Classification of North Africa for Use as an Extended Pseudo Invariant Calibration Site for Radiometric Calibration and Stability Monitoring of Optical Satellite Sensors

Larry Leigh - Director SDSU IPLab
Mahesh Shrestha, Nahid Hasan and Morakot Kaewmanee
South Dakota State Image Processing Lab

CALCON 2019, Logan Utah
Outline

• Introduction
• Traditional PICS Based Calibration
• Extending PICS through the classification of North Africa desert.
  • EPICS Stability analysis
  • EPICS Based Trend to Trend Cross Calibration
  • EPICS Absolute Calibration Model (ExPAC)
• Conclusions
Introduction to PICS

• Pseudo Invariant Calibration Sites (PICS) have become a standard way to “independently” evaluate the performance of on orbit sensors.
  • Technique relies on very stable regions of the planet (both target and atmosphere)
  • Generally bright
  • Spatially uniform

• PICS are used to address;
  • Stability of the sensor over time
  • Provide optimal sensor to sensor cross calibration sites for absolute calibration
  • Direct absolute calibration through a absolute calibration model for the site (several developed SDSU APICS is one)
Introduction to PICS

• If they are so great, why improve?

• Two key factors, time and site independence.

• For any given site, the number of observations / measurements are limited by orbital repeat patterns.
  • For example at best 16 days for Landsat, potential of 32 to 48 days if impacted by clouds.
  • At this rate of measurement, time needed to detect small drifts in response pushes towards years.

• Individual sites could develop “issues” over time, which would impact ability to accurately retrieve satellite performance.
  • Long lasting: “issues” like agriculture in the middle of the Egyptian desert, or Short term “issues”: like dust storms and the rare rain event.

Region of human action in the middle of the desert near a traditional PICS location
Extending PICS through the classification of North Africa desert

• The goal is simple, move from “small” (~1 km x ~1 km) to “large” (continental?) scale
  • Take what we know from PICS, and extend it, again as a solution to temporal revisit, and site dependent issues.
• Basic Process...
  1. Find all “stable pixels”, of the Saharan Desert
  2. Classification each pixel via an unsupervised K-means algorithm
  3. Combine all pixels in a continuous continental scale PICS

• Goal is to achieve daily (or near-daily) assessment, while limiting the impact of any one portion of the globe.
Start: Find all "stable pixels", of the Saharan Desert

- Used Google Earth Engine to "stack" every pixel across the deserts of North Africa seen by Landsat 8, filtering for cloud cover, etc...
- Produce a tiled product of mean reflectance and temporal variability.
- Filter the data that had a temporal variability of less than 5% and requirement of at least 25 observations.
Classification each pixel via an unsupervised K-means algorithm

The temporally filtered dataset was then used as the input for a classic unsupervised k-means algorithm for bands 1-7 of Landsat 8.

- Terminating criteria: 5% or less uncertainty across all spectral bands
- Resulted in 19 unique spectral clusters of “sand” across North Africa
  - Resulted in three key clusters that achieved the spatial uncertainty of less than 5%, across all spectral bands
    - Cluster 5: 3.65 millions pixels
    - Cluster 13: 3 millions pixels
    - Cluster 18: 2.4 millions pixels

