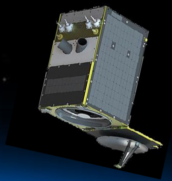
GSICS VIS/NIR Meeting - April 14, 2022

Evaluating Radiometry within a Heterogenous Satellite Fleet

via Continuous Moon Monitoring



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Introduction

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Agenda

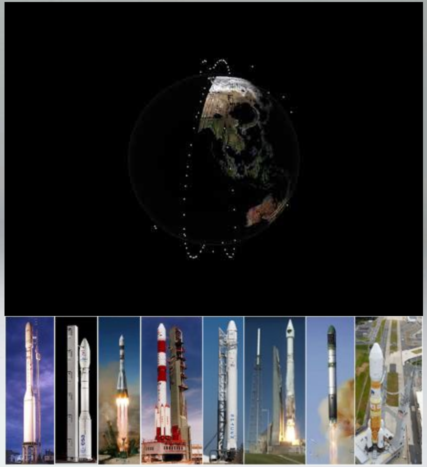
01 | Overview of Planet Platform

02 | Moon Observations on Planet Platform

03 | Challenges on SuperDove Architecture

04 | Radiometric Analysis via Moon Imagery

Rapidly innovating nano-satellite platform

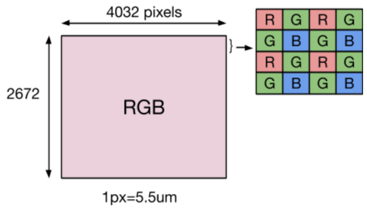


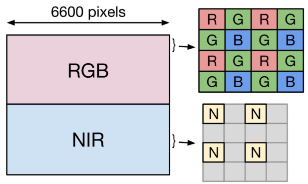
200+

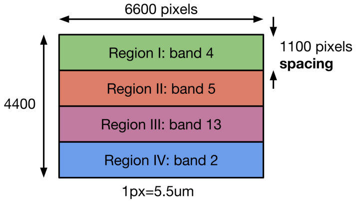
Nano-satellites (3U)

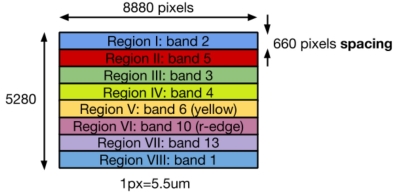
- Near-nadir field of view
- ~ Daily revisits globally
- 3 m resolution
- 4 bands (VIS + NIR)

Planet payloads over the years



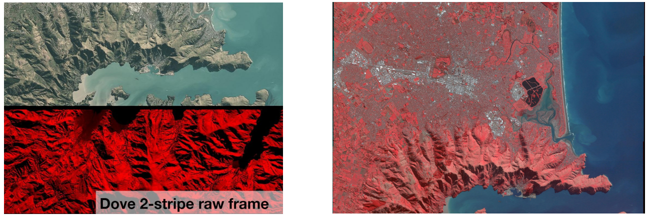




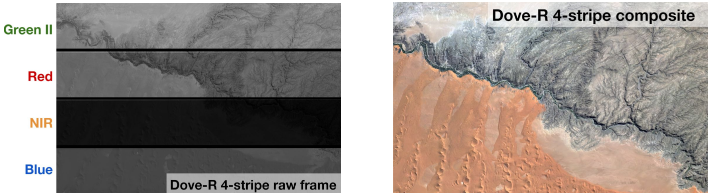


Dove Pilot (~50 satellites)

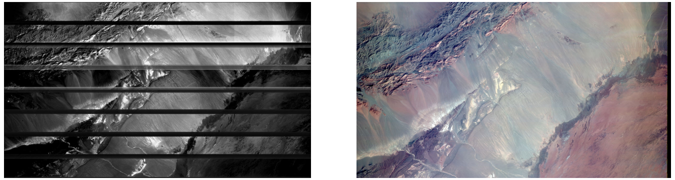
Dove (~150 satellites)



