Vicarious Calibration
Reflectance-Based Approach
Cross-Calibration Method
Evaluation of Uncertainties

Cibele Teixeira Pinto, Ph.D.
Imaging Engineer
Image Processing Laboratory
South Dakota State University
Cibele.TeixeiraPinto@sdstate.edu

Workshop - CALCON Technical Meeting
Meeting on Characterization and Radiometric Calibration for Remote Sensing

Eccles Conference Center, Utah State University, Logan, UT, June 18, 2018
Agenda

1. Introduction
2. Reflectance-Based Vicarious Field Campaigns
   a. Reflectance surface measurements
   b. Atmospheric measurements
   c. Radiative Transfer Code
   d. Image analysis and calibration coefficients
3. Cross-Calibration Method
   a. Spectral Response Function
   b. Spectral Band Adjustment Factor
   c. Geometry Differences
   d. Atmosphere Difference
   c. Image Pair
4. Evaluation of Uncertainties
   a. ISO-GUM Method
   b. Monte Carlo Simulation Method
   c. Source of Uncertainties in Reflectance-Based approach
   d. Source of Uncertainties in Cross-Calibration Method
5. Final Consideration
6. Question
High degree of reliability in the sensor absolute radiometric calibration is indispensable to use the data for quantitative investigations.

\[ L_\lambda = G_\lambda \times DN_\lambda + offset_\lambda \]
Introduction

Quantitative Analysis

Absolute Radiometric Calibration
- On-board calibration

Vicarious Calibration refers to those calibration methods that are performed without the use of systems on-board the satellite.

- Reflectance-Based Approach
- Cross-Calibration Method
- Pseudo-Invariant Calibration Sites

Image Source: Romero da Costa Moreira
Reflectance-Based Approach

\[ L = G \times DN + \text{offset} \]
Reflectance-Based Approach

1. Laboratory Work
   Instruments calibration

2. Field Work
   - Surface Radiance Measurements
   - Atmospheric Characterization

3. Radiative Transfer Code
   Atmospheric Interference Determination

4. Image Analysis
   - Sensor Image
   - DN Image Analysis

5. Calibration Coefficients
   \[ L_{TOA} \pm \sigma \]

\[ DN_{Mean} \pm \sigma \]
Reflectance-Based Approach

**Laboratory Work**

Characterize and determine the conditions of the instruments (before and after the fieldwork).

**Reference Panel**

**Spectroradiometer**
Reflectance-Based Approach

Laboratory Work

<table>
<thead>
<tr>
<th>Level</th>
<th>Lamps</th>
<th>Total Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150, 100, 45 and 45 W</td>
<td>340</td>
</tr>
<tr>
<td>2</td>
<td>150, 45 and 45 W</td>
<td>240</td>
</tr>
<tr>
<td>3</td>
<td>45 and 45 W</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>45 W</td>
<td>45</td>
</tr>
</tbody>
</table>
Reflectance-Based Approach

Laboratory Work

F6426 → Reference spectroradiometer (Lab)
F18184 → Fieldwork spectroradiometer

Uncertainties:
F6426: 0.0013 to 0.84%
F18184: 0.0018 to 0.76%

< 1%
# Reflectance-Based Approach

## Laboratory Work

### Reference Panel

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Reflectance Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>500</td>
<td>0.98</td>
</tr>
<tr>
<td>1000</td>
<td>0.96</td>
</tr>
<tr>
<td>1500</td>
<td>0.94</td>
</tr>
<tr>
<td>2000</td>
<td>0.92</td>
</tr>
<tr>
<td>2500</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Reference Panel (Lab)
Uncertainty : 0.001 - 0.067%
LABSPHERE (2012)
Reflectance-Based Approach

Laboratory Work

Reference Panel

Uncertainties:

- < 0.21%  for 350 to 450 nm
- < 0.030% for 450 to 2200 nm
- < 0.11%  for 2200 to 2500 nm
- < 0.25%  overall
Reflectance-Based Approach

1. Laboratory Work
   Instruments calibration

2. Field Work
   Surface Radiance Measurements
   Atmospheric Characterization

3. Radiative Transfer Code
   Atmospheric Interference Determination

4. Image Analysis
   Sensor Image
   DN Image Analysis
   \[ L_{TOA} \pm \sigma \]
   \[ DN_{Mean} \pm \sigma \]
Reflectance-Based Approach

FieldWork
Reflectance Factor

- FieldSpec Pro;
- Spectralon Panel;

Atacama Desert, Chile

\( RF_{\text{target}}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) = \frac{L_{\text{target}}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)}{L_{\text{panel}}(\theta_i, \phi_i, \lambda)} \times k(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) \)

\( RF_{\text{target}} = \frac{L_{\text{target}}}{L_{\text{panel}}} \times k_{\lambda} \)
Reflectance-Based Approach

FieldWork

Reflectance Factor

→ FieldSpec Pro;
→ Spectralon Panel;

Algodones Dunes, USA

RF_{target}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) = \frac{L_{target}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)}{L_{panel}(\theta_i, \phi_i, \lambda)} \times k(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)

RF_{target} = \frac{L_{target}}{L_{panel}} \times k_{\lambda}
Reflectance-Based Approach

FieldWork
Reflectance Factor

Coefficient of Variation:

08/19/14 → 2.12 - 3.03%
08/20/14 → 3.06 - 3.99%
08/21/14 → 2.63 - 3.47%
08/22/14 → 2.70 - 3.72%

General: CV < 4%

Except: Water absorption (around 1.4 μm and 1.9 μm)
Very noisy >2.4 μm
Reflectance-Based Approach

FieldWork
Atmospheric Characterization

CE317/CIMEL
Manual Sun Photometer

CE318 (CIMEL)
Automated Sun Photometer

Automated Solar Radiometer (ASR)

The sun photometer output signal can be modeled according to Beer’s Law:

\[ V_\lambda = \frac{V_{0,\lambda} \times e^{-\tau_\lambda \times m}}{D^2} \]

Source: PINTO et al. (2015)

\( V_\lambda \) is sun photometer output, proportional to the solar irradiance for the wavelength \( \lambda \);
Reflectance-Based Approach

FieldWork

The sun photometer output signal can be modeled according to Beer's Law:

\[ V_\lambda = \frac{V_{0,\lambda} \times e^{-\tau_\lambda \times m}}{D^2} \]

- \( V_\lambda \) is sun photometer output, proportional to the solar irradiance for the wavelength \( \lambda \);
- \( V_{0,\lambda} \) is the calibration constant for the wavelength \( \lambda \);
- \( d \) is Earth-Sun distance factor in Astronomical Units;
- \( m \) is the optical airmass [unitless]; and
- \( \tau_\lambda \) is the total optical depth [unitless] for the wavelength \( \lambda \).

