to noise by $\sqrt{N}$
  - Depends if supported by acquisition software
- Equalization filter
  - Quantum efficiency of detector not uniform over the spectral range



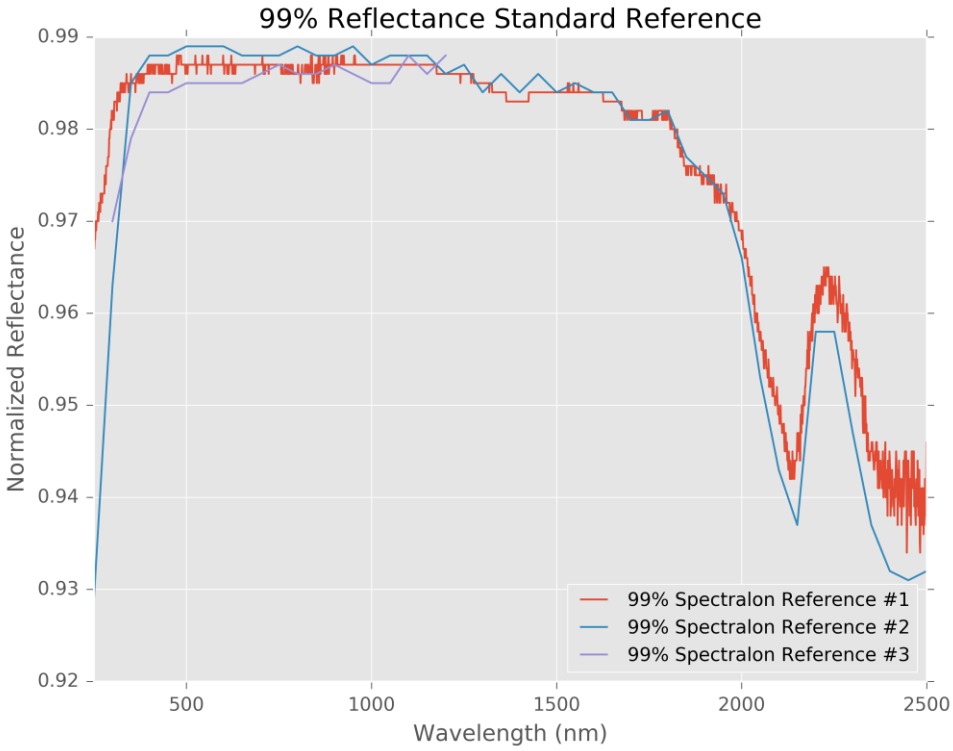


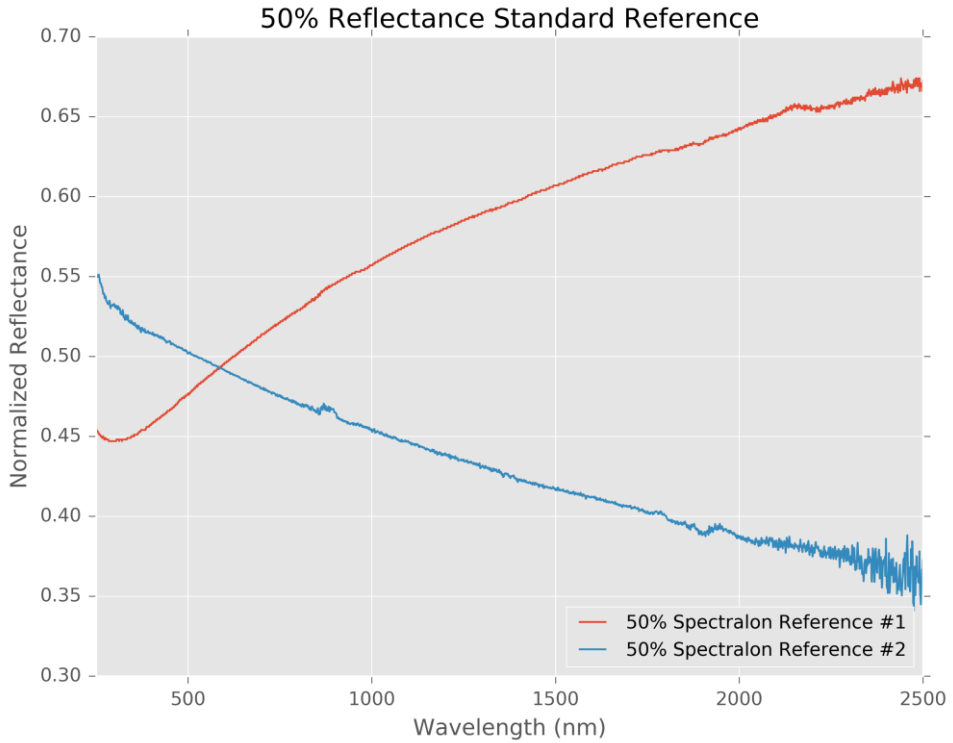
Zoom