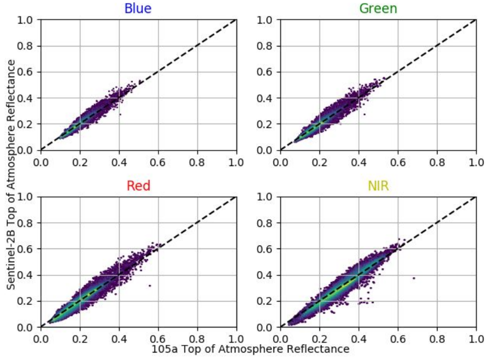
Dove-R (24 satellites)

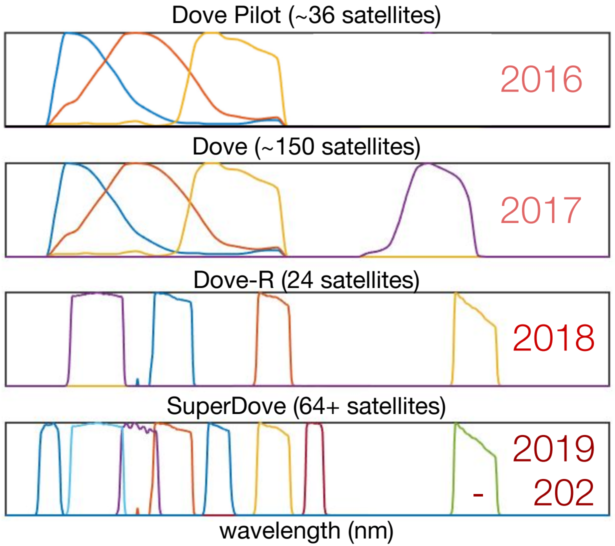


SuperDove (64+ satellites)