Atmospheric Characterization

The total optical depth, \( \tau_\lambda \), is the attenuation result by molecules (Rayleigh scattering), aerosols, ozone, water vapor and other mixed gases (ROLLI, 2000).

\[ \tau_\lambda = \tau_{Rayleigh,\lambda} + \tau_{Aerossols,\lambda} + \tau_{O3,\lambda} + \tau_{Water,\lambda} + \tau_{CO2,\lambda} + \tau_{Others,\lambda} \]

Water Band: 936 nm

This band can be used to estimate the concentrations of water vapor
Reflectance-Based Approach

FieldWork

Atmospheric Characterization

Atmospheric Parameters:
- Visibility
- Aerosol Optical Depth
- Water Column Abundance
- Ozone
- Temperature
- Pressure

<table>
<thead>
<tr>
<th></th>
<th>Atacama Desert</th>
<th>Algodones Dunes</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS (km)</td>
<td>31.3 ± 0.8</td>
<td>40.4 ± 2.3</td>
</tr>
<tr>
<td>$\tau_{\text{Aerosol,550nm}}$</td>
<td>0.114 ± 0.009</td>
<td>0.066 ± 0.017</td>
</tr>
<tr>
<td>$W$ (g/cm$^2$)</td>
<td>0.429 ± 0.020</td>
<td>1.055 ± 0.014</td>
</tr>
</tbody>
</table>

An AOD lower than 0.1 indicates clear sky, whereas a value of 1 corresponds to very hazy conditions.

Chile's Atacama desert: World's driest place.
Reflectance-Based Approach

1. Laboratory Work
   - Instruments calibration

2. FieldWork
   - Surface Radiance Measurements
   - Atmospheric Characterization

3. Radiative Transfer Code
   - Atmospheric Interference Determination

4. Image Analysis
   - Sensor Image
   - DN Image Analysis

5. Calibration Coefficients
   - $L_{TOA} \pm \sigma$
   - $DN_{Mean} \pm \sigma$
Reflectance-Based Approach

MODTRAN

Inputs to MODTRAN:
- Ground Reflectance
- Column Water Vapor
- VIS
- AOD
- Ozone
- Temperature
- Pressure

The data products derived from the ground measurements are used as input to Modtran

<table>
<thead>
<tr>
<th>Band (nm)</th>
<th>( \tau_{\text{Aerosol}} )</th>
<th>( \sigma_{\text{Relative}}(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/19/2014</td>
<td>1020 0.0789 ± 0.0023</td>
<td>2.87</td>
</tr>
<tr>
<td></td>
<td>870 0.074 ± 0.004</td>
<td>4.82</td>
</tr>
<tr>
<td></td>
<td>670 0.099 ± 0.003</td>
<td>3.23</td>
</tr>
<tr>
<td></td>
<td>440 0.133 ± 0.003</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>8/20/2014 1020 0.0989 ± 0.0012</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>870 0.0561 ± 0.0009</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td>670 0.0908 ± 0.0010</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>440 0.1187 ± 0.0014</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>8/21/2014 1020 0.0721 ± 0.0009</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>870 0.0328 ± 0.0011</td>
<td>3.21</td>
</tr>
<tr>
<td></td>
<td>670 0.0643 ± 0.0014</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>440 0.0835 ± 0.0012</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>8/22/2014 1020 0.0817 ± 0.0011</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>870 0.0386 ± 0.0006</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>670 0.0705 ± 0.0007</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>440 0.0978 ± 0.0009</td>
<td>0.95</td>
</tr>
</tbody>
</table>

The data products derived from the ground measurements are used as input to Modtran.
Reflectance-Based Approach

TOA radiance predicted by MODTRAN:

Uncertainty: 2.5-5.5%

Uncertainty: 2.2-4.9%
Reflectance-Based Approach

1. Laboratory Work
   - Instruments calibration

2. FieldWork
   - Surface Radiance Measurements
   - Atmospheric Characterization

3. Radiative Transfer Code
   - Atmospheric Interference Determination

4. Image Analysis
   - Sensor Image
   - DN Image Analysis

5. Calibration Coefficients
   - $L_{TOA} \pm \sigma$
   - $DN_{Mean} \pm \sigma$
Reflectance-Based Approach

Image Analysis

San Pedro de Atacama

Pixels

Pixels

$DN_{\text{mean}} \pm \sigma$
## Reflectance-Based Approach

### Image Analysis

**CBERS-4 Sensors:**

<table>
<thead>
<tr>
<th>Band</th>
<th>MUX</th>
<th>Digital Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td></td>
<td>56.4 ± 1.1</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td>66.8 ± 1.6</td>
</tr>
<tr>
<td>B3</td>
<td></td>
<td>74.2 ± 1.9</td>
</tr>
<tr>
<td>B4</td>
<td></td>
<td>66.7 ± 1.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Band</th>
<th>WFI</th>
<th>Digital Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td></td>
<td>258.8 ± 2.7</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td>212.7 ± 2.9</td>
</tr>
<tr>
<td>B3</td>
<td></td>
<td>320 ± 5</td>
</tr>
<tr>
<td>B4</td>
<td></td>
<td>260 ± 3</td>
</tr>
</tbody>
</table>

