The Spectral Response of Planet Doves: Pre-launch Method and Results

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South Passage, Australia – October 1, 2015

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Overview

- Planet Background
- Pre-launch Methods
- Ground Analysis Results
- Conclusion
Overarching Question:

Can a distributed smallsat constellation achieve precision and accuracy in its spectral response functions?
The Doves

Overview of Planet’s Dove Constellation. A large and diverse constellation enables daily imagery of the Earth with the opportunity for iterative payload improvements.

**Doves**

<table>
<thead>
<tr>
<th>SATELLITES</th>
<th>GSD</th>
<th>CAPACITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>120+</td>
<td>3.9 m</td>
<td>200 million km²/day</td>
</tr>
</tbody>
</table>

**ORBIT ALTITUDE**

475 km

**SPECTRAL BANDS**

RGB and NIR

**Dove Classic Sensor Layout.** The top half contains the red, green, and blue bands in a bayer pattern. The bottom half contains the NIR bands.

**Dove-R Sensor Layout.** The red, green, blue, and NIR bands are arranged vertically across the sensor in a butcher block pattern.

**Superdove Sensor Layout.** Additional spectral bands are added to the butcher block pattern.
Planet payloads over the years

**Dove Pilot (~50 satellites)**

**Dove (~150 satellites)**

**Dove-R (24 satellites)**

**SuperDove (~64 satellites)**

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Why SuperDoves?

SuperDove is a high resolution mapping mission with SPOT-5-class resolution with the spectral coverage of SENTINEL-⅔ plus:

- 2° max elevation orthophotos
- daily revisit today
- full effective FOV
- true 1-day revisit
- low stray light
- 2X NIR QE

SENTINEL-2
~750km
10° incidence
12-60m GSD
9-bands
5-day revisit (15-day effective)

SPOT-5
~800km
0-27° incidence
2.5-5.0m GSD
4-bands

SuperDove
~500km
2° incidence
3-12m GSD
8-bands
1-day revisit

Dove-R
~500km
1.5° incidence
3m GSD
4-bands
1-day revisit

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SuperDove sensor layout

<table>
<thead>
<tr>
<th>Band</th>
<th>Name</th>
<th>Notes</th>
<th>Wavelength (fwhm)</th>
<th>spatial sampling</th>
<th>GSD (m)</th>
<th>$\frac{L}{W}$ (W sr^-1 um^-1 m^2)</th>
<th>SNR @ $L_{in}$ (ts=10ms)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coastal Blue</td>
<td>core visible bands</td>
<td>443 (20)</td>
<td>0.25x</td>
<td>12</td>
<td>130</td>
<td>193</td>
</tr>
<tr>
<td>2</td>
<td>Blue</td>
<td></td>
<td>490 (50)</td>
<td>1x</td>
<td>3</td>
<td>130</td>
<td>170</td>
</tr>
<tr>
<td>3</td>
<td>Green I</td>
<td></td>
<td>531 (36)</td>
<td>1x</td>
<td>3</td>
<td>130</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>Green II</td>
<td></td>
<td>565 (36)</td>
<td>1x</td>
<td>3</td>
<td>130</td>
<td>154</td>
</tr>
<tr>
<td>5</td>
<td>Red</td>
<td></td>
<td>665 (31)</td>
<td>1x</td>
<td>3</td>
<td>130</td>
<td>138</td>
</tr>
<tr>
<td>6</td>
<td>Yellow</td>
<td>sediments, PC</td>
<td>610 (20)</td>
<td>1x</td>
<td>6</td>
<td>70</td>
<td>63</td>
</tr>
<tr>
<td>10</td>
<td>Red edge I</td>
<td>important for data compatibility with Sentinel-2</td>
<td>705 (15)</td>
<td>0.5x</td>
<td>6</td>
<td>70</td>
<td>57</td>
</tr>
<tr>
<td>13</td>
<td>NIR</td>
<td>narrow NIR</td>
<td>865 (40)</td>
<td>0.5x</td>
<td>6</td>
<td>130</td>
<td>137</td>
</tr>
</tbody>
</table>
RSR Application