Amplitude Errors

- Spectralon or similar usually used to normalize data to a reference reflectance
- However, reflectance not quite as flat as presumed

Reflectance Standards

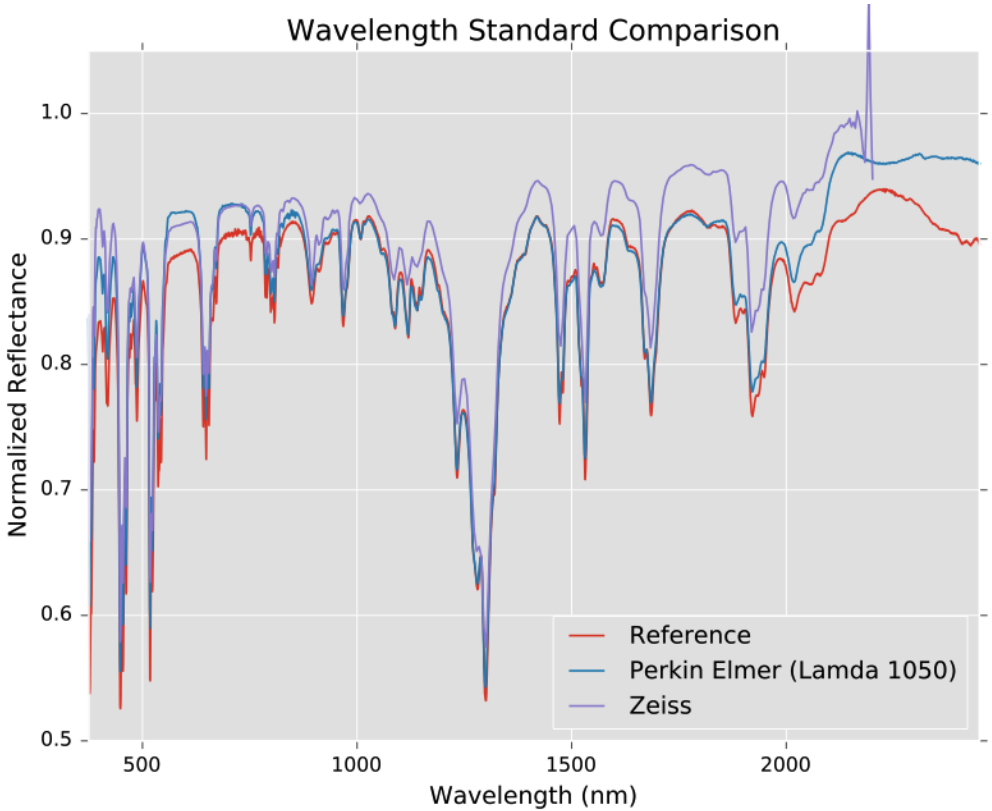




How Reliable are Reference Values?