**Why are these values so different if it is the same ground measured surface?**
Reflectance-Based Approach

1. Laboratory Work
   Instruments calibration

2. Field Work
   Surface Radiance Measurements
   Atmospheric Characterization

3. Radiative Transfer Code
   Atmospheric Interference Determination

4. Image Analysis
   Sensor Image
   DN Image Analysis

5. Calibration Coefficients
   \( L_{\text{TOA}} \pm \sigma \)
   \( DN_{\text{Mean}} \pm \sigma \)
Reflectance-Based Approach

TOA radiance predicted by MODTRAN:

The radiance at a spectral band for any sensor:

\[ L_{\text{band}} = \frac{\int_0^\infty L_\lambda \times SRF_\lambda d\lambda}{\int_0^\infty SRF_\lambda d\lambda} \]

<table>
<thead>
<tr>
<th>Band</th>
<th>MUX</th>
<th>Digital Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td></td>
<td>56.4 ± 1.1</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td>66.8 ± 1.6</td>
</tr>
<tr>
<td>B3</td>
<td></td>
<td>74.2 ± 1.9</td>
</tr>
<tr>
<td>B4</td>
<td></td>
<td>66.7 ± 1.6</td>
</tr>
</tbody>
</table>
Reflectance-Based Approach

The output from MODTRAN (hyperspectral TOA radiance) are averaged with the Spectral Response Function (SRF) of the sensor of interest to find the band averaged at-sensor radiance values at each spectral band.

Mathematical Model:

\[ L_{band} = \frac{\int_{0}^{\infty} L_\lambda \times SRF_\lambda d\lambda}{\int_{0}^{\infty} SRF_\lambda d\lambda} \]
## Reflectance-Based Approach

<table>
<thead>
<tr>
<th>Band</th>
<th>MUX</th>
<th>Digital Number</th>
<th>TOA Radiance MODTRAN (Watts/(m²<em>srad</em>μm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>56.4 ± 1.1</td>
<td>96 ± 3</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>66.8 ± 1.6</td>
<td>108 ± 4</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>74.2 ± 1.9</td>
<td>114 ± 5</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>66.7 ± 1.6</td>
<td>91 ± 4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Band</th>
<th>WFI</th>
<th>Digital Number</th>
<th>TOA Radiance MODTRAN (Watts/(m²<em>srad</em>μm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>258.8 ± 2.7</td>
<td>96 ± 3</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>212.7 ± 2.9</td>
<td>108 ± 4</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>320 ± 5</td>
<td>114 ± 5</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>260 ± 3</td>
<td>92 ± 4</td>
<td></td>
</tr>
</tbody>
</table>

Reflectance-based approach MUX/WFI/CBERS-4:

Uncertainty Algodones Dunes: 3.1-4.4%
Reflectance-Based Approach

\[ L = G \times ND + \text{offset} \]
Reflectance-Based Approach

Radiometric Coefficients

Reflectance-Based Approach

Blue Band

\[ L = G \cdot DN + \text{offset} \]

\[ L = G \cdot DN \]

Radiance [W/(m^2 \cdot sr \cdot \mu m)]

Digital Number

Atacama Desert

Algodones Dunes

Libya-4

Cross-Calibration
Cross-Calibration Method

Sensor A
Reference

Sensor B
Sensor to be calibrated

Common Area

Not just SBAF...

$DN_{\text{from image: Sensor A}}$ $\rightarrow L = G_{\text{Sensor A}} \times DN + offset_{\text{Sensor A}}$ $\rightarrow$ TOA Radiance from image ($L_{\text{TOA}}$)

Comparison:

$G_{\text{Sensor B}} + offset_{\text{Sensor B}}$

SBAF to compensate the SRF differences between the sensors.
The basic principle (or idealized conditions) of cross-calibration is that two sensors should make identical measurements when they view the same ground target, at the same time, with the same spatial and spectral responses and the same viewing geometry (CHANDER et al. 2013).

Cross-Calibration Method

**Sensor A**
Reference

**Sensor B**
Sensor to be calibrated

Common Area

$DN$ from image:
Sensor A

$L = G_{SensorA} \times DN + offset_{SensorA}$

TOA Radiance from image ($L_{TOA}$)
Sensor A

Spectral Band Adjustment

Comparison:
$G_{SensorB} \cdot offset_{SensorB}$

**$DN$ from image:**
Sensor B

SBAF to compensate the SRF differences between the sensors.
Cross-Calibration Method

However, all these “ideal” conditions rarely occur simultaneously, then, it is essential to apply a series of thresholds to set the measurements and adjusting the data in a comparable scale. For example, even if the same ground target is imaged at a same day by two instruments, sun-angle and off-nadir viewing geometry differences can occur between acquisitions.
Cross-Calibration Method

Need for Intercalibration

Regular cross-calibration is necessary for several reasons:

1) Cross-calibration has the advantage of reducing overall costs;

2) Data continuity requires consistency in quality and interpretation of image data acquired by different imaging sensors. Cross-calibration is the only viable solution to tie similar sensors and differing sensors onto a common radiometric scale, thus providing an important role in mission continuity, interoperability, and data fusion;

3) Cross-calibration is critical where onboard references are not available;
Cross-Calibration Method

1. Obtaining Images Pair
   - Target (Ground Surface)
     - Sensor\textsubscript{reference}
     - Image\textsubscript{reference}
     - Sensor\textsubscript{calibrate}
     - Image\textsubscript{calibrate}

2. Image Processing
   - $DN \rightarrow$ Radiance
   - $DN_{\text{calibrate}}$

3. Determination of the Spectral Band Adjustment Factor
   - Spectral Band Adjustment Factor (SBAF)

4. Comparison of the Data
   - Radiometric Coefficients
     - $L_{\text{TOA}} \pm \sigma \leftrightarrow DN_{\text{cal}} \pm \sigma$
Cross-Calibration Method

Image Pair

It is necessary to be careful when choosing the pair (or pairs) of images that will be used to perform the cross-calibration procedures:

1. **The first issue is related to the time interval between the two images;**

   (If the pair of images is acquired almost simultaneously it is possible to assume that the surface and the atmospheric conditions did not change significantly during the two image acquisitions).

