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

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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

### 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)

\[ y = 3.6458x + 407.15 \]

**Diagram:**
- 2D sensor
- Spatial
- \( \lambda \)
- Linear fit

\[ \text{Band number} \]

\[ \text{Wavelength} \]
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:

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

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

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

The DN(i,j) matrix is the image data.
The BG(i,j) matrix 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 \( \text{W/m}^2 \text{ nm sr} \)).
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
Colour patches:
Corresponding colours

HySpex VNIR-1800
RRT X-Rite CC data
RADIANCE image: (SI Unit (W/m^2 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)
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.

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.
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.
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 data

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.
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.

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, ...)

COST is supported by the EU Framework Programme Horizon 2020
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)

- Reference
- Hyspex VNIR1600
- Hyspex VNIR1800
- Specim V10E
- Specim V10E
- Specim SCMS-50-V10E

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Wavelength Standard Reflectances (SWIR)

Normalized Reflectance

Wavelength (nm)

Reference
Hyspex SWIR384
Specim SWIR
Specim N17E
Specim N17E
Specim SWIR (Factory)
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:

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

**Radiance (L)**

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

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

Relationship with sensor parameters and incoming light can be expressed as:

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

- \( i \) = 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 \( t \).

Radiometric Calibration

HySpex HSI cameras

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

The **BG(i,j)** matrix 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
Spectral Alignment Problems
Spectral Alignment Problems

Reflectance Spectra

Wavelength Dependent

Normalized Reflectance

Wavelength (nm)

Reference
Specim V10E
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
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
Amplitude Errors

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

99% Reflectance Standard Reference

Normalized Reflectance

Wavelength (nm)

50% Reflectance Standard Reference

Normalized Reflectance

Wavelength (nm)
How Reliable are Reference Values?

Measuring the wavelength standard with different spectrophotometers

Spectrophotometers generally calibrate with spectralon assuming spectral flatness
How Reliable are Reference Values?

Measuring the wavelength standard with different spectrophotometers

Spectrophotometers generally calibrate with spectralon assuming spectral flatness
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
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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