Reflectance-Based, Imaging Spectrometer Error Budget Training Course

Introduction to calibration - Calibration concepts

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Calibration concepts

• A well calibrated instrument does not compensate for:
  • Poor instrument performance
  • Poor methodology
  • Poor data collection

• A calibrated low performance instrument can be used to collect quality data if:
  • It is well characterised and not required to measure beyond it performance. For example the measurement requirements closely match the calibration setup.
  • Additional independent measurements are acquired to scale and compensate for equipment performance limitations.

• Most systems have their limitations and it is necessary to fully characterise them and apply them to the error budget.
  • Residual uncertainty after non linearity correction.
Calibration concepts

*for field spectroscopy instrumentation:*

- Spectral / wavelength calibration
  - Required accuracy
  - Wavelength verification
  - Interpolation and FWHM issues
- Reference panel calibration
  - Hemispherical – directional reflectance
  - Bi directional reflectance factors
  - Panel anisotropy
- Radiance & irradiance calibration standards
  - Radiance spheres
  - Comparison of radiance & irradiance standards
Reflectance Measurements I

• Spectral reflectance through radiometric measurements
  • Assumptions for simplicity:
    Surface reflectance is Lambertian
  • Measured with a calibrated radiance spectroradiometer
    
    \[ R_\lambda = \pi * L_\lambda / E_\lambda \]
    
    \[ = \left( \frac{DN_{L,\lambda} * S_{L,\lambda}}{DN_{E,\lambda} * S_{E,\lambda}} \right) \]

    where:
    \( DN_{L,\lambda} \) is the raw uncalibrated radiance signal at \( \lambda \)
    \( DN_{E,\lambda} \) is the raw uncalibrated irradiance signal at \( \lambda \)
    Where \( S_{L,\lambda} \) is the spectroradiometer’s radiance calibration factor at \( \lambda \)
    Where \( S_{E,\lambda} \) is the spectroradiometer’s irradiance calibration factor at \( \lambda \)

• When two instruments are used careful \( \lambda \) interpolation is required
• Demonstrates requirement for instrument spectral and radiometric calibration.
Reflectance Measurements II

• Spectral reflectance through comparison to Lambertian panel
  • Assumptions for simplicity:
    Reference panel & target surface reflectance are Lambertian
  • Measured with a single calibrated radiance spectroradiometer

\[ R_\lambda = \rho * \frac{L^{Tar}_\lambda}{L^{Ref}_\lambda} \]

\[ = \rho * \frac{DN^{Tar}_\lambda * S^L_\lambda}{DN^{Ref}_\lambda * S^L_\lambda} \]

\[ = \rho * \frac{DN^{Tar}_\lambda}{DN^{Ref}_\lambda} \]

• Demonstrates **no** requirement for radiometric calibration of spectroradiometer.
• Spectral calibration and panel reflectance calibration required.
Reflectance Measurements III

- Spectral reflectance through comparison to Reference Reflectance panel
  - No assumption that reference panel & target surface reflectance are Lambertian.
  - Measured with a single calibrated radiance spectroradiometer

\[
R_{\Omega,\lambda} = \beta_{0^\circ:45^\circ} \cdot \frac{L_{\text{Tar},\Omega,\lambda}}{L_{\text{Ref},\Omega,\lambda}}
\]

\[
= \beta_{0^\circ:45^\circ} \cdot \frac{DN_{\text{Tar},\Omega,\lambda}}{DN_{\text{Ref},\Omega,\lambda}}
\]

\(\Omega\) represents is illumination & viewing geometry (eg nadir view, 45° SZA).

\(\beta_{0^\circ:45^\circ}\) is the Panel radiance factor at wavelength \(\lambda\)

- Spectral calibration and bi-directional panel reflectance calibration required.
Spectral / Wavelength Cal.

• Note: When acquiring reflectance measurements using a single spectroradiometer and the reference reflectance panel method is it is not always necessary to seek sub-nanometer or sub-pixel accuracy when reflectance targets are featureless.

• The absolute opposite is true when using two different spectroradiometers and/or there are spectral features in the target reflectance.
Spectral Calibration Error
Single spectrometer (2nm error)
Spectral Calibration Error
Dual spectrometers – ($\Delta \lambda = 0.5 \text{ nm, unknown}$)
Spectral / Wavelength Verification.