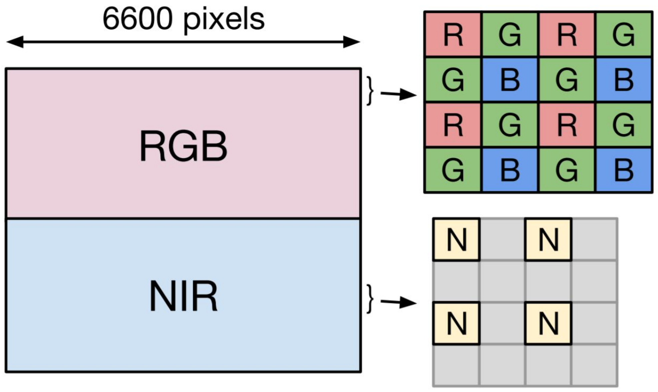


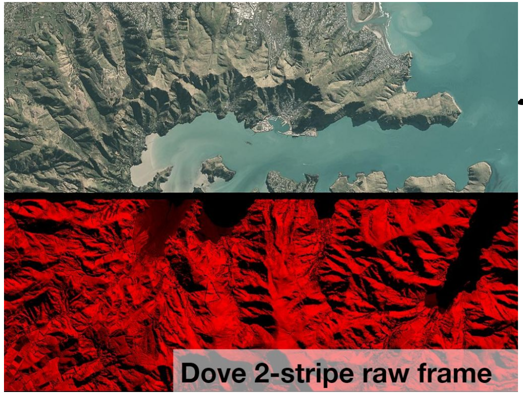
Dove-R versus Sentinel-2



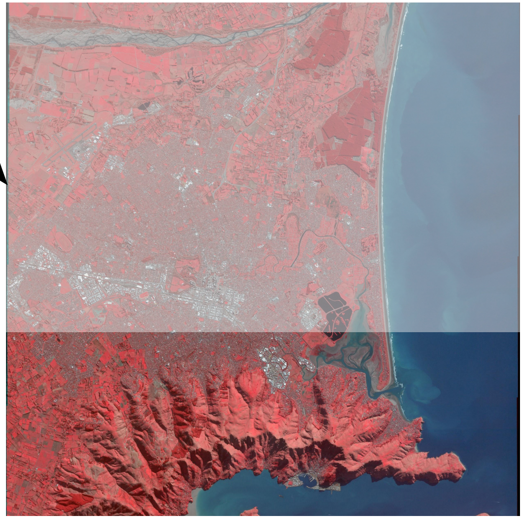


Dove Classic sensor layout





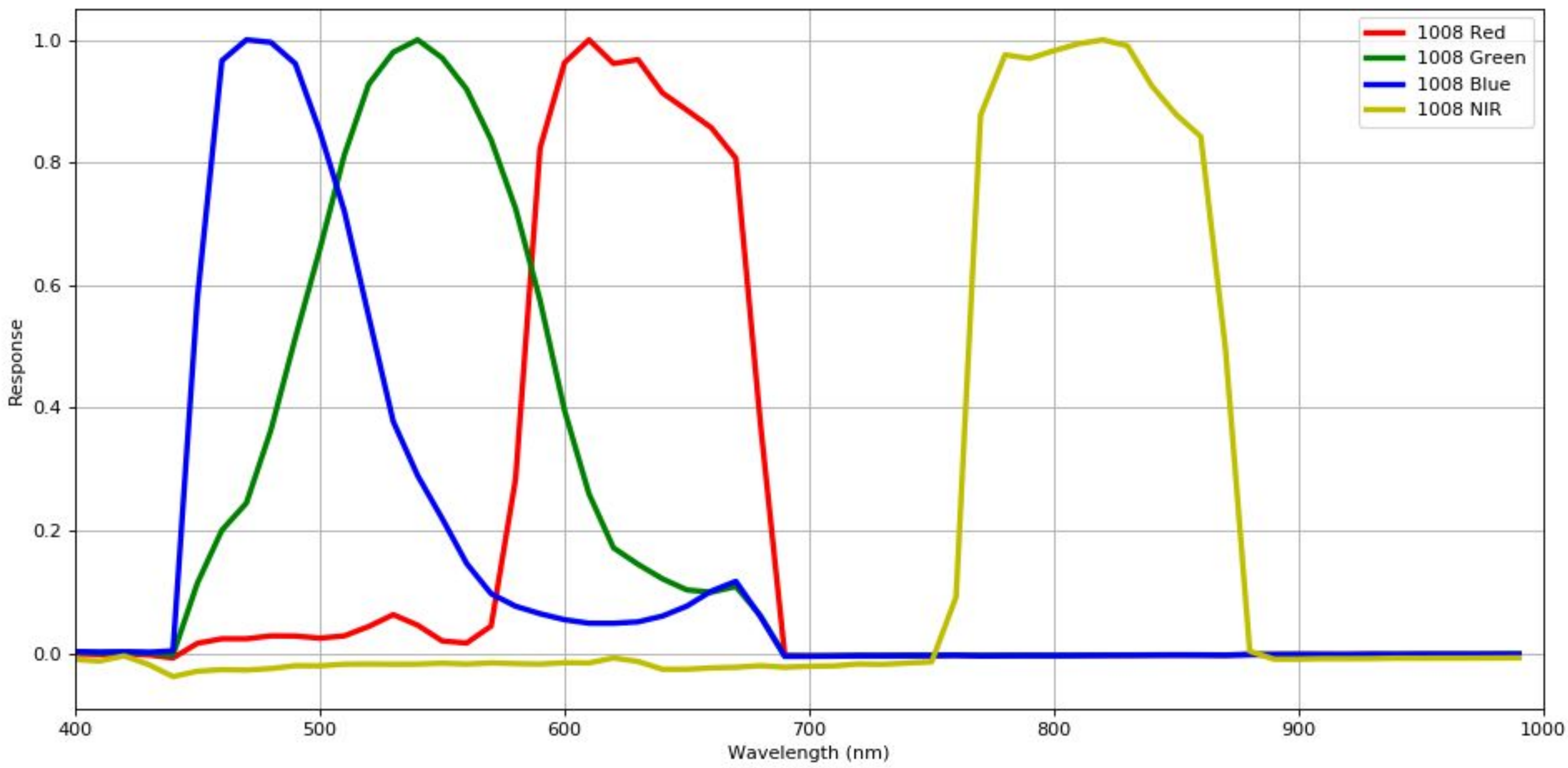
orthorectification



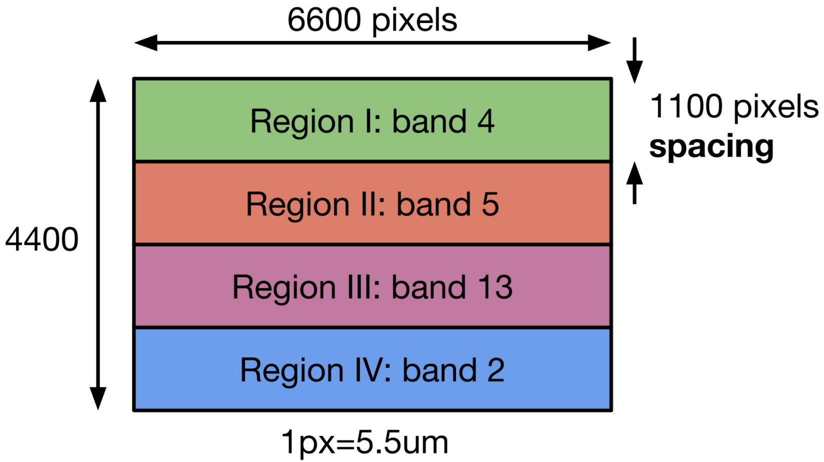
2-stripe half-frame composite

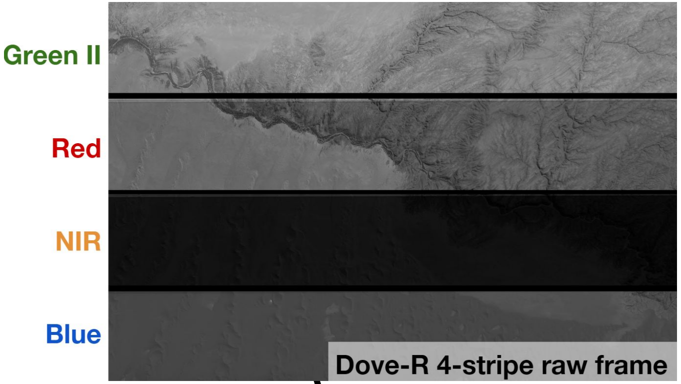
- This is the layout of the two-stripe Dove
  - The top stripe contains the red, blue and green bands in a Bayer pattern
  - The bottom stripe contains the NIR band
  - The orthorectification process allows a four band composite image to be produced

Typical Dove Classic RSR (measured at 10nm resolution)