<table>
<thead>
<tr>
<th>Cluster 13</th>
<th>Coastal</th>
<th>Blue</th>
<th>Green</th>
<th>Red</th>
<th>NIR</th>
<th>SWIR1</th>
<th>SWIR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.73</td>
<td>6.31</td>
<td>5.37</td>
<td>3.88</td>
<td>3.87</td>
<td>4.14</td>
<td>4.86</td>
</tr>
<tr>
<td>2</td>
<td>7.19</td>
<td>7.27</td>
<td>4.83</td>
<td>3.24</td>
<td>2.60</td>
<td>2.06</td>
<td>3.54</td>
</tr>
<tr>
<td>3</td>
<td>4.95</td>
<td>5.31</td>
<td>3.94</td>
<td>2.89</td>
<td>2.78</td>
<td>2.36</td>
<td>3.27</td>
</tr>
<tr>
<td>4</td>
<td>8.31</td>
<td>9.66</td>
<td>9.82</td>
<td>8.77</td>
<td>8.10</td>
<td>9.67</td>
<td>9.16</td>
</tr>
<tr>
<td>5</td>
<td>4.57</td>
<td>4.75</td>
<td>3.44</td>
<td>2.69</td>
<td>2.47</td>
<td>2.23</td>
<td>2.57</td>
</tr>
<tr>
<td>6</td>
<td>7.75</td>
<td>8.94</td>
<td>8.03</td>
<td>5.51</td>
<td>5.27</td>
<td>5.89</td>
<td>5.19</td>
</tr>
<tr>
<td>7</td>
<td>5.49</td>
<td>5.85</td>
<td>4.68</td>
<td>3.50</td>
<td>3.35</td>
<td>4.05</td>
<td>5.13</td>
</tr>
<tr>
<td>8</td>
<td>5.35</td>
<td>5.89</td>
<td>5.03</td>
<td>2.84</td>
<td>2.93</td>
<td>2.54</td>
<td>2.38</td>
</tr>
<tr>
<td>9</td>
<td>5.93</td>
<td>6.71</td>
<td>5.67</td>
<td>3.61</td>
<td>3.73</td>
<td>3.19</td>
<td>4.30</td>
</tr>
<tr>
<td>10</td>
<td>5.91</td>
<td>6.46</td>
<td>5.21</td>
<td>3.87</td>
<td>3.38</td>
<td>3.37</td>
<td>4.61</td>
</tr>
<tr>
<td>11</td>
<td>5.36</td>
<td>5.77</td>
<td>5.07</td>
<td>4.05</td>
<td>3.33</td>
<td>3.45</td>
<td>6.13</td>
</tr>
<tr>
<td>12</td>
<td>4.79</td>
<td>5.05</td>
<td>3.34</td>
<td>2.62</td>
<td>2.23</td>
<td>2.03</td>
<td>2.66</td>
</tr>
<tr>
<td>13</td>
<td>4.59</td>
<td>4.80</td>
<td>3.08</td>
<td>2.71</td>
<td>2.11</td>
<td>1.78</td>
<td>2.62</td>
</tr>
<tr>
<td>14</td>
<td>5.95</td>
<td>6.88</td>
<td>6.38</td>
<td>4.38</td>
<td>4.49</td>
<td>3.87</td>
<td>4.48</td>
</tr>
<tr>
<td>15</td>
<td>5.20</td>
<td>5.91</td>
<td>5.16</td>
<td>2.48</td>
<td>2.46</td>
<td>2.15</td>
<td>1.96</td>
</tr>
<tr>
<td>16</td>
<td>4.71</td>
<td>5.03</td>
<td>4.02</td>
<td>3.28</td>
<td>2.99</td>
<td>2.95</td>
<td>3.99</td>
</tr>
<tr>
<td>17</td>
<td>5.58</td>
<td>6.25</td>
<td>5.28</td>
<td>3.23</td>
<td>3.15</td>
<td>2.53</td>
<td>2.61</td>
</tr>
<tr>
<td>18</td>
<td>4.71</td>
<td>4.94</td>
<td>4.14</td>
<td>3.15</td>
<td>2.70</td>
<td>3.15</td>
<td>4.56</td>
</tr>
<tr>
<td>19</td>
<td>5.43</td>
<td>6.15</td>
<td>5.39</td>
<td>3.31</td>
<td>3.79</td>
<td>2.88</td>
<td>3.59</td>
</tr>
</tbody>
</table>
Cluster 13 becomes the prime initial candid

Looking at the three clusters achieving the lowest spatial variability for spatial extent and structure