- SuperDove has six bands similar to Sentinel-2A
- SuperDove covers a wider wavelength spectrum compared to previous Dove designs
- Additional bands picked primarily for agriculture applications

Spectral Response Pattern of Lawn Grass. Plots depict how SuperDove vs Sentinel-2A spectral responses cover this specific spectrum. Accurate RSRs are crucial for measurements such as this.
RSR Workflow Chart. A simplified version of the flow chart every satellite goes through, modified to highlight steps relevant to the spectral response of the Doves.
Spectral Station Diagram illustrating the general layout of the station and its various components.
Data Collection:

1. Camera Temp stabilization
   - CCD Temp stable within 1 deg C for 5 min and under 45 deg C
2. Collect Darks
   - Noise correction
3. Zero optical power meter (OPM)
4. Collect image and OPM reading through sweep of wavelengths
   - Range: 400-1000 nm
5. Collect Darks
   - Compare to darks at beginning of test

<table>
<thead>
<tr>
<th>Test Stats</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Avg Test Duration</td>
<td>3.3 hrs</td>
</tr>
<tr>
<td>Num of Images Captured</td>
<td>2600</td>
</tr>
<tr>
<td>Storage Size per Test</td>
<td>~120 GB</td>
</tr>
<tr>
<td>Spectral Sampling</td>
<td>1nm</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>1nm</td>
</tr>
</tbody>
</table>
Automated Preliminary Analysis:

- While images are still on the station’s computer:
  1. Average a region within each filter band, calculate the response in each image and produce a preliminary RSR. Save both tabulated and plotted RSR.
  2. Within a predefined region (i.e. filter band), find the wavelength with the strongest response. Save images at those wavelengths with unique names to quickly find later. Helpful in verifying raw images match produced RSR.

- All images, log files, and analysis files are uploaded to internal manufacturing test data storage.

**Upper Right:** Example preliminary spectral response curves.

**Bottom Middle:** Raw image of the sensor at 713 nm. Red box shows ROI used for preliminary analysis.
Complete RSR Method

1. At each wavelength, stack images for improved SNR
2. Create average dark image for later noise removal step
3. Define regions to be used for analysis (i.e. average entire band, separate band into smaller regions for more detailed output, etc)
4. For each wavelength’s image stack:
   a. Subtract average dark image
   b. Get mean response in each region
   c. Divide image by lamp intensity
5. Normalize each band to be between 0 and 1

![Uncorrected Spectral Response Curve. Y-Axis in DN.](image1)

Uncorrected Spectral Response Curve. Y-Axis in DN.

![Lamp Corrected Spectral Response Curve. Removes variations from lamp output.](image2)

Lamp Corrected Spectral Response Curve. Removes variations from lamp output.

![Relative Spectral Response Curve. All eight bands have been normalized.](image3)

Relative Spectral Response Curve. All eight bands have been normalized.

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Ground Results
In general, shows very good agreement with variations in the shape of the top of each band.

The slight visible offset between measured and theoretical, upon further analysis, is ~ 1 nm. This may be due to variations in the filter (this is an example payload, not an average).

These shifts can be corrected during on-orbit calibration.

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**Capability:** Able to measure out-of-band response for every satellite by scanning all wavelengths with 1 nm step size.

Planet doesn’t measure out-of-band response at the component level. Receive information from the filter vendor.

**Result:** Out-of-band relative response across filter bands is between 1E-2 and 1E-3.

*Top: Analysis regions plotted over instrument flatfield
Bottom: Relative Spectral Response (log scale) for Band 6 (Yellow). Full instrument level relative spectral response, displaying both in-band and out-of-band responses.*
Measurements with different analysis regions to distinguish signal based off vertical spatial position on the sensor.

Analysis regions closer to top/bottom of band have higher signal, indicating optical crosstalk.

All crosstalk below 1E-2 relative response.

Left: Analysis regions plotted over instrument flatfield. Color of analysis region based off vertical position matches RSR graph colors.