2. **The second issue is related to the type of surface chosen for calibration;**

   (It is advisable to use images that contain spatially uniform areas and some isotropic characteristics. By choosing images with these characteristics it is not necessary to correct (or make minimal corrections) due to differences between the solar illumination geometries conditions and observation geometry of the two sensors - BRDF).
### Cross-Calibration Method

**MUX/WFI/CBERS-4 and OLI/Landsat-8**

Metadata of scenes used for MUX/WFI/CBERS-4 and OLI/Landsat-8 cross-calibration:

<table>
<thead>
<tr>
<th>Sensor/Satellite</th>
<th>Date</th>
<th>Acquisition Time</th>
<th>Path/Row</th>
<th>Solar zenith angle</th>
<th>Solar azimuth angle</th>
<th>Look Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLI/Landsat-8</td>
<td>07/07/2015</td>
<td>08:54</td>
<td>181/040</td>
<td>22.5°</td>
<td>102.0°</td>
<td>Nadir</td>
</tr>
<tr>
<td>MUX/CBERS-4</td>
<td>07/07/2015</td>
<td>09:20</td>
<td>095/068</td>
<td>17.2°</td>
<td>106.6°</td>
<td>Nadir</td>
</tr>
<tr>
<td>WFI/CBERS-4</td>
<td>07/07/2015</td>
<td>09:20</td>
<td>094/069</td>
<td>16.4°</td>
<td>106.3°</td>
<td>Nadir</td>
</tr>
</tbody>
</table>

**Libya-4**

<table>
<thead>
<tr>
<th>Sensor/Satellite</th>
<th>Date</th>
<th>Acquisition Time</th>
<th>Path/Row</th>
<th>Solar zenith angle</th>
<th>Solar azimuth angle</th>
<th>Look Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLI/Landsat-8</td>
<td>11/28/2015</td>
<td>14:31</td>
<td>233/76</td>
<td>25.3°</td>
<td>91.26°</td>
<td>Nadir</td>
</tr>
<tr>
<td>MUX/CBERS-4</td>
<td>11/28/2015</td>
<td>14:52</td>
<td>177/126</td>
<td>19.8°</td>
<td>88.43°</td>
<td>Nadir</td>
</tr>
<tr>
<td>WFI/CBERS-4</td>
<td>11/28/2015</td>
<td>14:51</td>
<td>177/123</td>
<td>18.9°</td>
<td>97.8°</td>
<td>Nadir</td>
</tr>
</tbody>
</table>

**Atacama Desert**

<table>
<thead>
<tr>
<th>Sensor/Satellite</th>
<th>Date</th>
<th>Acquisition Time</th>
<th>Path/Row</th>
<th>Solar zenith angle</th>
<th>Solar azimuth angle</th>
<th>Look Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLI/Landsat-8</td>
<td>11/28/2015</td>
<td>14:31</td>
<td>233/76</td>
<td>25.3°</td>
<td>91.26°</td>
<td>Nadir</td>
</tr>
<tr>
<td>MUX/CBERS-4</td>
<td>11/28/2015</td>
<td>14:52</td>
<td>177/126</td>
<td>19.8°</td>
<td>88.43°</td>
<td>Nadir</td>
</tr>
<tr>
<td>WFI/CBERS-4</td>
<td>11/28/2015</td>
<td>14:51</td>
<td>177/123</td>
<td>18.9°</td>
<td>97.8°</td>
<td>Nadir</td>
</tr>
</tbody>
</table>
Cross-Calibration Method

MUX/WFI/CBERS-4 and OLI/Landsat-8

Libya-4

Atacama Desert, Chile
Cross-Calibration Method

1. Obtaining Images Pair
   - Target (Ground Surface)
     - Sensor \(_{\text{reference}}\)
       - Image \(_{\text{reference}}\)
     - Sensor \(_{\text{calibrate}}\)
       - Image \(_{\text{calibrate}}\)

2. Image Processing
   - \(DN \rightarrow \text{Radiance}\)
   - \(D\bar{N}_{\text{calibrate}}\)

3. Determination of the Spectral Band Adjustment Factor
   - Spectral Band Adjustment Factor (SBAF)

4. Comparison of the Data
   - Radiometric Coefficients
     - \(L_{\text{TOA}} \pm \sigma \leftrightarrow D\bar{N}_{\text{cal}} \pm \sigma\)
**Cross-Calibration Method**

**MUX/WFI/CBERS-4 and OLI/Landsat-8**

**Libya-4**

**Landsat-8/OLI**

**CBERS-4/MUX**

**CBERS-4/WFI**

\[ L_{\text{mean}} \pm \sigma \]

\[ L = G \times DN + \text{offset} \]

\[ DN_{\text{mean}} \pm \sigma \]
Cross-Calibration Method

1. Obtaining Images Pair
   - Target (Ground Surface)
   - Sensor \text{reference}
   - Image \text{reference}
   - Sensor \text{calibrate}
   - Image \text{calibrate}

2. Image Processing
   - \( DN \rightarrow \text{Radiance} \)
   - \( D\bar{N} \) \text{calibrate}

3. Determination of the Spectral Band Adjustment Factor
   - Spectral Band Adjustment Factor (SBAF)

4. Comparison of the Data
   - Radiometric Coefficients
   - \( L_{TOA} \pm \sigma \leftrightarrow D\bar{N}_{\text{cal}} \pm \sigma \)
### Cross-Calibration Method

#### Spectral Response Function

<table>
<thead>
<tr>
<th>#</th>
<th>OLI Landsat-8</th>
<th>MUX CBERS-4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Band (µm)</td>
<td>Spatial Resolution</td>
</tr>
<tr>
<td>B1</td>
<td>0.433 – 0.453</td>
<td>30</td>
</tr>
<tr>
<td>B2</td>
<td>0.450 – 0.515</td>
<td>30</td>
</tr>
<tr>
<td>B3</td>
<td>0.525 – 0.600</td>
<td>30</td>
</tr>
<tr>
<td>B4</td>
<td>0.630 – 0.680</td>
<td>30</td>
</tr>
<tr>
<td>B5</td>
<td>0.845 – 0.885</td>
<td>30</td>
</tr>
<tr>
<td>B6</td>
<td>1.560 – 1.660</td>
<td>30</td>
</tr>
<tr>
<td>B7</td>
<td>2.100 – 2.300</td>
<td>30</td>
</tr>
<tr>
<td>B8</td>
<td>0.500 – 0.680</td>
<td>15</td>
</tr>
<tr>
<td>B9</td>
<td>1.360 – 1.390</td>
<td>30</td>
</tr>
</tbody>
</table>