- It is possible for all users to verify the accuracy of their instruments spectral calibration for a relative small investment.
- This should be conducted prior to and immediately after field campaigns.
- Recalibration of the spectroradiometer’s wavelength cal. should only be conducted after exhaustive tests and where there is a significant spectral error.
- Tools required:
  - Spectral line lamps with access to NIST atomic spectral database
  - Spectrally absorbing material
  - Doped reflectance panel option
  - Data analysis tool (example Excel spreadsheet)
Spectral Verification

• Spectral line lamps
  • Number of lamps available in either convenient packages or bare lamps for use with integrating spheres.
  • Fibre based spectroradiometers may be coupled to OO type sources.
  • Direct viewing systems with large fore optics will require an integrating sphere to fill the field of view of the system. The spectral line lamp cannot be successfully couple to the entrance optics with sufficient precision.
Emission Lines

<table>
<thead>
<tr>
<th>Element</th>
<th>Wavelength (nm)</th>
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</thead>
<tbody>
<tr>
<td>Hg-Ar</td>
<td>365.0</td>
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<tr>
<td>Ar</td>
<td>388.9</td>
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<tr>
<td>He</td>
<td>556.9</td>
</tr>
<tr>
<td>Kr</td>
<td>585.2</td>
</tr>
<tr>
<td>Ne</td>
<td>585.2</td>
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</tbody>
</table>

Be aware of doublets and triplets within the FWHM of your spectroradiometers.
Spectral Verification

Curve Fit

Data Points

FWHM = 3.2nm

Sampling Interval ≈ 1.4nm

λ

<table>
<thead>
<tr>
<th>Data Points</th>
<th>Curve Fit</th>
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<tbody>
<tr>
<td>430.63</td>
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<tr>
<td>432.02</td>
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<td>433.42</td>
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<td>436.21</td>
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<td>437.61</td>
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<td>439.01</td>
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<td>440.40</td>
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<tr>
<td>441.80</td>
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</tbody>
</table>

λ

50

100

0
Spectral Data Analysis Tool

Ocean Optocs QE Pro (Fluorescence) Spectrometer

Wavelength [nm]

Normalized Data
Spectral Data Analysis Tool
Spectral Data Analysis Tool
Gaussian Fit

ASD Field Spectroradiometers

<table>
<thead>
<tr>
<th>Equipment ID</th>
<th>ASD FR #6418 with RCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Date</td>
<td>2115</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Data</th>
<th>Norm</th>
<th>Continuum Removed</th>
<th>Norm</th>
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<tbody>
<tr>
<td>435.8</td>
<td>436.0</td>
<td>0.2</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>696.5</td>
<td>696.5</td>
<td>0.0</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>912.1</td>
<td>912.1</td>
<td>0.2</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>1046.9</td>
<td>1047.4</td>
<td>0.5</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>1371.9</td>
<td>1368.8</td>
<td>3.1</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>1694.1</td>
<td>1693.9</td>
<td>0.2</td>
<td>6.7</td>
<td></td>
</tr>
</tbody>
</table>

ASD FR #6418 with RCR

- **λ peak @ 435.8nm**: 436.0 nm (Error: 0.2 nm, FWHM: 6.7 nm)
- **λ peak @ 696.5nm**: 696.5 nm (Error: 0.0 nm, FWHM: 3.0 nm)
- **λ peak @ 912.1nm**: 912.1 nm (Error: -0.2 nm, FWHM: 4.9 nm)
- **λ peak @ 1046.9nm**: 1047.4 nm (Error: 0.5 nm, FWHM: 13.3 nm)
- **λ peak @ 1371.9nm**: 1368.8 nm (Error: -3.1 nm, FWHM: 15.4 nm)
- **λ peak @ 1694.1nm**: 1693.9 nm (Error: -0.2 nm, FWHM: 12.6 nm)
Spectral Data Analysis Tool

<table>
<thead>
<tr>
<th><strong>ASD Field Spectroradiometers</strong></th>
<th><strong>ASD FR #6418 with RCR</strong></th>
</tr>
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<td>ASD FR #6418 with RCR</td>
</tr>
<tr>
<td><strong>Test Date</strong></td>
<td>2115</td>
</tr>
<tr>
<td>λ&lt;sub&gt;peak&lt;/sub&gt; @ 435.8nm</td>
<td>436.0</td>
</tr>
<tr>
<td>λ Error</td>
<td>0.2</td>
</tr>
<tr>
<td>FWHM</td>
<td>6.7</td>
</tr>
<tr>
<td>λ&lt;sub&gt;peak&lt;/sub&gt; @ 696.5nm</td>
<td>696.5</td>
</tr>
<tr>
<td>λ Error</td>
<td>0.0</td>
</tr>
<tr>
<td>FWHM</td>
<td>3.0</td>
</tr>
<tr>
<td>λ&lt;sub&gt;peak&lt;/sub&gt; @ 912.3nm</td>
<td>912.1</td>
</tr>
<tr>
<td>λ Error</td>
<td>-0.2</td>
</tr>
<tr>
<td>FWHM</td>
<td>4.9</td>
</tr>
<tr>
<td>λ&lt;sub&gt;peak&lt;/sub&gt; @ 1046.9nm</td>
<td>1047.4</td>
</tr>
<tr>
<td>λ Error</td>
<td>0.5</td>
</tr>
<tr>
<td>FWHM</td>
<td>13.3</td>
</tr>
<tr>
<td>λ&lt;sub&gt;peak&lt;/sub&gt; @ 1371.9nm</td>
<td>1368.8</td>
</tr>
<tr>
<td>λ Error</td>
<td>-3.1</td>
</tr>
<tr>
<td>FWHM</td>
<td>15.4</td>
</tr>
<tr>
<td>λ&lt;sub&gt;peak&lt;/sub&gt; @ 1694.1nm</td>
<td>1693.9</td>
</tr>
<tr>
<td>λ Error</td>
<td>-0.2</td>
</tr>
<tr>
<td>FWHM</td>
<td>12.6</td>
</tr>
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</table>