- Cluster 13 was chosen for two important reasons.
  - Includes large portions of traditional PICS sits (Libya 4 and Egypt 1), knowledge can then be extended to the extended cluster
  - Cluster 13 is more grouped / contiguous

So we found our initial candid, can we take this large continent scaled PICS and achieve what Traditional PICS can?
Using Cluster 13 EPICS for stability analysis

Key goal for stability analysis is detection of change / drift of the sensor.
Detection of drift is driven by frequency of measurement
Temporal frequency, one collect per day or better is achievable for Landsat
Cluster 13 has enough spatial extent to intersect with each day of orbital coverage.
Evaluate of C13 EPICS site for use in Temporal analysis

For the test case, data limited to 16 unique Landsat 8 Path/Row locations

Test Path/Rows are chosen, to allow maximum intersection with Cluster 12 while achieving daily observation.

Intersection of the Landsat 8 image, cluster 13 mask, and Landsat 8 quality control band is determined.

Results for an individual scenes masks are used to collect all “good” pixels.

Means and standard deviations for each scenes “good” pixels are determined.
Cluster 13 EPICS .vs. Libya 4 PICS

- Develop a temporal trend of Libya 4 PICS using all available images, and Cluster 13 using all available images from 16 path/row subset between ~ launch and August 2018. (no BRDF correction)
  - Libya 4: 110 cloud free scenes (~18 days between measurement on average)
  - Cluster 13: 1434 cloud free scenes (~1.4 days between measurement on average)

- While the “trends” are a little “fuzzier” the resultant mean and standard deviation are the same! Same response, but 13x more often!
Create Cluster-Based EPICS BRDF Model

- To address the seasonality seen in the data, driven primarily from solar illumination geometry, a BRDF model needs development, which is based on lessons learned from traditional PICS experience.
- A Cluster 13 BRDF correction is applied, based on the variation of the Four Angles of solar and view geometry.
  - The first step in model generation was to project angles into a two-dimensional Cartesian coordinate space:
    \[
    \begin{align*}
    x_1 &= \sin(SZA) \times \cos(SAA) \\
    y_1 &= \sin(SZA) \times \sin(SAA) \\
    x_2 &= \sin(VZA) \times \cos(VAA) \\
    y_2 &= \sin(VZA) \times \sin(VAA)
    \end{align*}
    \]
    Here SZA, SAA, VZA, and VAA are the solar zenith/azimuth and sensor viewing zenith and azimuth angles, respectively.
- A second-order generic model was selected to represent a cluster-specific BRDF effect with respect to the transformed solar and view zenith and azimuth angles:
  \[
  \rho_{BRDF} = \beta_0 + \beta_1 x_1 + \beta_2 y_2 + \beta_3 y_2 + \beta_4 y_2 + \beta_5 y_1 x_1 + \beta_6 x_1 x_2 + \beta_7 x_1 y_2 + \beta_8 y_1 x_2 + \beta_9 y_1 y_2 + \beta_{10} x_2 y_2 + x_1^2 + \beta_{12} y_1^2 + \beta_{13} x_2^2 + \beta_{14} y_2^2
  \]
  This correction is applied to the data, and the results are......
Results: Summary Temporal trending statistics using BRDF correcting OLI images

Given Cluster 13’s extent, it was expected that daily or near daily imaging would be possible, assuming cloud-free conditions. The cloud filtering applied in this analysis resulted in an observed imaging frequency of 1.43 days on average throughout the OLI’s lifetime, which is a substantial improvement over the ~18 day frequency for individual PICS.
Cross Calibration with Cluster 13 EPICS
Cluster Based Trend to Trend Cross Calibration Procedure
Landsat 8 vs Sentinel 2A

Generate binary mask to only filter in Cluster 13 pixels

→ Calculate TOA reflectance of Cluster 13 pixels (L8 and S2A)

→ Calculate and apply SBAF for Sentinel 2A (make S2A look like L8)

