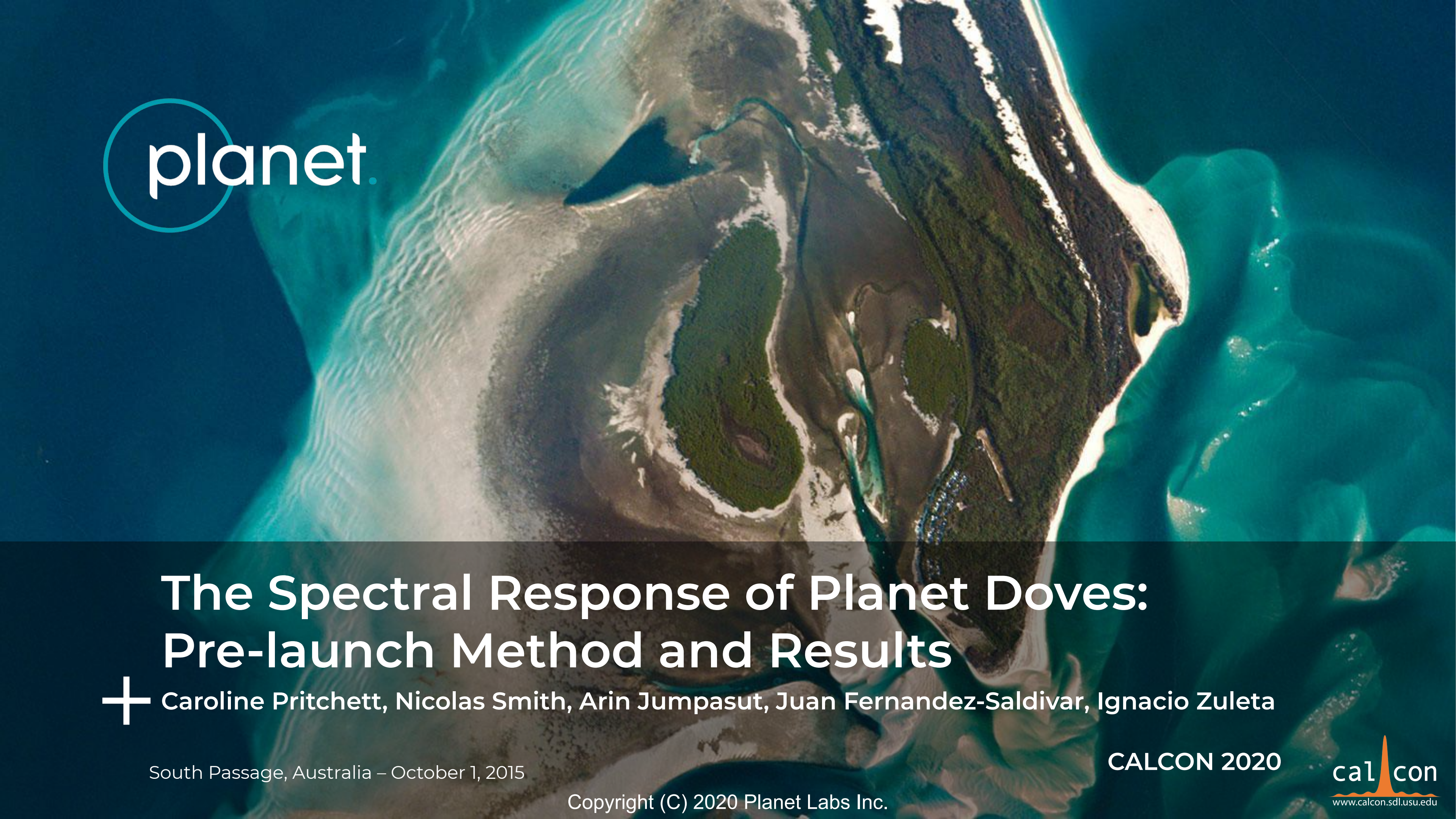


planet.

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

Caroline Pritchett, Nicolas Smith, Arin Jumpasut, Juan Fernandez-Saldivar, Ignacio Zuleta