✓ The spectral bands of MUX/CBERS-4 operate in region of the electromagnetic spectrum nearby bands 2, 3, 4 and 5 of the OLI/Landsat-8 sensor;
Cross-Calibration Method

Spectral Response Function

These differences between two sensors caused by spectral response mismatches can be compensated by using a Spectral Band Adjustment Factor (SBAF)
Cross-Calibration Method

**Spectral Band Adjustment Factor (SBAF)**

The value of the reflectance in a specific spectral band of a sensor is calculated by integrating the SRF of the sensor with the hyperspectral reflectance profile, averaged by the respective SRF:

\[
\rho_{band} = \frac{\int_0^\infty \rho_\lambda \times SRF_\lambda \, d\lambda}{\int_0^\infty SRF_\lambda \, d\lambda}
\]

\(\rho_{band}\) is the averaged reflectance for each spectral band of the sensor [unitless]; \(\rho_\lambda\) is the hyperspectral reflectance incident [unitless]; and \(SRF\) is the Spectral Response Function [unitless].
Cross-Calibration Method

Spectral Band Adjustment Factor (SBAF)

**Reference Sensor**

\[
\rho_{\text{band}, \text{ref}} = \frac{\int_0^\infty \rho_\lambda \times SRF_{\text{ref}, \lambda} d\lambda}{\int_0^\infty SRF_{\text{ref}, \lambda} d\lambda}
\]

**Un-calibrated Sensor**

\[
\rho_{\text{band}, \text{cal}} = \frac{\int_0^\infty \rho_\lambda \times SRF_{\text{cal}, \lambda} d\lambda}{\int_0^\infty SRF_{\text{cal}, \lambda} d\lambda}
\]

**SBAF**

\[
SBAF_{\text{band}} = \frac{\rho_{\lambda, \text{ref}}}{\rho_{\lambda, \text{cal}}}
\]

\[
SBAF_{\text{band}} = \frac{\int_0^\infty \rho_\lambda \times SRF_{\lambda, \text{ref}} d\lambda}{\int_0^\infty SRF_{\lambda, \text{ref}} d\lambda} \times \frac{\int_0^\infty SRF_{\lambda, \text{cal}} d\lambda}{\int_0^\infty \rho_\lambda \times SRF_{\lambda, \text{cal}} d\lambda}
\]
Cross-Calibration Method

Spectral Band Adjustment Factor (SBAF)

\[ SBAF_{\text{band}} = \frac{\rho_{\lambda, \text{ref}}}{\rho_{\lambda, \text{cal}}} \]

\[ SBAF_{\text{band}} = \frac{\int_{0}^{\infty} \rho_{\lambda} \times SRF_{\lambda, \text{ref}} \, d\lambda}{\int_{0}^{\infty} SRF_{\lambda, \text{cal}} \, d\lambda} \times \frac{\int_{0}^{\infty} \rho_{\lambda} \times SRF_{\lambda, \text{cal}} \, d\lambda}{\int_{0}^{\infty} SRF_{\lambda, \text{ref}} \, d\lambda} \]

Hyperspectral reflectance profile?

EO-1 Hyperion!
Cross-Calibration Method

Spectral Band Adjustment Factor (SBAF)

\[
SBAF_{\text{band}} = \frac{\rho_{\lambda, \text{ref}}}{\rho_{\lambda, \text{cal}}}
\]

\[
SBAF_{\text{band}} = \frac{\rho_{\lambda}}{\int_{0}^{\infty} SRF_{\lambda, \text{ref}} d\lambda} \times \frac{\int_{0}^{\infty} SRF_{\lambda, \text{cal}} d\lambda}{\rho_{\lambda} \times \int_{0}^{\infty} SRF_{\lambda, \text{cal}} d\lambda}
\]

Hyperspectral reflectance profile?

Measurements of surface reflectance! (after “adding” the atmosphere)
Cross-Calibration Method

Reference sensor vs Uncalibrated Sensor

TOA reflectance:

\[ \rho_{\text{ref}, \lambda} = \frac{\pi \times L_{\text{ref}, \lambda} \times d_{\text{ref}}^2}{\left( E_{0, \lambda} \times \cos \theta \right)_{\text{ref}}} \]

\[ \rho_{\text{cal}, \lambda} = \frac{\pi \times L_{\text{cal}, \lambda} \times d_{\text{cal}}^2}{\left( E_{0, \lambda} \times \cos \theta \right)_{\text{cal}}} \]

\[ \pi = \frac{\rho_{\text{ref}, \lambda} \times \left( E_{0, \lambda} \times \cos \theta \right)_{\text{ref}}}{L_{\text{ref}, \lambda} \times d_{\text{ref}}^2} \]

\[ \pi = \frac{\rho_{\text{cal}, \lambda} \times \left( E_{0, \lambda} \times \cos \theta \right)_{\text{cal}}}{L_{\text{cal}, \lambda} \times d_{\text{cal}}^2} \]

After algebraic manipulation…
Cross-Calibration Method

Reference sensor vs Uncalibrated Sensor

\[
(L_{cal,\lambda}) = \frac{\rho_{cal,\lambda}}{\rho_{ref,\lambda}} \times \frac{d_{ref}^2}{d_{cal}^2} \times \frac{\cos \theta_{cal}}{\cos \theta_{ref}} \times \frac{E_{cal,\lambda}}{E_{ref,\lambda}} \times (L_{ref,\lambda})
\]

- Spectral Band Adjustment Factor (SBAF)
- Earth-Sun distance
- \(\theta\) is the solar zenith angle (illumination)
- Exoatmospheric solar irradiance