→ Perform BRDF correction

Estimate gain from ROI and cluster based method

\[
\text{Cross} - \text{Cal Gain Ratio}_{S2AToL8} = \frac{\rho_{L8,Trend}}{\rho_{S2A,SBAFCorrected,Trend}}
\]

- Key requirements for cross calibration
  - Traditional: each satellite looks at the same locate
  - Cluster: each satellite looks at “some portion” of the cluster (probably different portions)

- Traditional: Normalize scene pair to the same view / solar geometry
- Cluster: Normalize all data to a single view / solar geometry

- Correct for spectral band differences, needed by both. Requires some level of info on the hyperspectral nature of the target.

- Key difference, in Traditional techniques, the comparison is done “scene to scene”, cluster version is “trend to trend” cross calibration
  - This allows takes advantage of the wealth of near daily measurements, while pushing the noise of the measurements down.
Hyperspectral profile for Cluster 13

• Generation of a hyperspectral signature, grab all Hyperion data that intersects with cluster 13, normalize, and combine to produce a “cluster 13 hyperspectral response” for all locations.

North Africa: 3715 hyperspectral images
North Africa: 216 hyperspectral images inserted with cluster 13
Cluster 13 hyperspectral curve, after BRDF normalization

The result of this work leads to a hyperspectral understanding of Cluster 13, good to 5% uncertainty. Really we are after the shape of the curve for SBADF calculations.
Trend to Trend Cross Calibration with Cluster 13

- BRDF corrected Landsat 8 data for Cluster 13
- BRDF and BAF corrected Sentinel 2A data for Cluster 13

For trend to trend to work, we need an estimation of Cluster 13s response for every single day. Also due to a lack of data over north Africa early in the mission for Sentinel 2A, we decide to limit the data from April 2016 – 2018.

Moving average of window size 15 is used for the daily trend interpolating and smoothing.
Trend to trend calibration produces results with the “gold” range of traditional cross calibration, confirming consistency with traditional approaches, while giving a lot more insight into and quicker detection of changes with time.
Cluster 13 for Absolute Calibration
Key requirements of Extended PICS Absolute Calibration (ExPAC)

- The key is data, 3562 image acquisitions where used.
  - Landsat 8 multispectral images used to develop a full BRDF model to cover normal view and solar illumination angles
  - Hyperion used to extend these multispectral data, to cover the spectral responses of all possible spectral band passes.
  - Validation with remaining sensors.

### Twists on SDSU APICS Model

- Develop SZA BRDF Coefficients from Landsat8 data using 4 Angle BRDF model (Quadratic)
- Cluster 13 Hyperspectral profile, was normalized to VZA BRDF = 0 degree.
- B-scale factor was to scale Hyperion derived profile to be on Landsat 8 calibrated scale wrt. The BRDF Intercept for ExPAC Model.

<table>
<thead>
<tr>
<th>SATELLITE NAME</th>
<th>LAUNCH DATE</th>
<th>VZA</th>
<th>VAA</th>
<th>SZA</th>
<th>SAA</th>
<th>NO. SCENES</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LANDSAT8</td>
<td>11-Feb-13</td>
<td>3-8</td>
<td>104-280</td>
<td>20-60</td>
<td>73-160</td>
<td>1155</td>
<td>16 sites</td>
</tr>
<tr>
<td>LANDSAT7</td>
<td>15-Apr-99</td>
<td>3-8</td>
<td>92-298</td>
<td>19-58</td>
<td>73-158</td>
<td>1412</td>
<td>9 sites</td>
</tr>
<tr>
<td>SENTINEL2A</td>
<td>23-Jun-15</td>
<td>2-12</td>
<td>97-296</td>
<td>15-59</td>
<td>71-167</td>
<td>556</td>
<td>16 sites</td>
</tr>
<tr>
<td>SENTINEL2B</td>
<td>7-Mar-17</td>
<td>2-12</td>
<td>98-291</td>
<td>15-59</td>
<td>71-167</td>
<td>349</td>
<td>16 sites</td>
</tr>
<tr>
<td>EO-1 HYPERION</td>
<td>21-Nov-00</td>
<td>10-13</td>
<td>98-278</td>
<td>22-58</td>
<td>85-153</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