South Passage, Australia – October 1, 2015

CALCON 2020

calcon
www.calcon.sdl.usu.edu

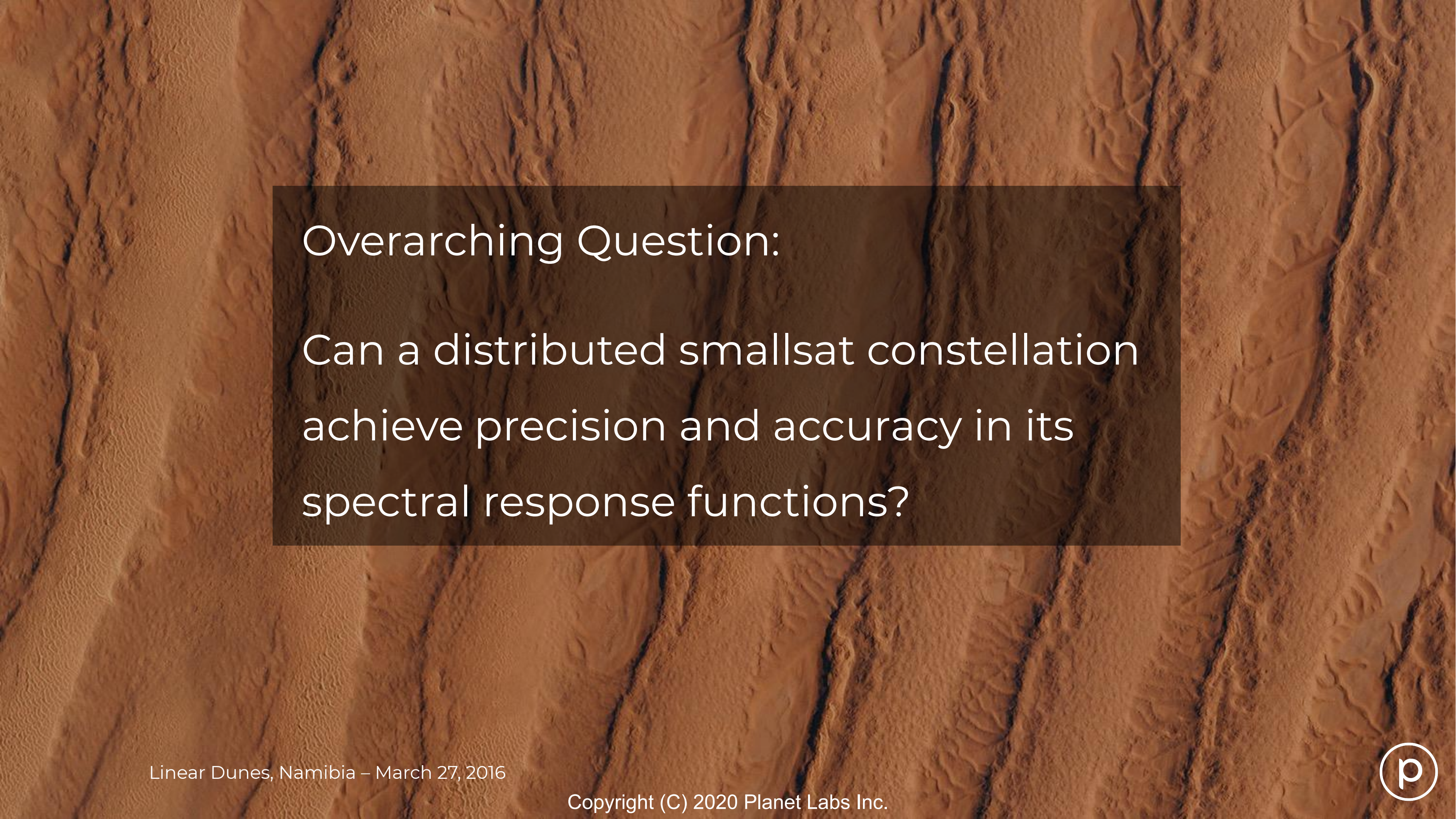
Overview

- Planet Background
- Pre-launch Methods
- Ground Analysis Results
- Conclusion

London Array Wind Farm, United Kingdom – April 17, 2016

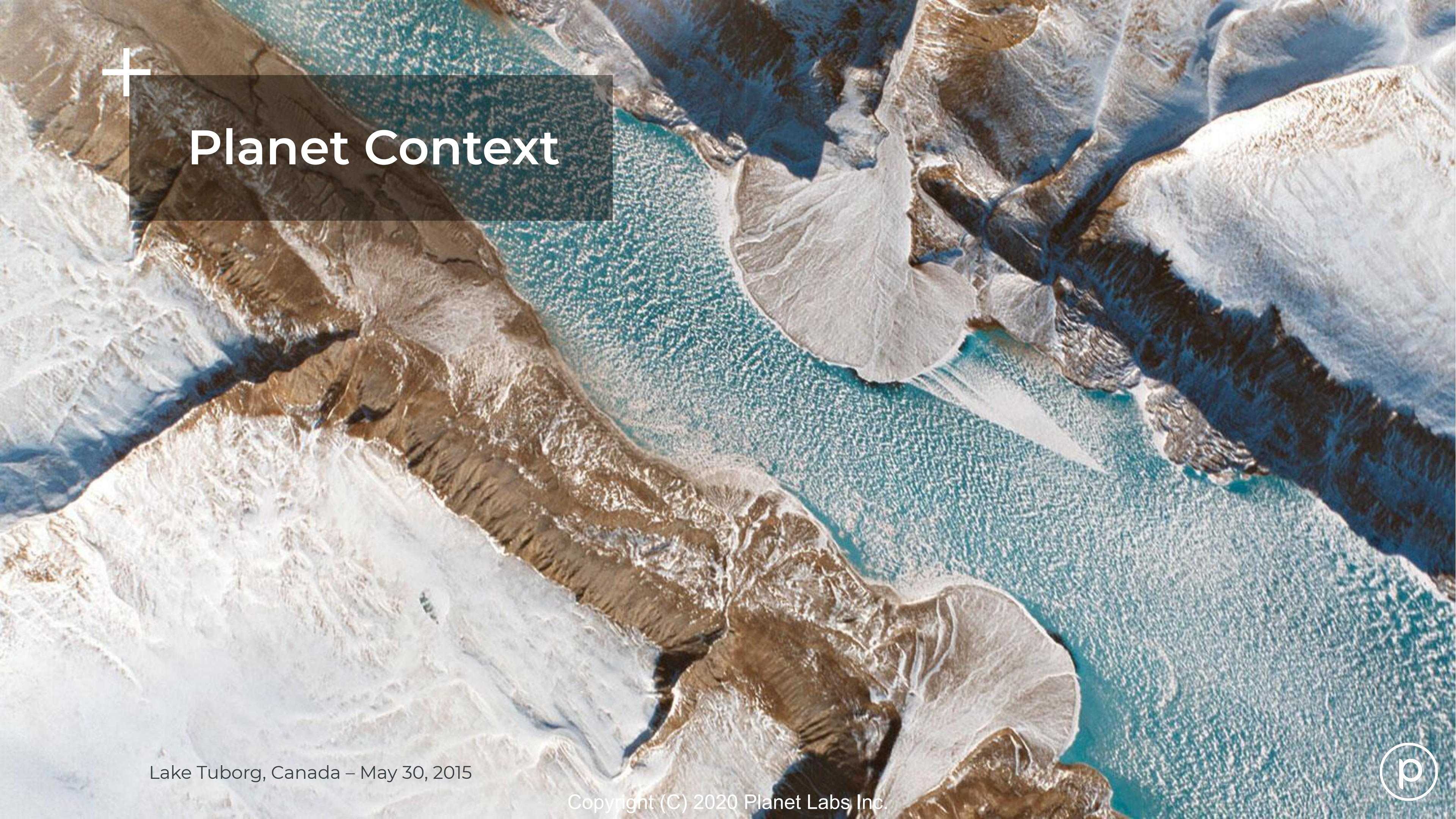
Overarching Question:

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



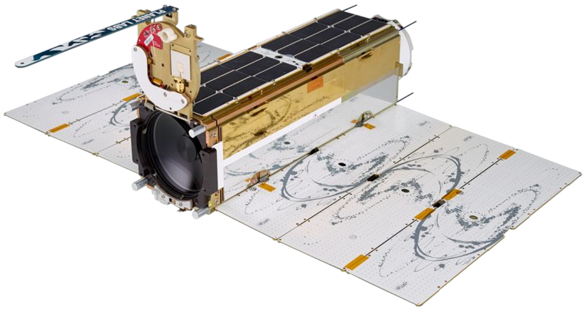
Linear Dunes, Namibia – March 27, 2016

Planet Context



Lake Tuborg, Canada – May 30, 2015

The Doves

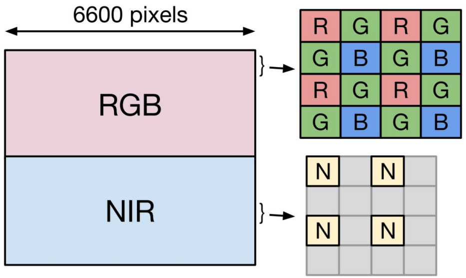


Doves

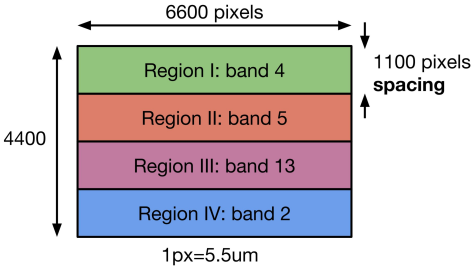
SATELLITES	GSD	CAPACITY
120+	**3.9 m**	**200 million km²**/day

ORBIT ALTITUDE	SPECTRAL BANDS
475 km	**RGB** and **NIR**

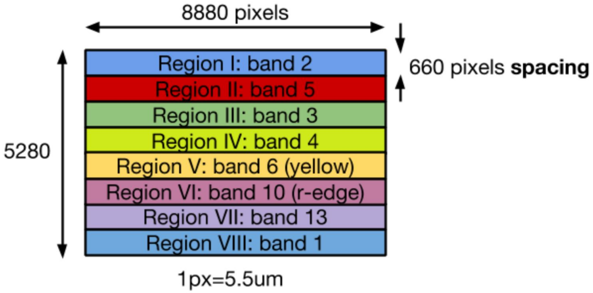
Overview of Planet's Dove Constellation. A large and diverse constellation enables daily imagery of the Earth with the opportunity for iterative payload improvements.



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.

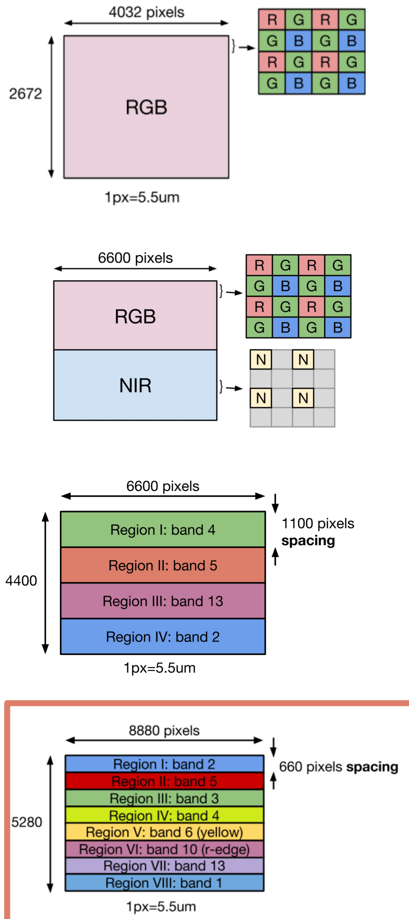


Dove-R Sensor Layout. The red, green, blue, and nir bands are arranged vertically across the sensor in a butcher block pattern.



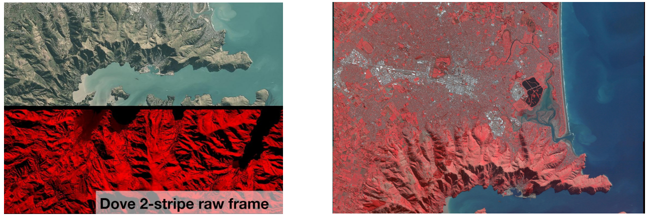
Superdove Sensor Layout. Additional spectral bands are added to the butcher block pattern.