Measuring the wavelength standard with different spectrophotometers

Spectrophotometers generally calibrate with spectralon assuming spectral flatness



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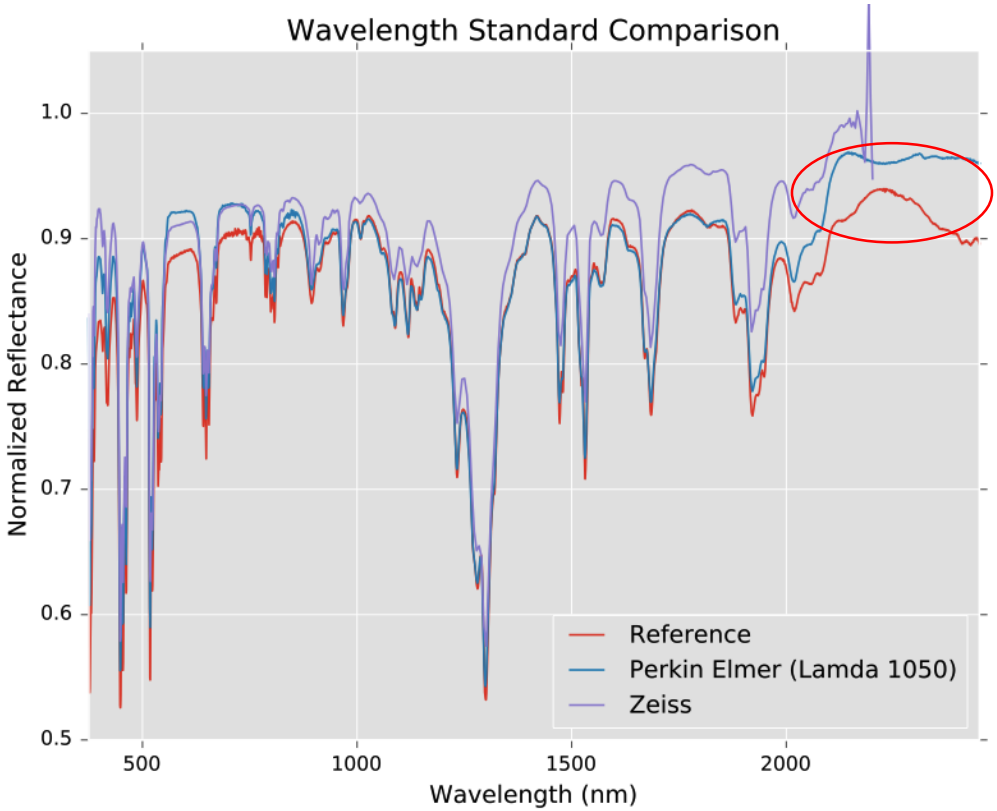
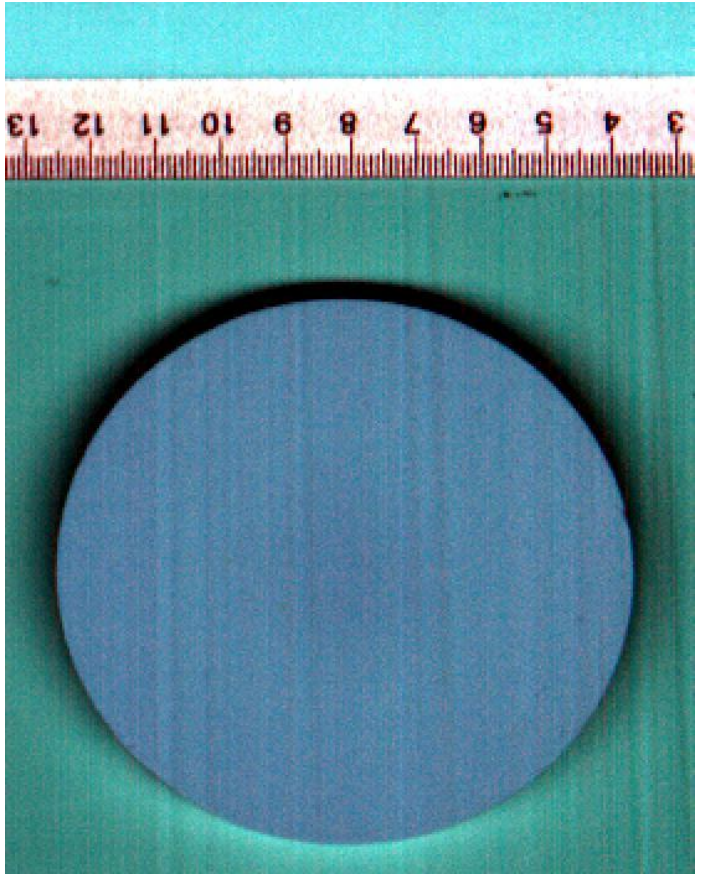