Top Right: Relative Spectral Response (log scale) for Band 2 (Red)

Bottom Right: Relative Spectral Response (log scale) for Band 3 (Green I)
The spread of measured center wavelength by filter band across 22 satellites. The largest standard deviation being 1.42 nm with the smallest at 0.35 nm.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1 (Blue)</td>
<td>490</td>
<td>490</td>
<td>489</td>
<td>491</td>
<td>0.6102</td>
<td>0.1301</td>
</tr>
<tr>
<td>Band 2 (Red)</td>
<td>665</td>
<td>666</td>
<td>664</td>
<td>667</td>
<td>0.8728</td>
<td>0.1861</td>
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<tr>
<td>Band 3 (Green I)</td>
<td>531</td>
<td>532</td>
<td>530</td>
<td>533</td>
<td>1.0970</td>
<td>0.2338</td>
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<tr>
<td>Band 4 (Green II)</td>
<td>565</td>
<td>565</td>
<td>564</td>
<td>565</td>
<td>0.3513</td>
<td>0.0748</td>
</tr>
<tr>
<td>Band 5 (Red Edge)</td>
<td>705</td>
<td>707</td>
<td>706</td>
<td>708</td>
<td>0.6901</td>
<td>0.1471</td>
</tr>
<tr>
<td>Band 6 (Yellow)</td>
<td>610</td>
<td>611</td>
<td>609</td>
<td>614</td>
<td>1.4241</td>
<td>0.3036</td>
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<tr>
<td>Band 7 (NIR)</td>
<td>865</td>
<td>865</td>
<td>863</td>
<td>867</td>
<td>1.4019</td>
<td>0.2989</td>
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<tr>
<td>Band 8 (Coastal Blue)</td>
<td>443</td>
<td>443</td>
<td>442</td>
<td>445</td>
<td>0.8541</td>
<td>0.1821</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------</td>
<td>-------------</td>
<td>----------</td>
<td>----------</td>
<td>-------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Band 1 (Blue)</td>
<td>50</td>
<td>53</td>
<td>52</td>
<td>54</td>
<td>0.5885</td>
<td>0.1255</td>
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<tr>
<td>Band 2 (Red)</td>
<td>31</td>
<td>34</td>
<td>33</td>
<td>35</td>
<td>0.7509</td>
<td>0.1600</td>
</tr>
<tr>
<td>Band 3 (Green I)</td>
<td>36</td>
<td>39</td>
<td>38</td>
<td>40</td>
<td>0.5602</td>
<td>0.1194</td>
</tr>
<tr>
<td>Band 4 (Green II)</td>
<td>36</td>
<td>40</td>
<td>40</td>
<td>41</td>
<td>0.4767</td>
<td>0.1017</td>
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<tr>
<td>Band 5 (Red Edge)</td>
<td>15</td>
<td>18</td>
<td>18</td>
<td>19</td>
<td>0.3513</td>
<td>0.0749</td>
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<tr>
<td>Band 6 (Yellow)</td>
<td>20</td>
<td>24</td>
<td>23</td>
<td>25</td>
<td>0.4264</td>
<td>0.0910</td>
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<tr>
<td>Band 7 (NIR)</td>
<td>40</td>
<td>42</td>
<td>41</td>
<td>43</td>
<td>0.6311</td>
<td>0.1345</td>
</tr>
<tr>
<td>Band 8 (Coastal Blue)</td>
<td>20</td>
<td>23</td>
<td>21</td>
<td>24</td>
<td>0.9989</td>
<td>0.2130</td>
</tr>
</tbody>
</table>

The spread of measured bandpass by filter band across 22 satellites. Bandpass determined by FWHM.

*Note: Design bandpass defined by top of band, not FWHM, explaining the discrepancy.*
Percent Difference of four metrics. Percent Difference is relative to average value from the 22 satellites (center wavelength is relative to design value). Top two plots illustrate the info from the previous two slides while uniformity of lower and upper edge is shown in the bottom two plots.
Summary

- Agile automated workflow for collecting, processing, and analyzing spectral data per satellite
- Measured RSRs in good alignment with design RSRs
- Out-of-Band and Crosstalk measurements 0.1% average
  - Possible design updates to further mitigate crosstalk
- Low RSR variance across payloads

Overarching Question Answer: Yes! Consistent spectral performance across a smallsat constellation is achievable.
Questions?

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