With this equation the radiance value of the sensor to be calibrated is obtained from the reference sensor radiance.
Cross-Calibration Method

1. Obtaining Images Pair
   - Target (Ground Surface)
     - Sensor \(_{reference}\)
     - Image \(_{reference}\)
     - Sensor \(_{calibrate}\)
     - Image \(_{calibrate}\)

2. Image Processing
   - \(DN \rightarrow\) Radiance
   - \(DN\) \(_{calibrate}\)

3. Determination of the Spectral Band Adjustment Factor
   - Spectral Band Adjustment Factor (SBAF)

4. Comparison of the Data
   - Radiometric Coefficients
     \(L_{TOA} \pm \sigma \leftrightarrow DN_{cal} \pm \sigma\)
## Cross-Calibration Method

<table>
<thead>
<tr>
<th>Band</th>
<th>Digital Number</th>
<th>TOA Radiance from OLI [W/(m²·sr·μm)]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MUX</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>90 ± 3</td>
<td>147 ± 9</td>
</tr>
<tr>
<td>B2</td>
<td>112 ± 4</td>
<td>183 ± 11</td>
</tr>
<tr>
<td>B3</td>
<td>131 ± 4</td>
<td>214 ± 13</td>
</tr>
<tr>
<td>B4</td>
<td>118 ± 3</td>
<td>171 ± 11</td>
</tr>
<tr>
<td><strong>WFI</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>379 ± 12</td>
<td>149 ± 9</td>
</tr>
<tr>
<td>B2</td>
<td>373 ± 12</td>
<td>182 ± 11</td>
</tr>
<tr>
<td>B3</td>
<td>590 ± 17</td>
<td>214 ± 13</td>
</tr>
<tr>
<td>B4</td>
<td>495 ± 13</td>
<td>173 ± 11</td>
</tr>
</tbody>
</table>

**Uncertainty Libya-4:** 6.0-6.4%
Cross-Calibration Method

Radiometric Coefficients

Reflectance-Based Approach

Blue Band

\[ L = G \times DN + \text{offset} \]

\[ L = G \times DN \]

Radiance \([W/(m^2 \cdot sr \cdot \mu m)]\)

Digital Number

0 40 80 120 160 200 240 280 320 360 400

0

20

40

60

80

100

120

140

160

180

Algodones Dunes

Atacama Desert

Libya-4
Reflectance-Based Approach
Cross-Calibration Method

**WFI/CBERS-4**
Linear regression

**Fit Equation:**
[free intercept]

**Fit Equation:**
[forced zero intercept]
## Radiometric Coefficients

Reflectance-Based Approach Cross-Calibration Method

### Fit Equation:

- **[free intercept]**

- **[forced zero intercept]**

<table>
<thead>
<tr>
<th>Band</th>
<th>Slope ($G_i$) [W/(m²·sr·μm)]/DN</th>
<th>Intercept ($offset_i$) [W/(m²·sr·μm)]</th>
<th>Slope ($G_i$) [W/(m²·sr·μm)]/DN</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUX</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td>1.56 ± 0.29</td>
<td>8 ± 18</td>
<td>1.69 ± 0.05</td>
</tr>
<tr>
<td>Green</td>
<td>1.63 ± 0.30</td>
<td>-2 ± 22</td>
<td>1.61 ± 0.05</td>
</tr>
<tr>
<td>Red</td>
<td>1.73 ± 0.27</td>
<td>-14 ± 22</td>
<td>1.57 ± 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-11 ± 17</td>
<td>1.40 ± 0.05</td>
</tr>
<tr>
<td>WFI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>0.37 ± 0.06</td>
<td>-13 ± 21</td>
<td>0.375 ± 0.010</td>
</tr>
<tr>
<td>NIR</td>
<td>0.34 ± 0.05</td>
<td>18 ± 18</td>
<td>0.484 ± 0.014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-5 ± 20</td>
<td>0.354 ± 0.011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 ± 15</td>
<td>0.342 ± 0.011</td>
</tr>
</tbody>
</table>

There was no statistical evidence for using offsets other than zero.
Uncertainties

✓ Measured values are always approximate;

✓ Every measurement of physical quantities has intrinsic uncertainties in their assessments;

✓ Variability in the results of repeated measurements occurs because variables that can affect the measurement result are impractical to hold constant, even in precisely controlled conditions;
Then, when reporting the measurement result of a physical quantity, it is essential giving some quantitative indication of the quality of the result (JCGM, 2008a).

\[ x = (\bar{x} \pm \sigma) u \]

- \( x \): quantity
- \( \bar{x} \): value
- \( \sigma \): uncertainty
- \( u \): unit
Uncertainties

The total uncertainty of a measurement is found by the combination of the entire contributing uncertainties component.

Factors that influence the measurement process:
The conventional method for the uncertainties evaluation is described in the Guide to the Expression of Uncertainty in Measurement (ISO), also known as the ISO-GUM method (ABNT and INMETRO, 2003; JCGM, 2008a).

In some situations, however, the ISO-GUM method is inappropriate and an alternative approach is applying the Monte Carlo simulation method (JCGM, 2008b).
Every experimental estimation of uncertainty should take into account both, the data statistical fluctuation and the experimental aspects of the measurement. Evaluation of measurement uncertainties are classified into Type A and Type B.