Striping Errors

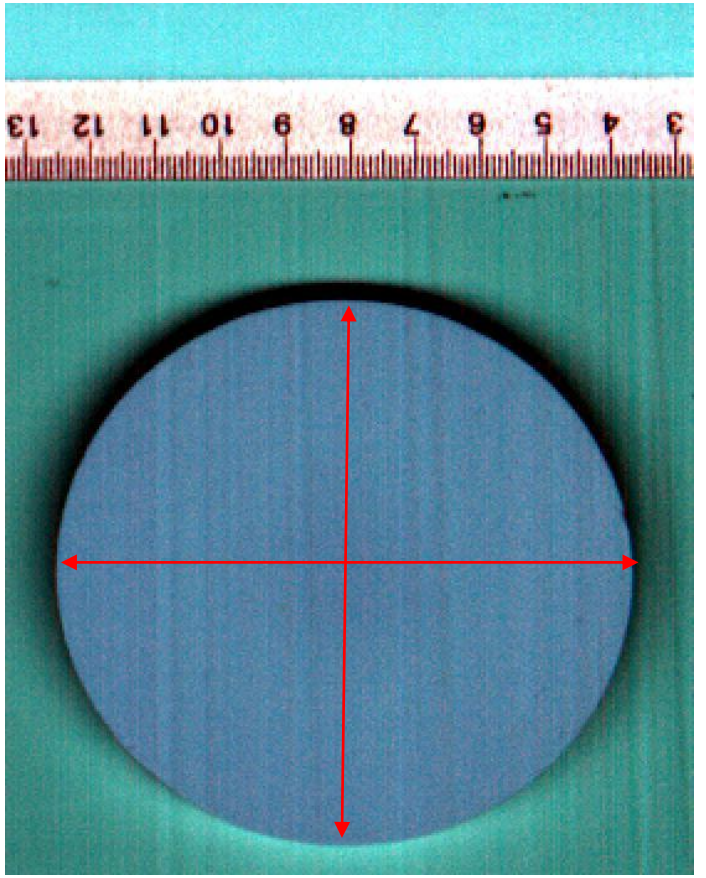
- Different cross-track pixel sensitivities
- Spectralon target not at the same distance to the target



Spatial Distortions

Pixel aspect ratio

- Scan speed calibration
- Appropriate scan speed depends on distance to target
- Some systems require manual calculation

