On-Orbit Radiometric Calibration and Validation of Planet’s Constellations

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Topics

- Introduction to the constellations
  - Dove
  - RapidEye
  - SkySat

- Cross-calibration approach

- Some recent results
  - Validation of Dove and RapidEye versus RadCalNet
  - Validation of SkySat versus RapidEye
Dove Satellite
Intro to the Constellations
(Active, calibrated satellites)

>100 Doves

5 RapidEye sats

13 SkySats
# Dove Constellation

<table>
<thead>
<tr>
<th></th>
<th>ISS Orbit</th>
<th>Sun Synchronous Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Lifetime</td>
<td>1 year per satellite</td>
<td>2-3 years per satellite</td>
</tr>
<tr>
<td>Mission Continuity</td>
<td>Up to 55 satellite constellation (continually replenish / upgrade satellites)</td>
<td>100-150 satellite constellation (continually replenish / upgrade satellites)</td>
</tr>
<tr>
<td>Inclination</td>
<td>52 deg</td>
<td>98 deg</td>
</tr>
<tr>
<td>Orbital Insertion Altitude</td>
<td>420km</td>
<td>505km</td>
</tr>
<tr>
<td>Ground Sampling Distance (Nadir)</td>
<td>2.7m-4.0m</td>
<td>4.0m</td>
</tr>
<tr>
<td>Sensor Type</td>
<td>Bayer-masked CCD camera</td>
<td></td>
</tr>
</tbody>
</table>
| Spectral Bands       | Blue: 420-530nm  
Green: 500-590nm  
Red: 610-700nm  
NIR: 760-860nm       |                                             |
Calibration Approach

Overview

- RapidEye is well-calibrated to ±2.5%. We present here a validation against RadCalNet.

- Doves are calibrated using cross-calibration with RapidEye, and validated using cross-calibration with Landsat8 and Sentinel, with lunar cal, and with RadCalNet site measurements.

- SkySat block 1 (morning crossing) are calibrated using RadCalNet, and block 2 (afternoon) via cross-cal with block 1. They’re validated using cross-cal with RapidEye.
Calibration Approach

Terminology

- We use the term “crossover event” to mean a strip-strip intersection analyzed over an AOI.

- A crossover event can pass over hundreds or even thousands of predefined sample grid cells, yielding many measurement pairs per crossover event.
Calibration Approach

Cross-Calibrating Doves to RapidEye

- Instantaneous crossovers over specific sites sampled, corrected, and stored.
  - Crossovers sourced from RapidEye (RE) and Dove to Dove Crossovers if RE data lacking
- Crossovers cover the brightness range from 50 to 150 watts/m² sr⁻¹ um⁻¹
- About 13 (±4) crossover events and 900 (±350) samples over a 3 month period used per-satellite/band to update calibration
- Each sample comprises 100k to 600k pixels at 4m GSD.
Calibration Sites

Globally distributed network of desert calibration sites

27 sites covering a range of bright and dark features to capture full dynamic range
Orthotile Crossover Pair: Example

@ “LibyaB” site

2016-08-14

0E0E: 9:45 am

RE-5: 11:16 am

<----- 25 km ----->
Instantaneous Crossovers

Crossover Event Requirements

Maximum time delta between collects: 2 hours *
Maximum view angle: 15 degrees
Maximum saturated pixel percent: 20%
Maximum cloud percent: 20%

Clouds & saturated pixels masked using UDM

Approach is fully automated - crossovers are queried daily, processed, and measurements stored for analysis.

* where crossing times make this possible.
Calibration Site Sampling

Criteria for Calibration Site Sampling

- Sample size is 1000 X 1000 Pixels (~3.5 km resolution)
- Sampling in spectrally homogenous locations within calibration site
- Spectra is characterized using Hyperion Imagery
- All clouds, vegetation, in-homogenous, and saturated pixels are masked
- Minimum valid number of unmasked pixels: 100000 per sample.

Example Calibration Site sample grids

- Dunhuang
- Namibia B
- Railroad Valley
Analyzing Samples:
Example histogram for NIR band of one sample
Area (100k - 600k pixel region)

(the histogram’s mode is the little white star)

Using the mode as the sample summary statistic is resilient against outliers (e.g. clouds, cloud shadows).
Crossover Sample Processing

Crossover samples are compared in TOA Radiance Space

**Spectral Band Adjustment Factor (SBAF)**
Calculated per-band to adjust for RSR differences between sensors

\[
SBAF_{1\rightarrow2,b} \equiv \frac{\int q(\lambda) RSR_{2,b}(\lambda) \, d\lambda}{\int RSR_{2,b}(\lambda) \, d\lambda} \cdot \frac{\int q(\lambda) RSR_{1,b}(\lambda) \, d\lambda}{\int RSR_{1,b}(\lambda) \, d\lambda}
\]

**Sun Angle Correction**
Adjusts for up to 2 hour time difference between collects

\[
R_{LSatLcor} = R_{LsatLorig} \cdot \frac{\cos (1-\theta_{SunPL})}{\cos (1-\theta_{SunLsat})}
\]

* Applied to Landsat 8 imagery, correcting Landsat 8 to Planet Dove bands & crossover illumination
Dove & RapidEye RSR
Characterizing Calibration Sites

Hyperion-Derived Spectra
Initial process: Derive a single spectra for a calibration site representing the yearly average spectra.