Total 3562
Converted from Spherical to Cartesian Coordinate

\[ X_1 = \sin(SZA) \cdot \sin(SAA) ; \quad X_2 = \sin(VZA) \cdot \sin(VAA) ; \]
\[ Y_1 = \sin(SZA) \cdot \cos(SAA) ; \quad Y_2 = \sin(VZA) \cdot \cos(VAA) ; \]

**Quadratic(SZA, SAA)+Linear (SZA, SAA, VZA, VAA)**

\[
B_{BRDF} = \beta_0 + \beta_1 Y_1^2 + \beta_2 X_1^2 + \beta_3 X_1 Y_1 + \beta_4 Y_1 + \beta_5 X_1 + \beta_6 Y_2 + \beta_7 X_2
\]

Where \( \beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7 \) are the coefficients of the model which are calculated with known parameters \( Y_1, X_1, X_1 Y_1, Y_2, X_2 \) and Reflectance.

Simple conversion of all data from Spherical to Cartesian angle

Data is fit to simple quadratic, plus linear, plus significant interaction terms. Model has extensive variation in solar geometry, limited by minimal view variation. Model is reduced to the most significant dependences = linear plus quadratic
B-Scale Factor: Calculating the scale factors to anchor Hyperion to Landsat 8 OLI

- Landsat 8 OLI is the radiometer reference which all Cluster 13 data were used to create BRDF Model
- Cluster 13 spectral profile is the average of 90 Hyperion scenes representing Cluster 13 after normalized to 0 degree VZA.
- Scale Factor calculated using 3 Sensors, Landsat 8, Sentinel 2A and 2B and C13 spectral profile to place the Hyperion spectra on Landsat 8 OLI calibrated scale with respect to the derived BRDF- ExPAC Model
- Hyperspectral gain model was then developed using stepwise function in CA, Red, NIR, SWIR1 and SWIR2 and linear model for Blue and Green bands
Result: 4 Angle BRDF Model- ExPAC Model

<table>
<thead>
<tr>
<th>Wavelengths</th>
<th>( C1(X_1^2) )</th>
<th>( C2(Y_1^2) )</th>
<th>BRDF-Intercept</th>
<th>BFactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>442</td>
<td>0.01092</td>
<td>-0.03587</td>
<td>0.2306</td>
<td>1.0289</td>
</tr>
<tr>
<td>483</td>
<td>0.00704</td>
<td>-0.05052</td>
<td>0.2497</td>
<td>0.9958</td>
</tr>
<tr>
<td>562</td>
<td>-0.00404</td>
<td>-0.00052</td>
<td>0.3404</td>
<td>1.0183</td>
</tr>
<tr>
<td>656</td>
<td>-0.01997</td>
<td>0.06053</td>
<td>0.4688</td>
<td>1.0260</td>
</tr>
<tr>
<td>864</td>
<td>-0.03323</td>
<td>0.01371</td>
<td>0.5943</td>
<td>1.0306</td>
</tr>
<tr>
<td>1609</td>
<td>-0.0759</td>
<td>0.04107</td>
<td>0.6890</td>
<td>1.0674</td>
</tr>
<tr>
<td>2201</td>
<td>-0.04048</td>
<td>0.10359</td>
<td>0.5885</td>
<td>1.0351</td>
</tr>
</tbody>
</table>

**The model:**

\[
\rho_{C13}(\lambda, X_1, Y_1) = B(\lambda) \ast \rho_h(\lambda) + X_1^2 \ast C_1(\lambda) + Y_1^2 \ast C_2(\lambda)
\]