**Type A**
Based on a statistical analysis

**Type B**
*Not* based on a statistical analysis
Uncertainties

**Conventional Method: ISO-GUM**

**Type A Uncertainty**

[Direct Measurements]

The individual observations $x_i$ differ in value because of random variations in the influence quantities. The experimental standard deviation, is given by:

$$
\sigma = \sqrt{\frac{1}{n-1} \times \sum_{i=1}^{n} (x_i - \bar{x})^2}
$$

Type A uncertainty is the experimental standard deviation of the mean

$$
\sigma_m = \frac{\sigma}{\sqrt{n}}
$$
Uncertainties

**Conventional Method: ISO-GUM**

**Type B Uncertainty**

The type B uncertainty is evaluated by scientific judgement based on all of the available information on the possible variability of the quantity. The pool of information may include:

- previous measurement data;
- experience with or general knowledge of the behavior and properties of relevant materials and instruments;
- manufacturer's specifications;
- data provided in calibration and other certificates;
- uncertainties assigned to reference data taken from handbooks.
Uncertainties

Conventional Method: ISO-GUM

Quantities obtained indirectly (secondary quantities), calculated as a function of other quantities:

\[ g = f(a, b, c, \ldots) \]

In order to quantify the uncertainty of \( g \), the statistical procedure called the **Propagation of Uncertainties** can be apply:

\[
\sigma_g^2 = \left(\frac{\partial g}{\partial a}\right)^2 \times \sigma_a^2 + \left(\frac{\partial g}{\partial b}\right)^2 \times \sigma_b^2 + \left(\frac{\partial g}{\partial c}\right)^2 \times \sigma_c^2 + \ldots + COV
\]

\[
COV = 2 \times \left(\frac{\partial g}{\partial a}\right) \times \left(\frac{\partial g}{\partial b}\right) \times \sigma_{ab}^2 + 2 \times \left(\frac{\partial g}{\partial a}\right) \times \left(\frac{\partial g}{\partial c}\right) \times \sigma_{ac}^2 + 2 \times \left(\frac{\partial g}{\partial b}\right) \times \left(\frac{\partial g}{\partial c}\right) \times \sigma_{bc}^2 + \ldots
\]
Uncertainties

Alternative Method: Monte Carlo simulation

- The Monte Carlo method is a computational algorithm that depends on random and repeated sampling to obtain approximate results;
- Monte Carlo simulation allows determining some possible outcomes;
- This method is based on random numbers generation for each primary quantity, according to their probability distribution function (PDF) and propagated through a mathematical model of measurement;
- This propagation consists of assuming a distribution for each input quantity (e.g., uniform distribution, normal or triangular);
- The distributions are propagated M times (where M is the number of iterations) by a mathematical model of measurement, and a new distribution is generated as a result.
Uncertainties

Alternative Method: Monte Carlo simulation

\[ L_{\text{band}} = \frac{\int_{0}^{\infty} L_\lambda \times SRF_\lambda d\lambda}{\int_{0}^{\infty} SRF_\lambda d\lambda} \]

**Input**
- Mathematical Model
- \( SRF_\lambda \) and \( L_{\text{TOA},\lambda} \)
- Number of Iterations (M)

**Processing**
- Gaussian Random Sampling \( SRF_\lambda \)
- Gaussian Random Sampling \( L_{\text{TOA},\lambda} \)
- Mathematical Model \( L_{\text{TOA}} \) at each band of the Sensor
- Number of Iterations
  - < M
  - = M
- P.D.F determination of \( L_{\text{TOA}} \) at each band of the Sensor

**Output**
- TOA Radiance (Watts/(m² * sr * µm))
- Standard Deviation
- Relative Uncertainty (%)
- Spectral Response Function (SRF)
Uncertainties

Alternative Method: Monte Carlo simulation

- **Input**
  - Mathematical Model
  - \( SRF_\lambda \) and \( L_{TOA,\lambda} \)
  - Number of Iterations (M)

- **Processing**
  - Gaussian Random Sampling \( SRF_\lambda \)
  - Gaussian Random Sampling \( L_{TOA,\lambda} \)
  - Mathematical Model \( L_{TOA} \) at each band of the Sensor
  - Number of Iterations < M
  - Number of Iterations = M

- **Output**
  - P.D.F determination of \( L_{TOA} \) at each band of the Sensor

---

Graphs:
- **Top Graph**
  - Frequency distribution of SRF (Band 1) at 440 nm
  - 5000 samples

- **Bottom Graph**
  - TOA Radiance (Watts/(m²*srad*μm))
  - Frequency distribution at 440 nm
  - 5000 samples
Uncertainties

Alternative Method: Monte Carlo simulation

\[ L_{\text{band}} = \frac{\int_0^\infty L_\lambda \times SRF_\lambda \, d\lambda}{\int_0^\infty SRF_\lambda \, d\lambda} \]

5000 “results” (or possibilities)

PDF - probability distribution function

Output

P.D.F determination of \( L_{\text{TOA}} \) at each band of the Sensor

Processing

Mathematical Model

\( SRF_\lambda \) and \( L_{\text{TOA,}\lambda} \)

Number of Iterations (M)

Input

Gaussian Random Sampling

\( SRF_\lambda \)

Gaussian Random Sampling

\( L_{\text{TOA,}\lambda} \)

Mathematical Model

\( L_{\text{TOA}} \) at each band of the Sensor

\(< M \)

\( = M \)
The Monte Carlo approach is known as the propagation of distributions method and the ISO-GUM technique as the propagation of uncertainty method.

Source: Couto et al. (2013)
Uncertainties

Reflectance-Based Approach

- Early work showed that the reflectance-based approach had an absolute radiometric uncertainty of 5%, and new results with improvements showed an uncertainty of 3% in the middle of the visible portion of the spectrum.

There are several sources of uncertainty in the reflectance-based approach, including:

1. ground reflectance measurement;
2. atmospheric characterization;
3. radiative transfer code; and
4. computation of the site-average DNs.
If it is assumed that all sources of uncertainty are independent, then a root sum of squares (RSS) approach leads to an overall uncertainty.

\[ \sigma_{\text{TOA Radiance}} = \sqrt{\left(\sigma_{\text{VIS}}\right)^2 + \left(\sigma_{\text{Water}}\right)^2 + \left(\sigma_{\text{AOD}}\right)^2 + \left(\sigma_{\text{RF}}\right)^2 + \left(\sigma_{\text{O3}}\right)^2 + \left(\sigma_{\text{Accuracy Modtran}}\right)^2} \]
Uncertainties

Reflectance-Based Approach

The main source of uncertainty is the reflectance surface:

- Site homogeneity;
- Operator experience;
- Spectroradiometer;
- Reference Panel;
Uncertainties