Planet payloads over the years

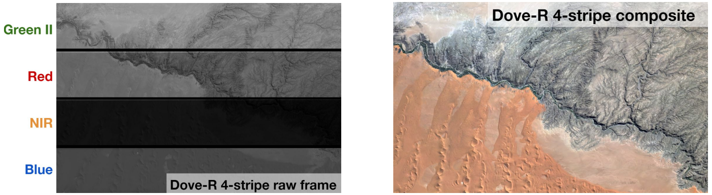


Dove Pilot (~50 satellites)

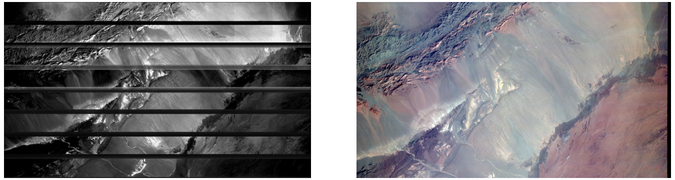
Dove (~150 satellites)



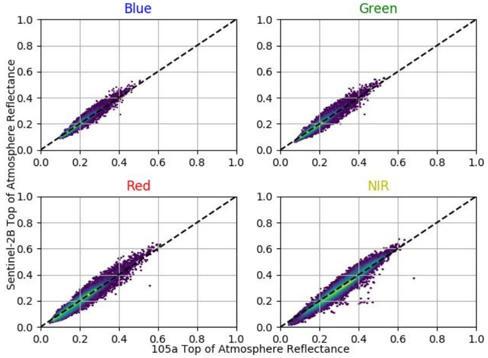
Dove-R (24 satellites)



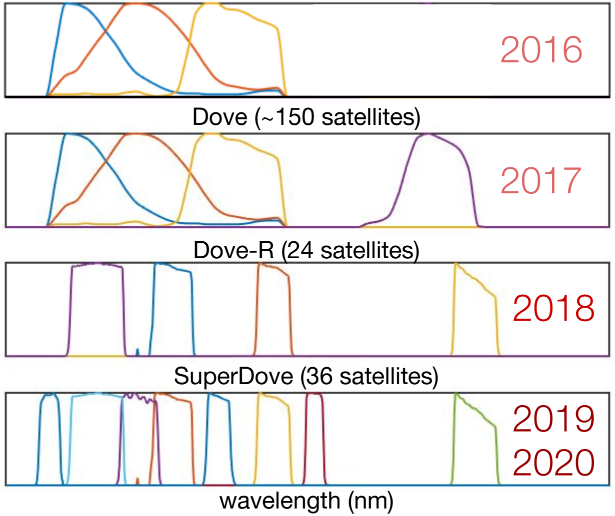
SuperDove (~64 satellites)



Dove-R versus Sentinel-2



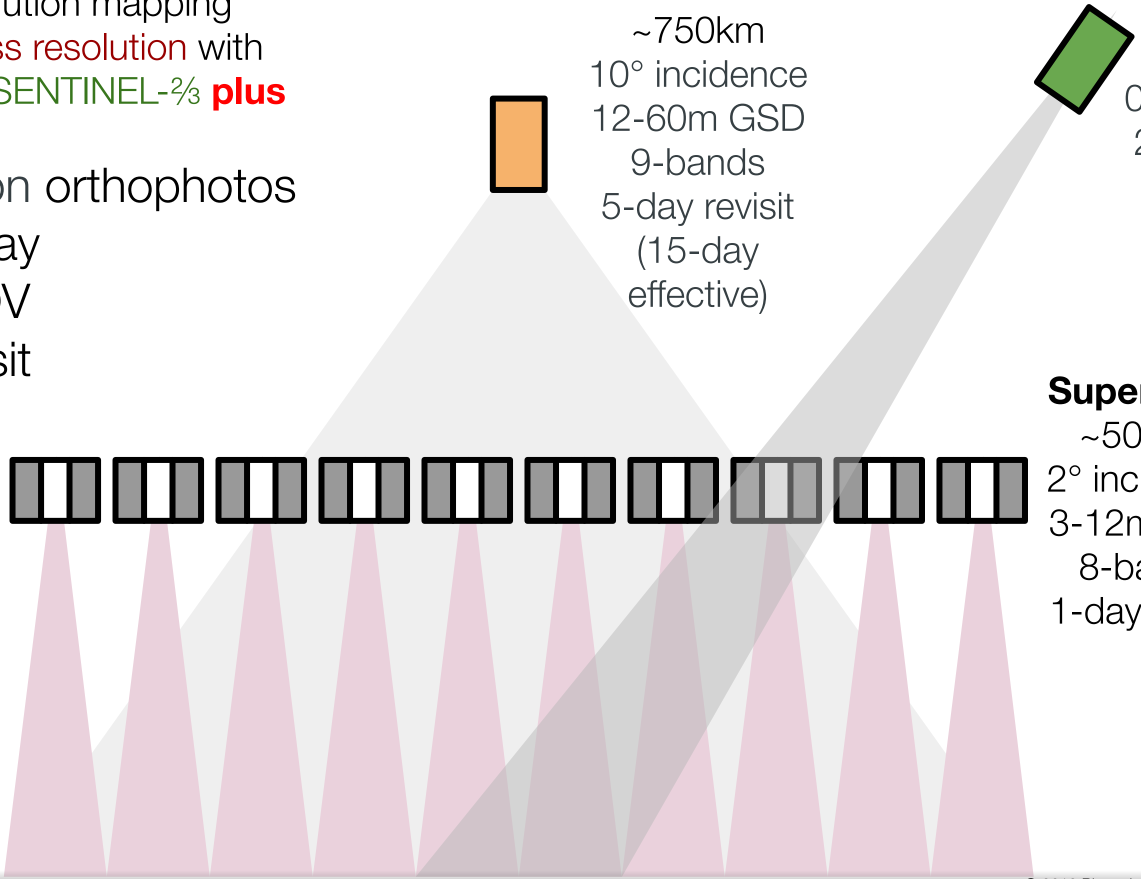
Dove Pilot (~36 satellites)



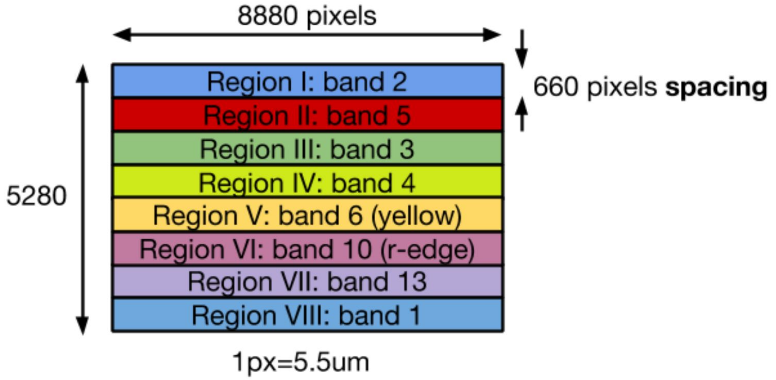
Why SuperDoves?