\( X_1 = \sin(SZA) * \sin(SAA) \); \( SZA = \) Solar Zenith Angle, \( SAA = \) Solar Azimuth Angle  
\( Y_1 = \sin(SZA) * \cos(SAA) \)  
\( \rho_h(\lambda) = \) Cluster13 spectral profile, obtained from 90 Hyperion scenes, normalized to 0 VZA  
\( \rho_{C13}(\lambda) = \) Predicted Cluster13 Toa Reflectance  
\( B(\lambda) = \) Intercept scaling factor, to place sensor’s BRDF intercept to match BRDF- ExPAC Intercept  
\( C_1(\lambda), C_2(\lambda) = \) The BRDF coefficients for \( X_1, Y_1 \) quadratic model
Landsat 8 data versus ExPAC Cluster predictions

Would expect the best fit with Landsat 8, due to Landsat 8 being the data driving the model. Generally the prediction model is predictions are within 4% for shorter wavelengths, but ~2% for everything else.

<table>
<thead>
<tr>
<th>Band</th>
<th>CA</th>
<th>Blue</th>
<th>Green</th>
<th>Red</th>
<th>NIR</th>
<th>SWIR1</th>
<th>SWIR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>3.95%</td>
<td>3.96%</td>
<td>1.92%</td>
<td>2.23%</td>
<td>2.63%</td>
<td>3.95%</td>
<td>2.70%</td>
</tr>
<tr>
<td>Measure</td>
<td>0.2274</td>
<td>0.2437</td>
<td>0.3396</td>
<td>0.4739</td>
<td>0.5904</td>
<td>0.5924</td>
<td>0.5962</td>
</tr>
<tr>
<td>Model</td>
<td>0.2270</td>
<td>0.2399</td>
<td>0.3422</td>
<td>0.4725</td>
<td>0.5898</td>
<td>0.5925</td>
<td>0.5925</td>
</tr>
</tbody>
</table>
• L7 results, show some interesting “shifts over time” between the model and the measurement, but still achieve results on pair with the Landsat 8 results.
**Sentinel 2A shows a little more spread, even a bit of bi-model response.**

**Potential limit of the BRDF model for Sentinel’s wider field of view**
ExPAC Model Results: S2B

Sentinel 2B similar to 2A a little spread, less sense of bi-model response. But still potential limit of the BRDF model for Sentinel’s wider field of view.
Comparison of ExPAC Model Performance Across Sensors

%Difference = \( 100\% \times \frac{\text{Observed} - \text{Predicted}}{\text{Predicted}} \)

- **L8**: all data available between April 2013 and August 2018
  - OLI absolute calibration is generally within 1.5% for all bands
- **L7**: all data available between April 1999 and August 2018
  - L7 absolute calibration is generally within 2% for all bands
- **S2A**: all data available between August 2015 and August 2018
  - MSI-A absolute calibration is generally within 2% for all bands
- **S2B**: all data available between July 2017 and August 2018
  - MSI-B absolute calibration is generally within 2% for all bands

*** All 4 sensors agree very well with the ExPAC Model with differences between sensors are within 2% or for all bands
Traditional versus Cluster based PICS

• Slope detection....
  • Based on Spooner et. al [5][6] using data from Libya 4 vs Cluster 13, sees minimal detectable drift Landsat 8 drop from $0.10 \% / \text{year}$ to $0.057 \% / \text{year}$ on average across all bands of Landsat. Giving nearly twice the sensitivity for cluster based

• Cross calibration....
  • Provides on average the same results as traditional cross calibration, but with 1000 of points compared to handfuls, this results in lower overall uncertainty and greater insight into short term differences

• Absolute Calibration....
  • Tie, provides nearly the same levels Libya 4 APICS based model performance, but with daily observations possible, Cluster leads out. Better BRDF model could really push this over the top.

Main Key, greater ability to perform sensors evaluation quicker, at or better capability, to address missions with short operational life, and sensors that with smaller foot prints that may miss traditional PICS site.