![Graph showing spectral data analysis](image)
ASD Data Interpolation

Further information: http://fsf.nerc.ac.uk/resources/general/asd_wavelength_interpolation.zip
Spectral Verification

- Spectral absorption material
  - Mylar & acetate sheet
  - Useful SWIR features
  - Convenient for in-field testing using reflectance probe accessories

- Doped reflectance panels
  - Erbium, Holmium & Dysprosium oxides doped reflectance panels
  - Convenient for in-field testing using reflectance probe accessories

- Curve fitting required
  - Spectral features have significant width
  - Cannot derive system FWHM from this data (?)

- Calibrated with or without continuum removal ?
- Spectral stability ?
Spectral Verification
Spectral Calibration

- Use monochromatic light and tuneable lasers to scan across each pixel and determine their centre wavelengths and FWHM.
Calibrated Reference Reflectance Panels

• Most reference reflectance panels are calibrated by the manufacture using an 8°/T directional-hemispherical measurement geometry.

• Field spectroscopy on clear blue sky days is closer to bi-directional measurement geometry (nadir/SZA) and will only have a significant diffuse illumination component from sky radiance at shorter wavelengths.

• Reference reflectance panels such as Spectralon do not have true Lambertian reflectance and therefore the two measurement geometries will yield difference calibration values depending on the illumination and measurement angles.
Calibration of Reference Reflectance Panels

- NIST Technical Note 1413 on reflectance factors of pressed PTFE reference panel, but inly 380 – 700nm.
- PTB and other NMIs offer bi-directional radiance factor calibration of Spectralon panels with improved uncertainties.
- Laboratory cross calibration possible
- Laboratory bi-directional tests indicate anisotropies of Spectralon are largely independent of wavelength.
Bi-directional radiance factors, $\beta_{0^\circ:45^\circ}$ for reference reflectance panel (2005)
Bi-directional radiance factors, $\beta_{0^\circ:45^\circ}$ for reference reflectance panel (2013)

Ref – 2013, AIP Proceedings, Providing Radiometric Traceability for the Calibration Home Base of DLR by PTB
D. R. Tauberta, .... and A. Baumgartner
Spectral Reflectance (8°/T) Bi-directional Radiance Factors

Requires refining and testing
Radiance Calibration Standards

- 0.5m $\phi$ sphere
- BaSO$_4$ coating
- Excellent flat field uniformity

- 0.25m $\phi$ sphere
- Spectralon liner
- Improved SWIR radiance
Irradiance & Radiance Calibration
Standard Uncertainty

**Comparison of NMI Calibration Uncertainty, Radiance Sphere vs FEL Irradiance Standards**
Irradiance -> Radiance Transfer Standard

- RASTA, spectral radiance transfer standard of the German Aerospace Center (DLR)
- FEL Irradiance Standard
- Spectralon reflectance panel calibrated for bi-directional radiance at 0°, 45°
- Multi-spectral monitors
- Transfer spectroradiometer

Ref – 2013, AIP Proceedings, D. R. Tauberta, .... and A. Baumgartner, Providing Radiometric Traceability for the Calibration Home Base of DLR by PTB
Conclusions:

• Calibration does not in general fix a broken instrument.

• Reflectance data require verification of instruments spectral calibration and analysis as to significance of these errors.

• Inclusion of an instrument's FWHM will enhance data quality.

• Bi-directional calibration of reference reflectance panels more closely matches field measurement conditions compared to directional -hemispherical calibration.

• Bi-directional spectral calibration of panels may be difficult for many users but panel calibration method should be stated in the meta data.