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



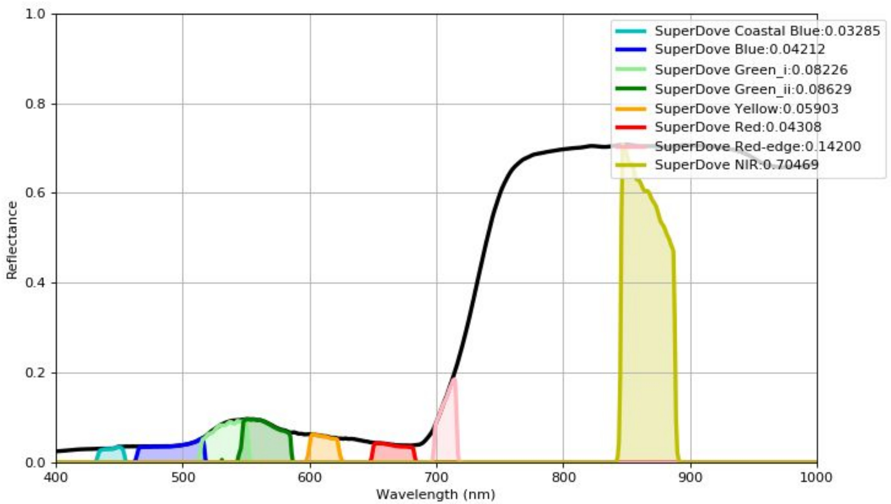
SuperDove sensor layout

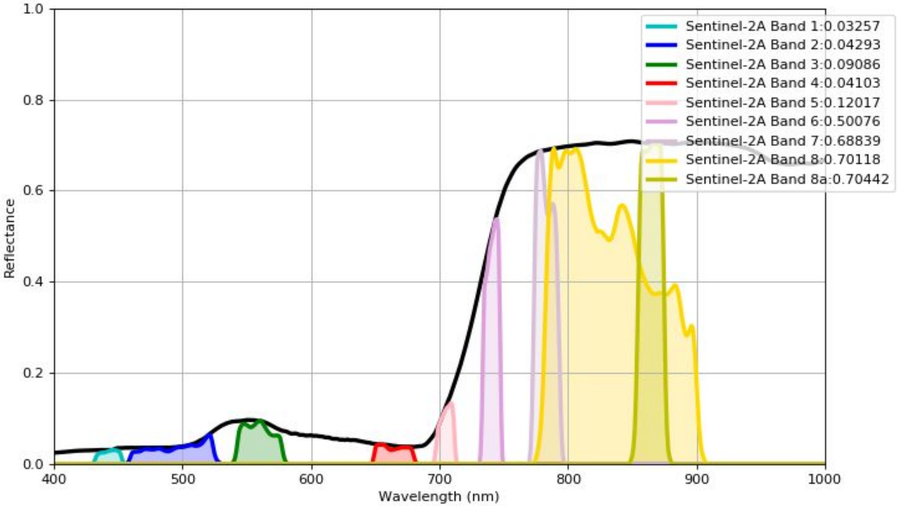


Band	Name	Notes	Wavelength (fwhm)	spatial sampling	GSD (m)	L_{ref} (W $sr^{-1}um^{-1}$ m^{-2})	SNR @ L_{ref} (t=10ms)*
1	Coastal Blue	core visible bands	443 (20)	**0.25x**	**12**	130	193
2	Blue		490 (50)	**1x**	**3**	130	170
3	Green I		531 (36)	**1x**	**3**	130	150
4	Green II		565 (36)	**1x**	**3**	130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

RSR Application

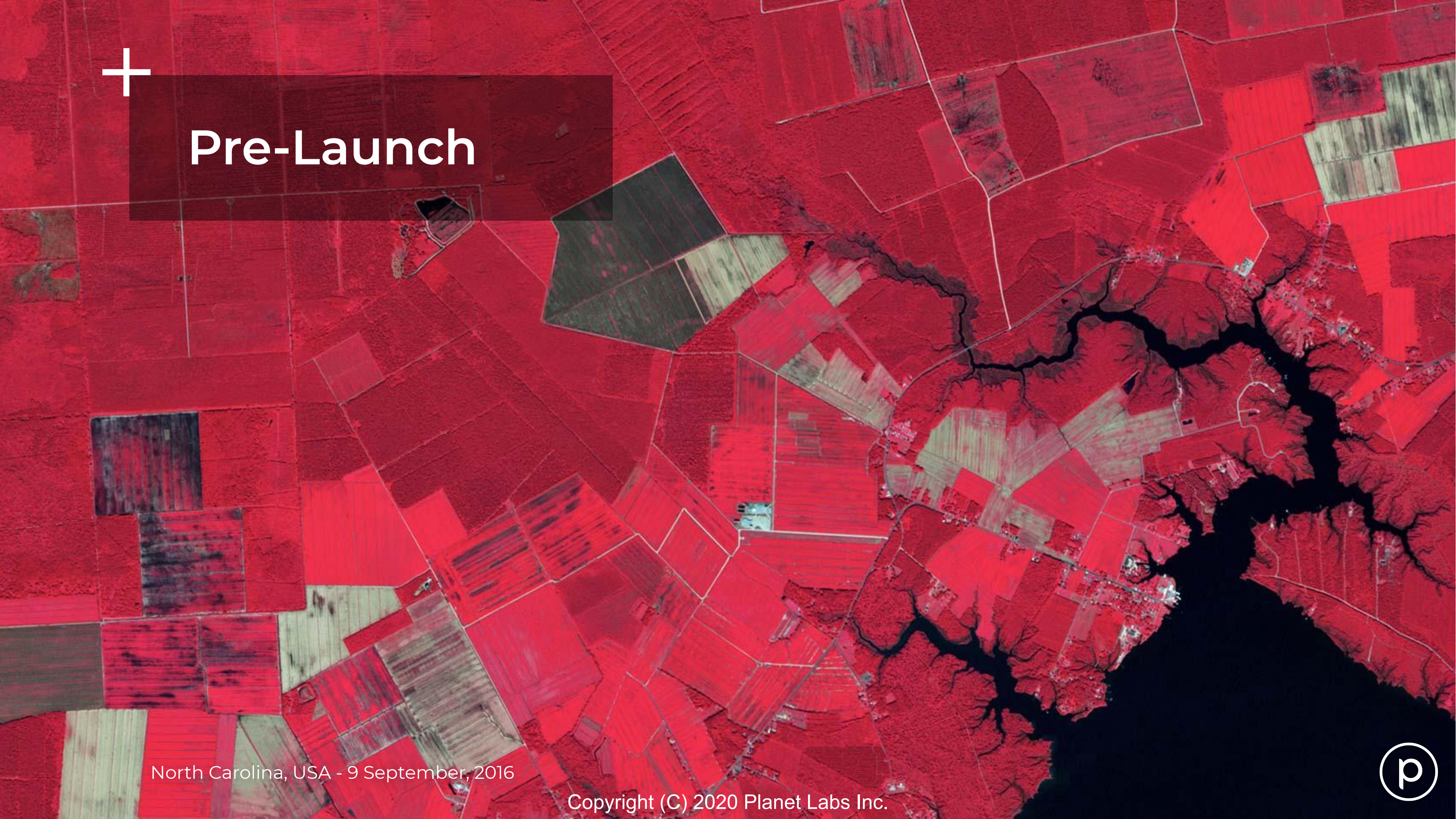
- SuperDove has six bands similar to Sentinel-2A
- SuperDove covers a wider wavelength spectrum compared to previous Dove designs
- Additional bands picked primarily for agriculture applications