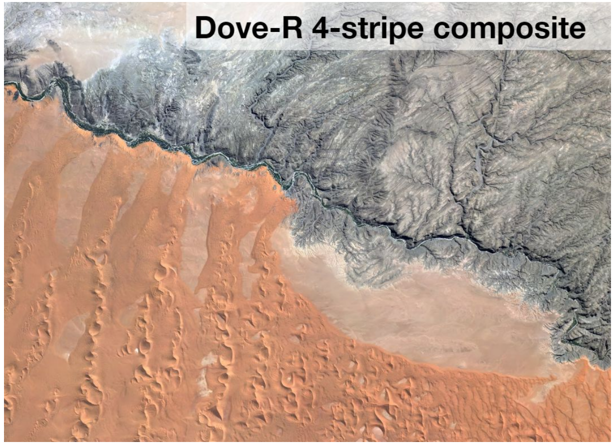


Dove-R sensor layout



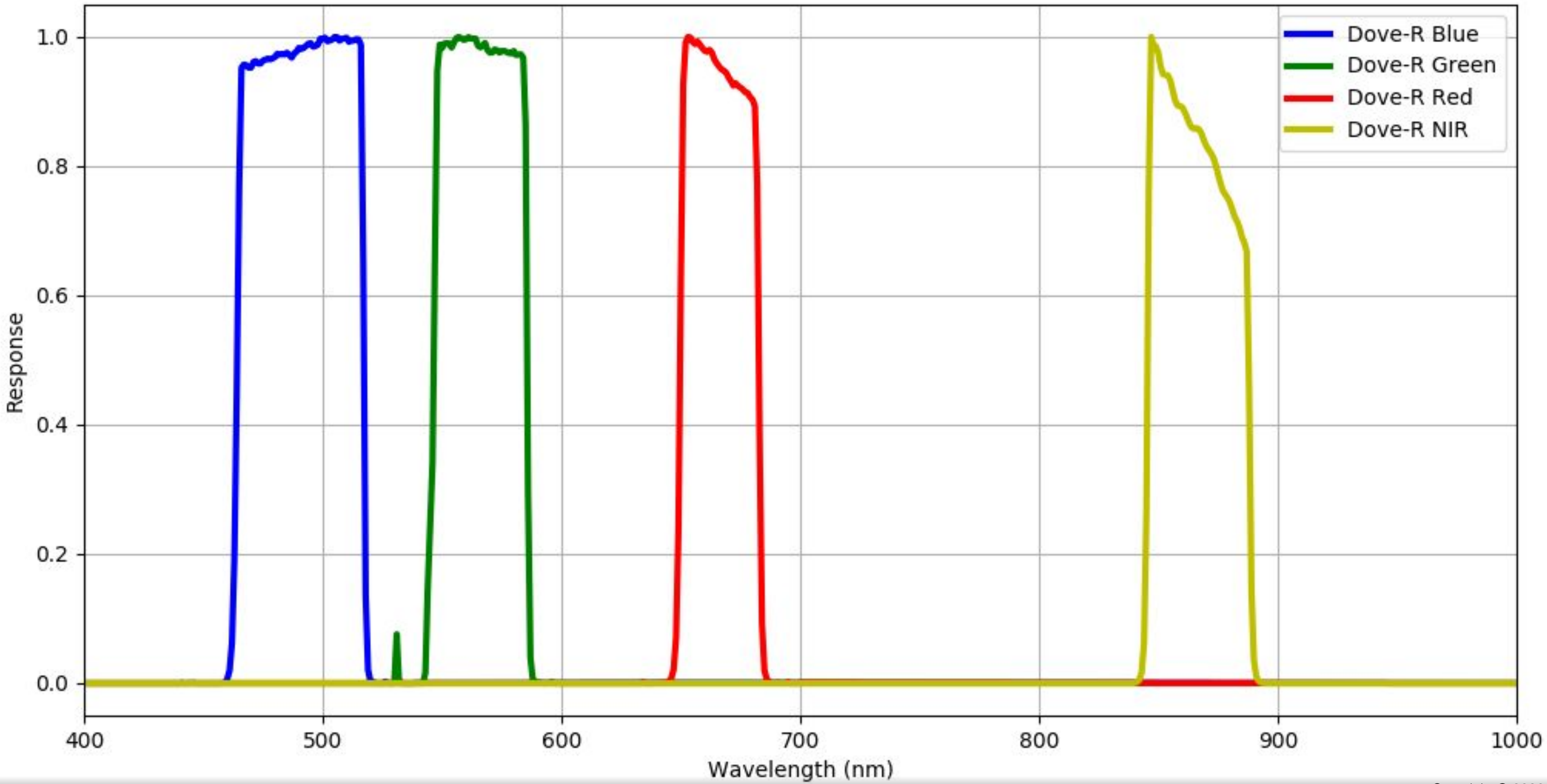


Structure from Motion pipeline

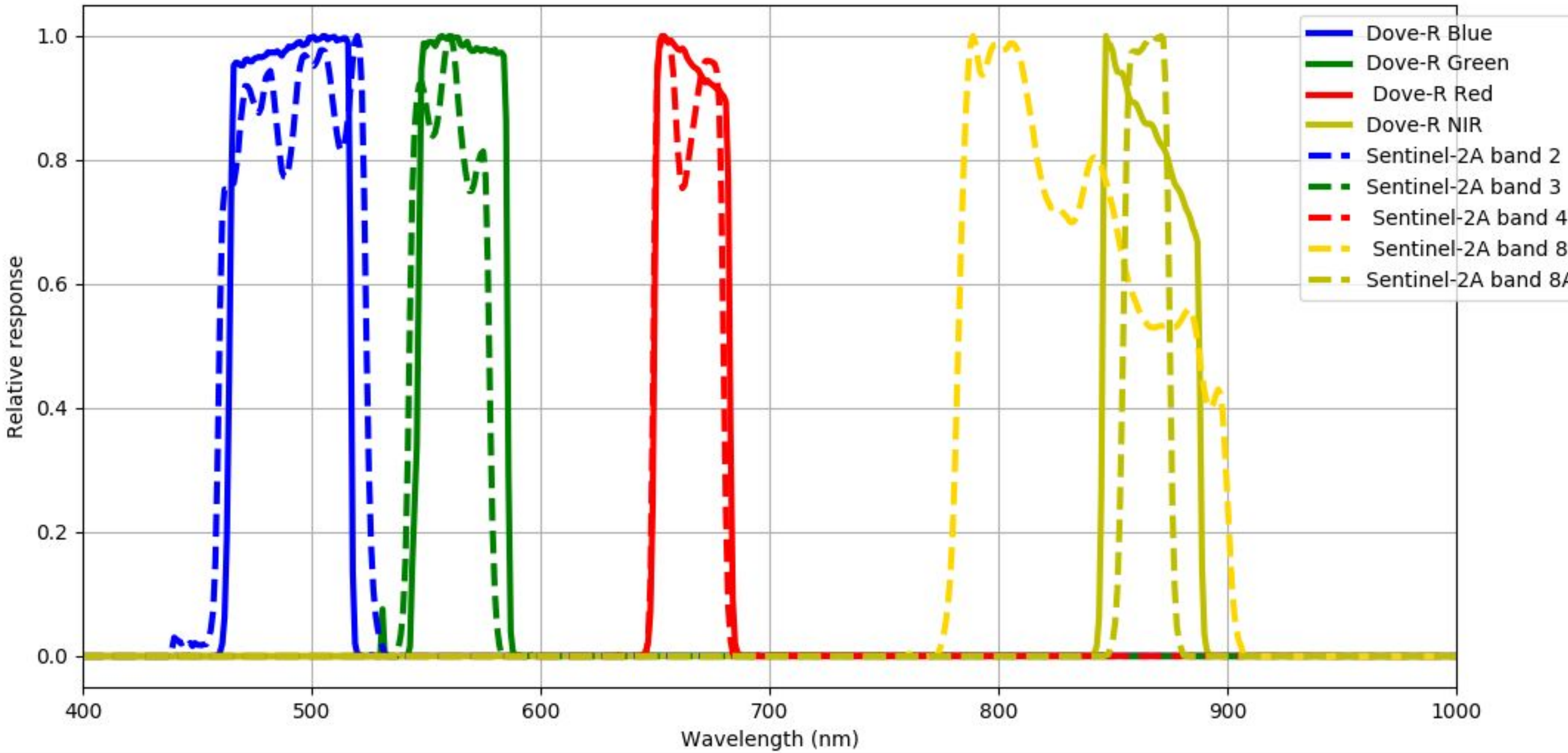


- This is the layout of a Dove-R
  - The four bands are arranged vertically across the sensor
  - Multiple images are taken in rapid succession so that the same point on the Earth is imaged by all the filters as the satellite orbits
  - Subsequent frames are composited together in a structure from motion pipeline to create a four band composite image

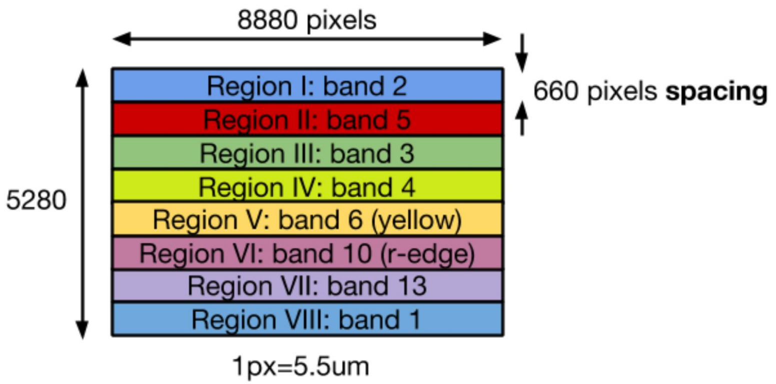
Typical Dove-R RSR (from manufacturer data)