Reflectance-Based Approach

The main source of uncertainty is the reflectance surface:

- West of Bahia state (Brazil)
  - CV < 11%
- Atacama Desert (Chile)
  - CV < 4%
- Algodones Dunes (USA)
  - CV < 5%
Uncertainties

Reflectance-Based Approach

These are the overall total uncertainty using the reflectance-based approach with each of the sites in the spectral region between 350-2400 nm.
There are several sources of uncertainties inherent in the cross-calibration process:

(a) the uncertainty from the sensor chosen as reference;
(b) the uncertainty due to different spectral response (SBAF);
(c) the uncertainty from Earth-Sun distance correction;
(d) the uncertainty from cosine of zenith angle correction;
(e) the uncertainty due changes in atmospheric conditions between near-simultaneous image pair acquisitions; and
(f) the uncertainty due the residual geometric mis-registration.
Uncertainties

Cross-Calibration Method

There are several sources of uncertainties inherent in the cross-calibration process:

<table>
<thead>
<tr>
<th>Band</th>
<th>Reference Sensor (TM-5)</th>
<th>Spectral Difference</th>
<th>Cosine of the solar angle</th>
<th>Mis-registration</th>
<th>Atmosphere</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>5.00%</td>
<td>0.72%</td>
<td>0.11%</td>
<td>0.24%</td>
<td>0.00%</td>
<td>5.06%</td>
</tr>
<tr>
<td>Red</td>
<td>5.00%</td>
<td>0.56%</td>
<td>0.11%</td>
<td>0.24%</td>
<td>0.00%</td>
<td>5.04%</td>
</tr>
<tr>
<td>NIR-1</td>
<td>5.00%</td>
<td>2.38%</td>
<td>0.11%</td>
<td>0.24%</td>
<td>0.00%</td>
<td>5.54%</td>
</tr>
<tr>
<td>NIR-2</td>
<td>5.00%</td>
<td>3.66%</td>
<td>0.11%</td>
<td>0.24%</td>
<td>0.00%</td>
<td>6.20%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Band</th>
<th>Reference Sensor (MSS-5)</th>
<th>Spectral Difference</th>
<th>Cosine of the solar angle</th>
<th>Mis-registration</th>
<th>Atmosphere</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>5.06%</td>
<td>0.47%</td>
<td>0.11%</td>
<td>0.24%</td>
<td>3.51%</td>
<td>6.18%</td>
</tr>
<tr>
<td>Red</td>
<td>5.04%</td>
<td>0.39%</td>
<td>0.11%</td>
<td>0.24%</td>
<td>2.57%</td>
<td>5.67%</td>
</tr>
<tr>
<td>NIR-1</td>
<td>5.54%</td>
<td>0.19%</td>
<td>0.11%</td>
<td>0.24%</td>
<td>4.09%</td>
<td>6.89%</td>
</tr>
<tr>
<td>NIR-2</td>
<td>6.20%</td>
<td>0.88%</td>
<td>0.11%</td>
<td>0.24%</td>
<td>7.75%</td>
<td>9.97%</td>
</tr>
</tbody>
</table>

(f) the uncertainty due the residual geometric mis-registration
Uncertainties

Cross-Calibration Method

The main source of uncertainty is the reference sensor:

It is worth remembering that the uncertainty of the sensor uncalibrated will never be less than the uncertainty of the reference sensor, because the uncertainty of the reference sensor will be propagated to the sensor uncalibrated.

The second largest source is due to atmospheric effects when use no-simultaneous acquisitions images:

Water Vapor
According to the simulation results, varying the water vapor content from 0.5 to 7 g/cm² has a 1% effect in the Green and Red spectral bands, and effects up to 9% in NIR spectral bands.

Aerosol Optical Depth (AOD) at 550 nm
Changing the AOD at 550 nm from 0.05 to 0.5 (dimensionless) suggested effects of 1.5% and 0.6% in the MSS Green and NIR bands, respectively.
Uncertainties

Cross-Calibration Method
Spectral Band Adjustment Factor (SBAF)

SBAF and its uncertainty used to compensate the MUX/CBERS-4 TOA reflectance to match OLI/Landsat-8 TOA reflectance.

<table>
<thead>
<tr>
<th>Libya-4</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>SBAF</td>
<td>Uncertainty (%)</td>
</tr>
<tr>
<td>Blue</td>
<td>0.982 ± 0.007</td>
<td>0.73</td>
</tr>
<tr>
<td>Red</td>
<td>1.008 ± 0.005</td>
<td>0.48</td>
</tr>
<tr>
<td>Green</td>
<td>0.992 ± 0.007</td>
<td>0.66</td>
</tr>
<tr>
<td>NIR</td>
<td>1.108 ± 0.015</td>
<td>1.37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atacama Desert</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>SBAF</td>
<td>Uncertainty (%)</td>
</tr>
<tr>
<td>Blue</td>
<td>1.0007 ± 0.0018</td>
<td>0.18</td>
</tr>
<tr>
<td>Red</td>
<td>1.0011 ± 0.0018</td>
<td>0.18</td>
</tr>
<tr>
<td>Green</td>
<td>1.006 ± 0.003</td>
<td>0.32</td>
</tr>
<tr>
<td>NIR</td>
<td>1.012 ± 0.006</td>
<td>0.59</td>
</tr>
</tbody>
</table>

✓ Libya-4: 0.48-1.37%

✓ Atacama Desert: 0.18-0.59%
Final Considerations

Radiometric Coefficients
Gain coefficients of the MUX/CBERS-4 spectral bands:

Individual Calibration → Uncertainties ranged from 4% to 7%
Combination of techniques (Points of calibration) → Uncertainties less than 3.5%
Final Considerations

Quantitative Analysis

Vicarious Calibration refers to those calibration methods that are performed without the use of systems on-board the satellite.

- Reflectance-Based Approach
- Cross-Calibration Method
- Pseudo-Invariant Calibration Sites

Image Source: Romero da Costa Moreira
Vicarious Calibration
Reflectance-Based Approach
Cross-Calibration Method
Evaluation of Uncertainties

Thank you!