- Derived from 12 hyperion images per site
- Source 1 hyperion image for each month
  - Query for available 2015 data and moving backwards in time until a collect for a given month is found
- Future steps will be to derive seasonal average spectra
Fitting Calibration Model

Fits to all Doves’ measurements at once using a linear mixed model:

- Accounts for within-crossover-event clustering using random intercepts for each event
- Accounts for correlation between magnitude of that random intercept and the crossover event’s median radiance
- Intercept for constellation mean is forced through a predetermined value
  - Calculated per-band using a separate ridge regression where the intercept alone is penalized.

Example of a per-satellite fit for the Red Band using Flock-wide parameter to reduce sat-to-sat variance
Example Constellation Mean Fit
Fitting Calibration Model

\[ y_i = \beta_{0,Flock} + (\beta_1 + a_{\text{sat}[i]}) \cdot x_i + \beta_2 \cdot (x_i - \bar{x}_{\text{event}[i]}) + u_{\text{event}[i]} + \epsilon_i, \]

where the index \( i \) ranges over all observations for a band, across all satellites considered, and:

- \( y_i \) = Dove radiance of the \( i \)th sample
- \( x_i \) = reference (e.g. RapidEye) radiance of the \( i \)th sample
- \( \beta_0,Flock \) = flock-wide intercept for this band, determined in advance
- \( \beta_1 \) = estimated mean satellite’s slope
- \( a_{\text{sat}[i]} \) = random slope for the Dove satellite that made the \( i \)th observation
- \( u_{\text{event}[i]} \) = nuisance random intercept accounting for within-event correlation
- \( x_{\text{event}[i]} \) = mean \( x \) value for the crossover event to which the \( i \)th observation belongs
- \( \beta_2 \) = nuisance parameter representing difference between within-event slope and between-event slope, necessary to account for correlation between \( u_{\text{event}[i]} \) and \( x_i \).
Summarizing Proposed Corrections

Proposed updates are looked at both individually and as a whole, to check for outliers and trends

- Distribution to the right is the proposed corrections for all Doves based on data from June to August, inclusive, 2018.
- X-axis values are relative difference between new and old

NIR: Distribution of called-for adjustments

NIR (count)
Notice also how each crossover event (cluster) tends to have its own y intercept!

The magnitude of the y intercept seems to correlate with the mean event brightness.
Validating Proposed Correction:
Example of Flock 3p vs Landsat 8

Flockwide variance (width of histogram) and bias (distance from 1.0) would both be decreased by this proposed update.
Validation of Doves with RadCalNet

Planetscope BOA Reflectance vs RadCalNet for G Band

Planetscope BOA Reflectance vs RadCalNet for B Band

Blue TOAR

Green TOAR
Validation of Doves with RadCalNet

Planetscope BOA Reflectance vs RadCalNet for R Band

Planetscope BOA Reflectance vs RadCalNet for N Band

Red TOAR

NIR TOAR
Validation of RapidEye with RadCalNet

RapidEye BOA Reflectance vs RadCalNet for G Band

RapidEye BOA Reflectance vs RadCalNet for B Band

Blue TOAR

Green TOAR
Validation of RapidEye with RadCalNet

RapidEye BOA Reflectance vs RadCalNet for R Band

RapidEye BOA Reflectance vs RadCalNet for N Band

Red TOAR

NIR TOAR
## Dove and RapidEye RadCalNet Results

### Dove (TOA reflectance)

<table>
<thead>
<tr>
<th>Band</th>
<th>Accuracy (%)</th>
<th>Precision (%)</th>
<th>Uncertainty (1 SD) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>3.42</td>
<td>5.29</td>
<td>6.3</td>
</tr>
<tr>
<td>G</td>
<td>6.23</td>
<td>5.57</td>
<td>8.35</td>
</tr>
<tr>
<td>R</td>
<td>5.26</td>
<td>6.82</td>
<td>8.61</td>
</tr>
<tr>
<td>N</td>
<td>5.38</td>
<td>8.53</td>
<td>10.08</td>
</tr>
</tbody>
</table>

### RapidEye (TOA reflectance)

<table>
<thead>
<tr>
<th>Band</th>
<th>Accuracy (%)</th>
<th>Precision (%)</th>
<th>Uncertainty (1 SD) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.21</td>
<td>5.64</td>
<td>5.64</td>
</tr>
<tr>
<td>G</td>
<td>1.1</td>
<td>5.44</td>
<td>5.55</td>
</tr>
<tr>
<td>R</td>
<td>2.49</td>
<td>5.86</td>
<td>6.37</td>
</tr>
<tr>
<td>N</td>
<td>1.17</td>
<td>6.06</td>
<td>6.17</td>
</tr>
</tbody>
</table>
Validation of SkySat with RapidEye

An example fit (SkySat “s4”) is shown to the right
SkySat Results

SkySat
absolute accuracy vs. RE

Radius percent difference

Satellite
Thank you.

Questions?