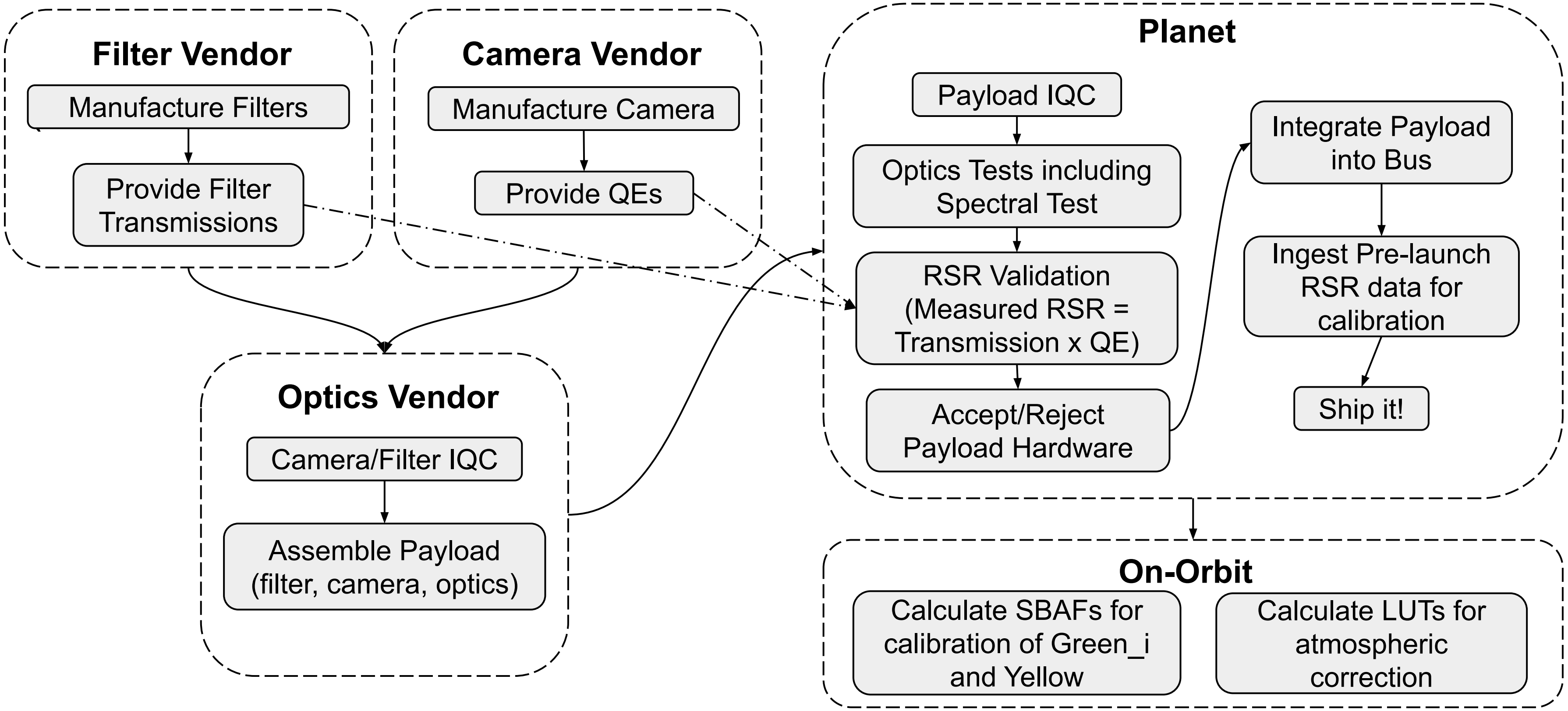
Spectral Response Pattern of Lawn Grass. Plots depict how SuperDove vs Sentinel-2A spectral responses cover this specific spectrum. Accurate RSRs are crucial for measurements such as this.

Pre-Launch



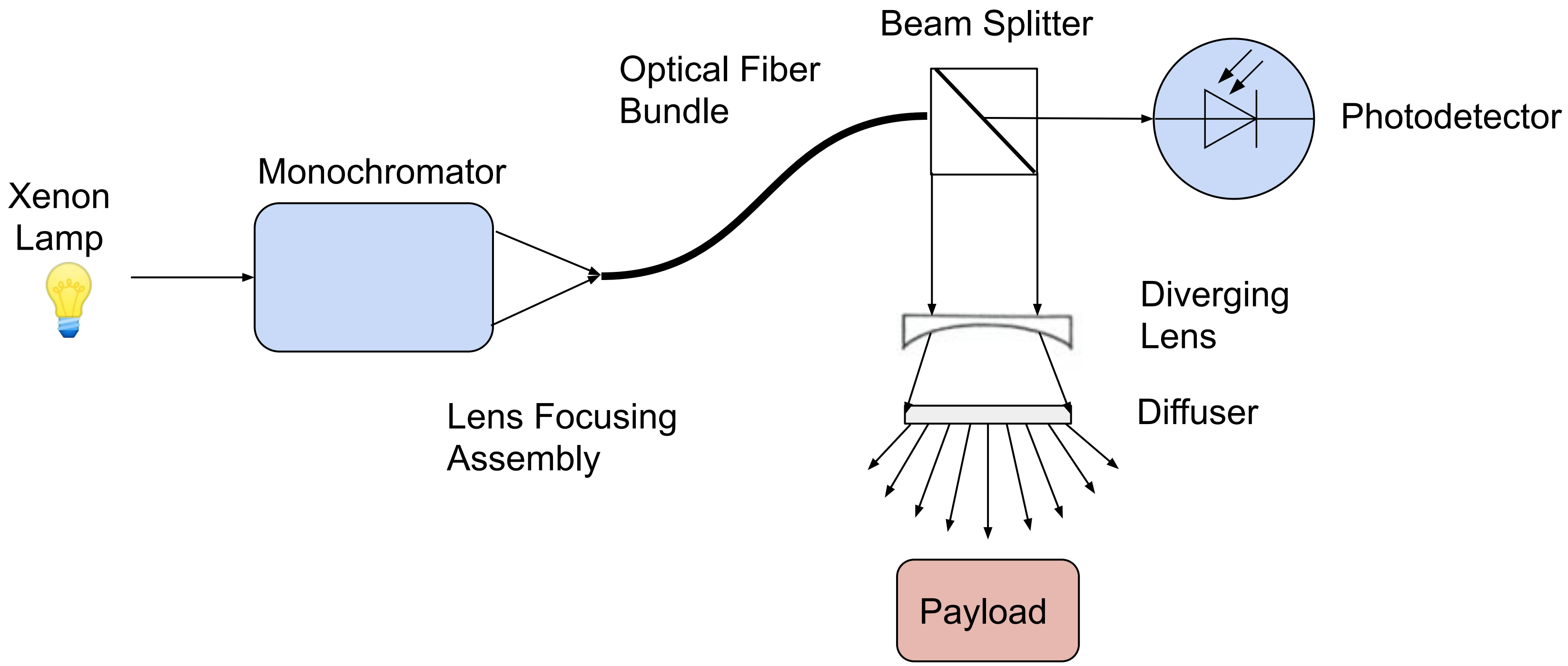
North Carolina, USA - 9 September, 2016

RSR Workflow



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



Spectral Station Diagram illustrating the general layout of the station and its various components.

Test Procedure

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

Test Stats	
Avg Test Duration	3.3 hrs
Num of Images Captured	2600
Storage Size per Test	~120 GB
Spectral Sampling	1nm
Spectral Resolution	1nm

Test Procedure

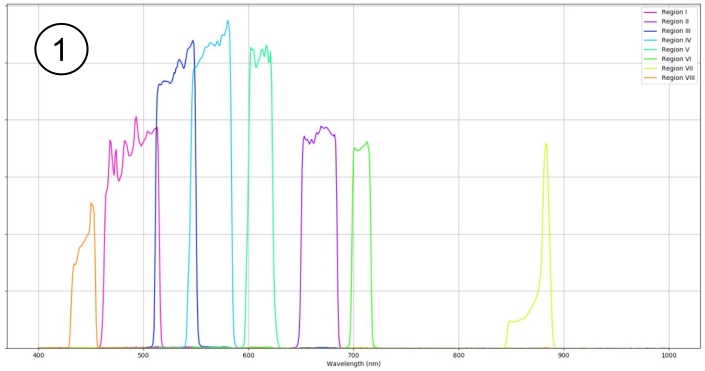
Automated Preliminary Analysis:

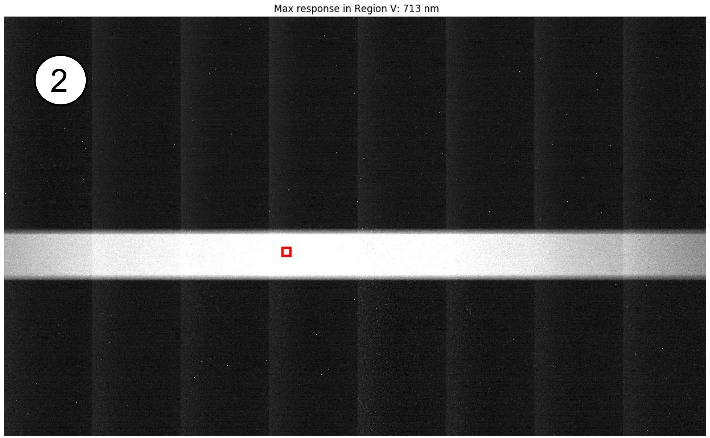
- While images are still on the station's computer:

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

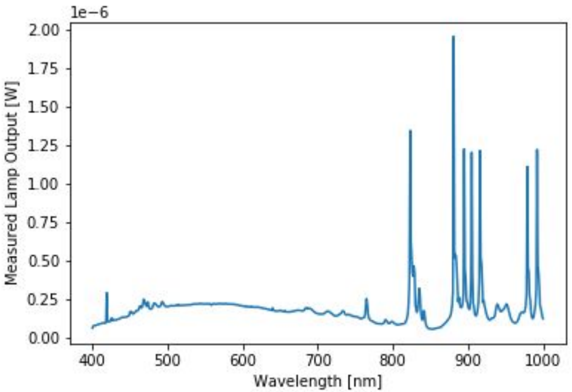




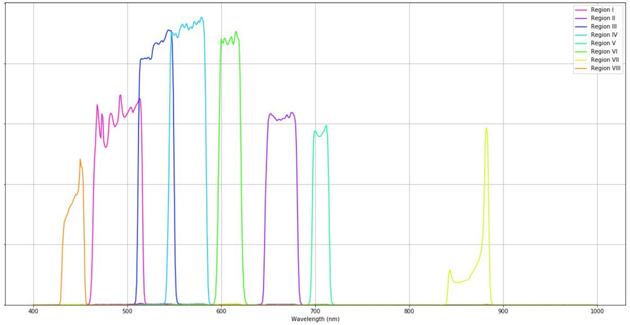
Upper Right: Example preliminary spectral response curves.
Bottom Middle: Raw image of the sensor at 713 nm. Red box shows ROI used for preliminary analysis.

Complete RSR Method

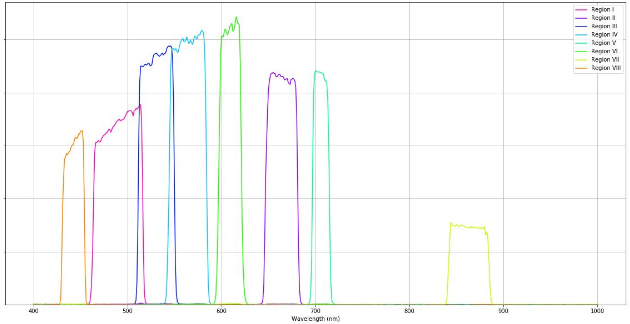
1. At each wavelength, stack images for improved SNR
2. Create average dark image for later noise removal step
3. Define regions to be used for analysis (i.e. average entire band, separate band into smaller regions for more detailed output, etc)
4. For each wavelength's image stack:
   a. Subtract average 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



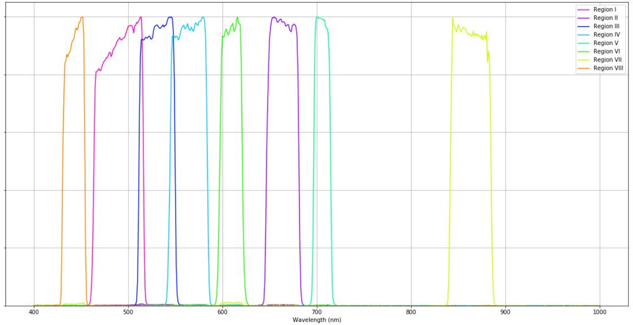
Measured Lamp Output Curve. Illustrates the characteristic Xenon spikes



Uncorrected Spectral Response Curve. Y-Axis in DN.



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

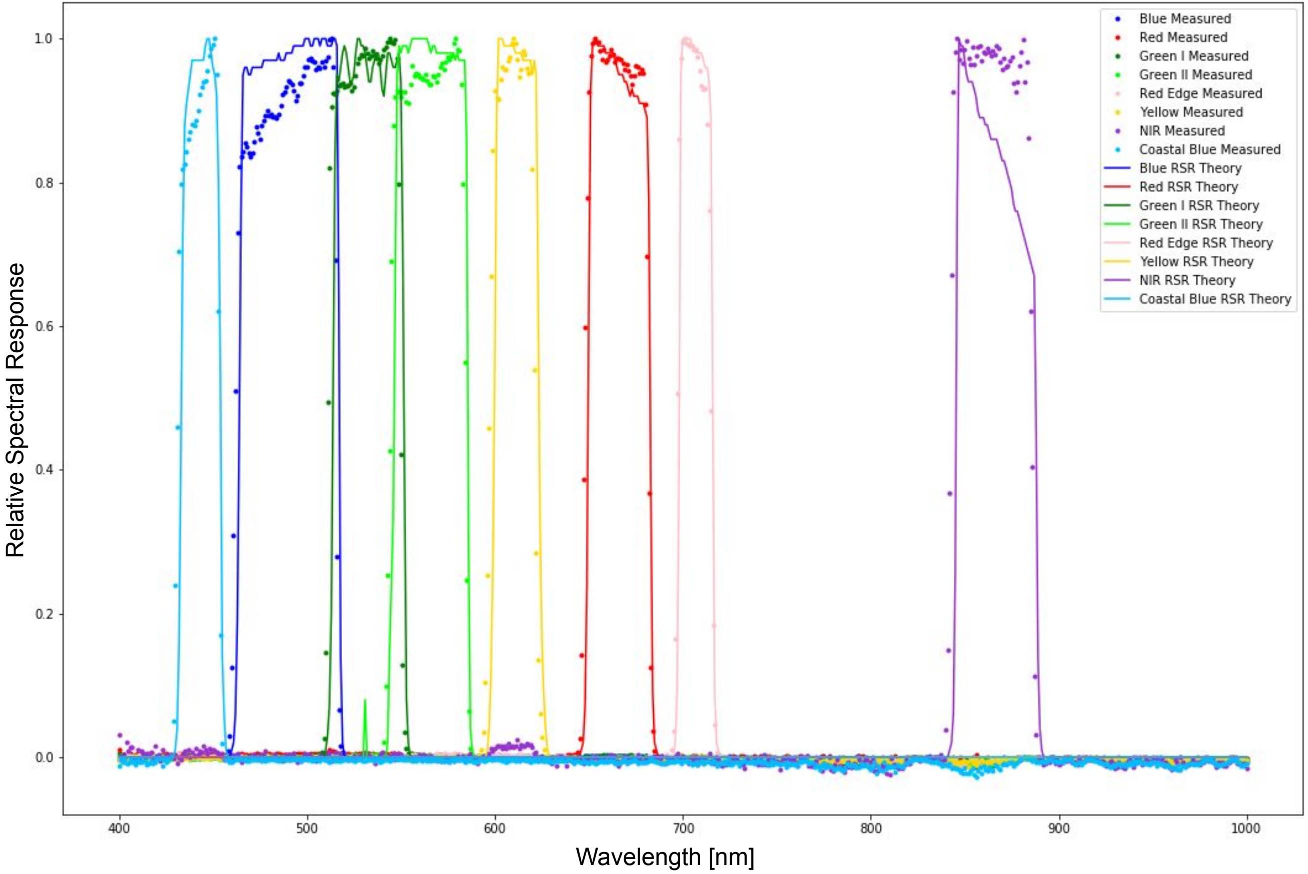


Relative Spectral Response Curve. All eight bands have been normalized.

Ground Results

Iguazú National Park, Brazil – September 23, 2016

Measured vs Theoretical



Measured RSR overlaid with payload design RSR.