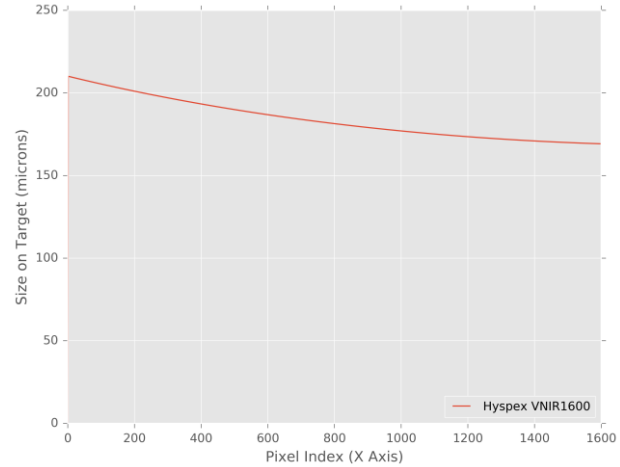


~10% Aspect Ratio Error

Spatial Distortions

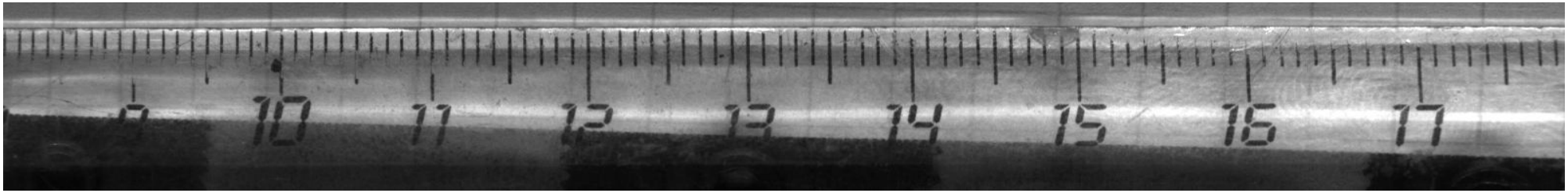
Sensor model

- Non-linear cross-track spatial response
- Requires sensor characterization



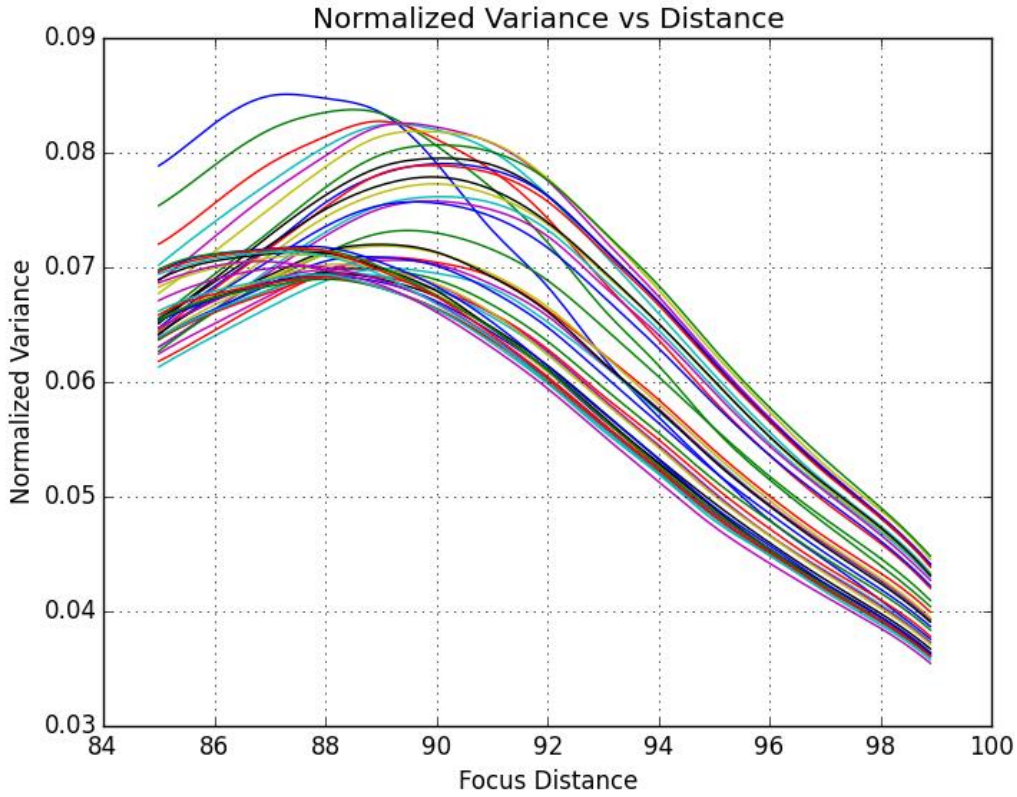
140 pixels

160 pixels



Focus

- Optimal focus is wavelength dependent
- If focussing manually, use appropriate wavelength for determining focus position



Conclusion

- Round-robin test revealed serious problems with sub-optimal acquisition practices and data processing
- Several possible sources of error
- Good calibration workflow critical
- Data quality can be dramatically improved by a better understanding of calibration pipeline
- Need for better guidance for cultural heritage users

Thank You!

Questions?

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