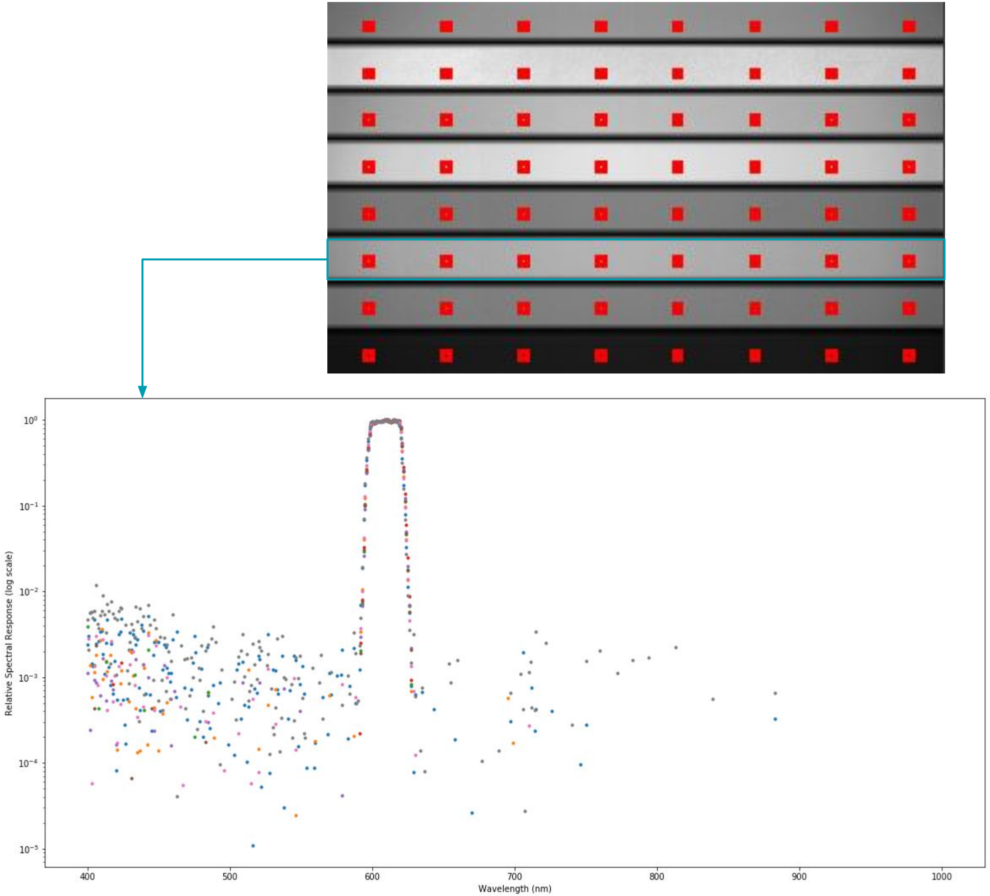
- In general, shows very good agreement with variations in the shape of the top of each band.
- The slight visible offset between measured and theoretical, upon further analysis, is ~ 1 nm. This may be due to variations in the filter (this is an example payload, not an average).
  - These shifts can be corrected during on-orbit calibration

Out-of-Band Measurements

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.

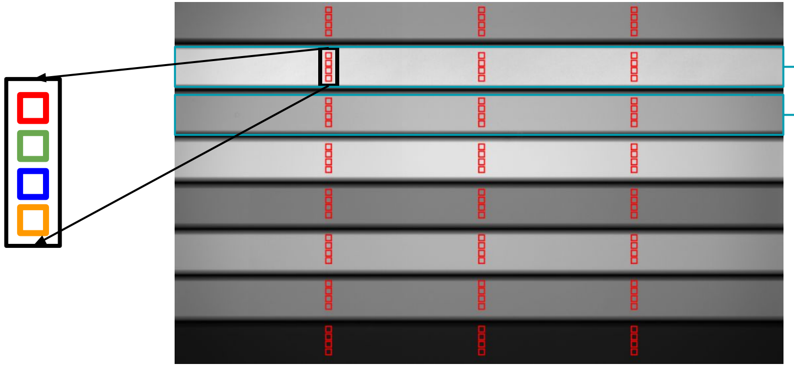
Result: Out-of-band relative response across filter bands is between 1E-2 and 1E-3

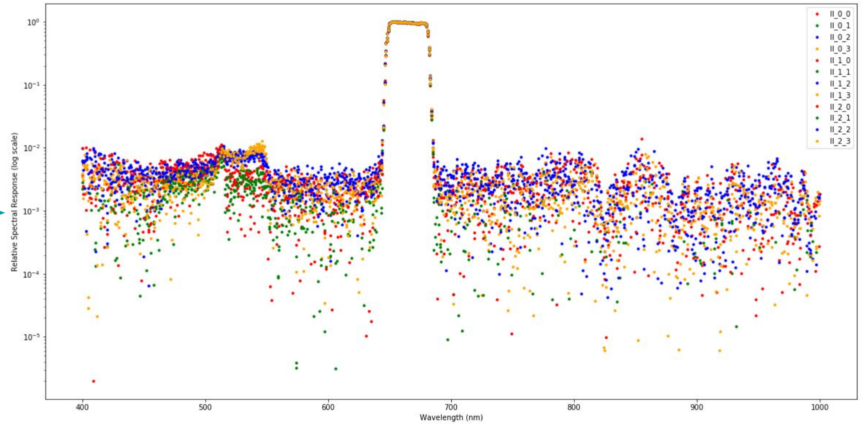


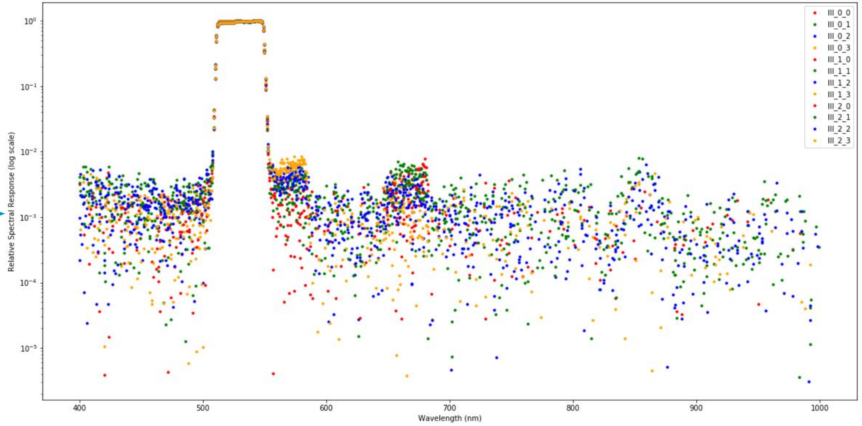
Top: Analysis regions plotted over instrument flatfield
Bottom: Relative Spectral Response (log scale) for Band 6 (Yellow). Full instrument level relative spectral response, displaying both in-band and out-of-band responses.

Crosstalk

- 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)

Uniformity Across Satellites - Center Wavelength

	Design [nm]	**Median** [nm]	**Min** [nm]	**Max** [nm]	**St Dev** [nm]	**St Error** [nm]
Band 1 (Blue)	490	490	489	491	0.6102	0.1301
Band 2 (Red)	665	666	664	667	0.8728	0.1861
Band 3 (Green I)	531	532	530	533	1.0970	0.2338
Band 4 (Green II)	565	565	564	565	0.3513	0.0748
Band 5 (Red Edge)	705	707	706	708	0.6901	0.1471
Band 6 (Yellow)	610	611	609	614	1.4241	0.3036
Band 7 (NIR)	865	865	863	867	1.4019	0.2989
Band 8 (Coastal Blue)	443	443	442	445	0.8541	0.1821

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.

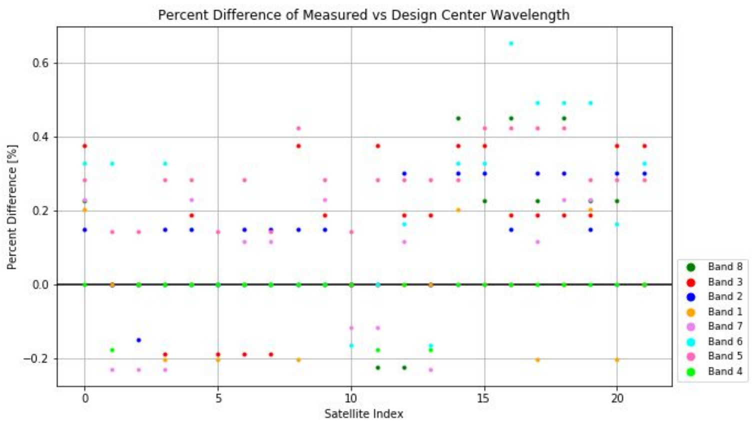
Uniformity Across Satellites - Bandpass

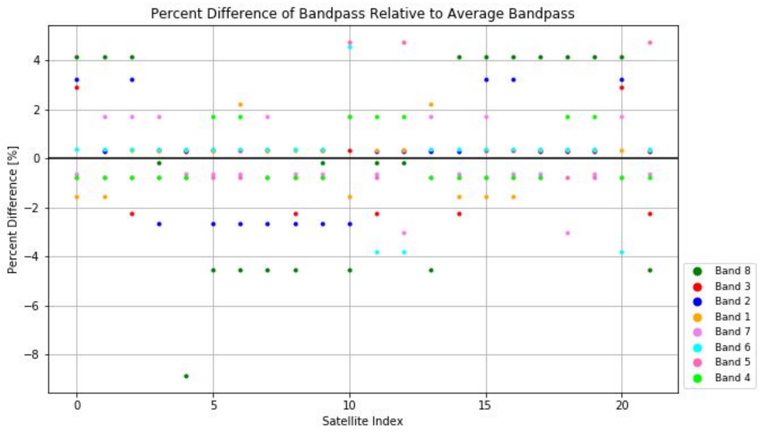
	Design [nm]*	**Median** [nm]	**Min** [nm]	**Max** [nm]	**St Dev** [nm]	**St Error** [nm]
Band 1 (Blue)	50	53	52	54	0.5885	0.1255
Band 2 (Red)	31	34	33	35	0.7509	0.1600
Band 3 (Green I)	36	39	38	40	0.5602	0.1194
Band 4 (Green II)	36	40	40	41	0.4767	0.1017
Band 5 (Red Edge)	15	18	18	19	0.3513	0.0749
Band 6 (Yellow)	20	24	23	25	0.4264	0.0910
Band 7 (NIR)	40	42	41	43	0.6311	0.1345
Band 8 (Coastal Blue)	20	23	21	24	0.9989	0.2130

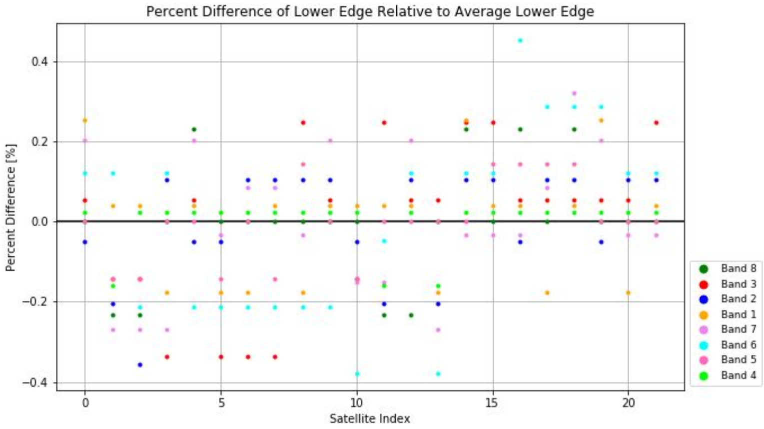
The spread of measured bandpass by filter band across 22 satellites. Bandpass determined by FWHM.

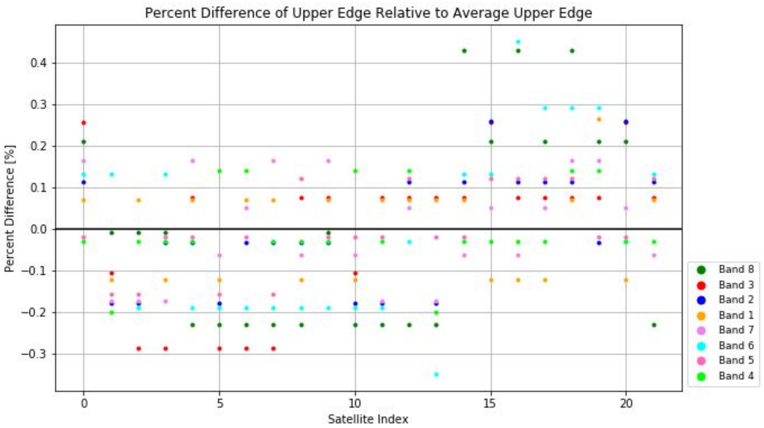
*Note: Design bandpass defined by top of band, not FWHM, explaining the discrepancy

Uniformity Across Satellites



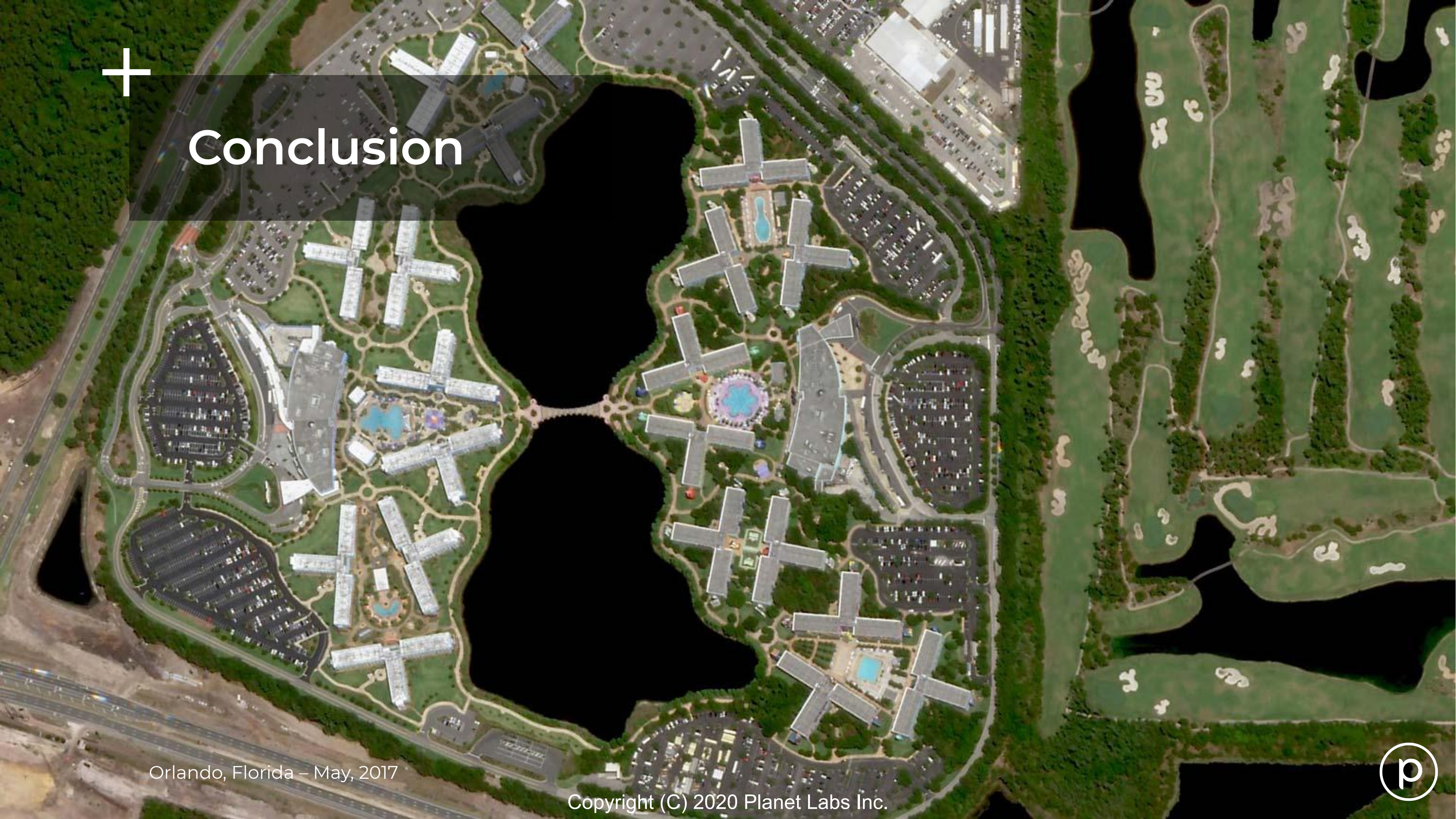






Percent Difference of four metrics. Percent Difference is relative to average value from the 22 satellites (center wavelength is relative to design value). Top two plots illustrate the info from the previous two slides while uniformity of lower and upper edge is shown in the bottom two plots.

Conclusion



Orlando, Florida – May, 2017

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?

caroline.pritchett@planet.com