RSR compared to Sentinel-2A



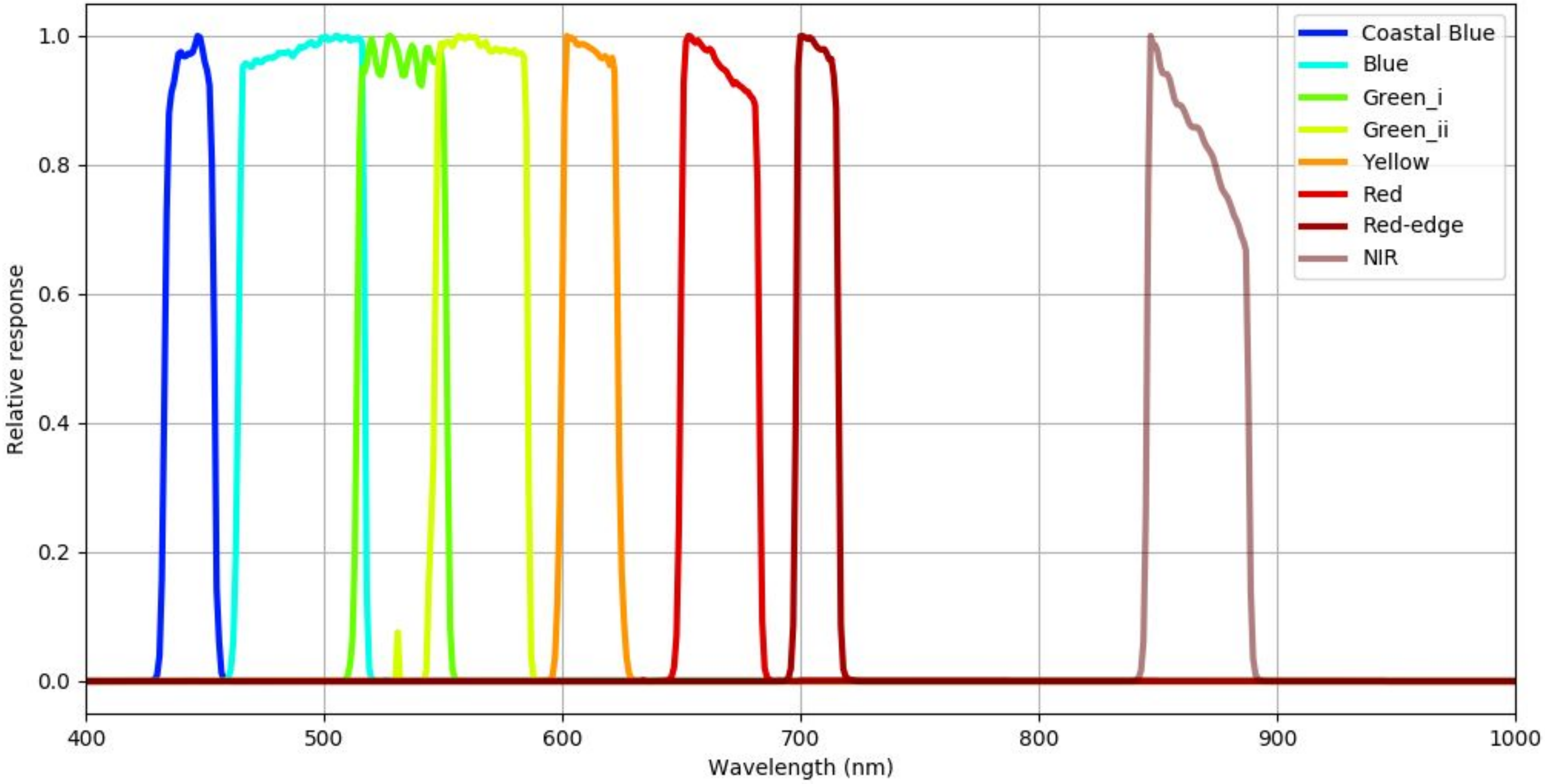
SuperDove 8-band sensor layout



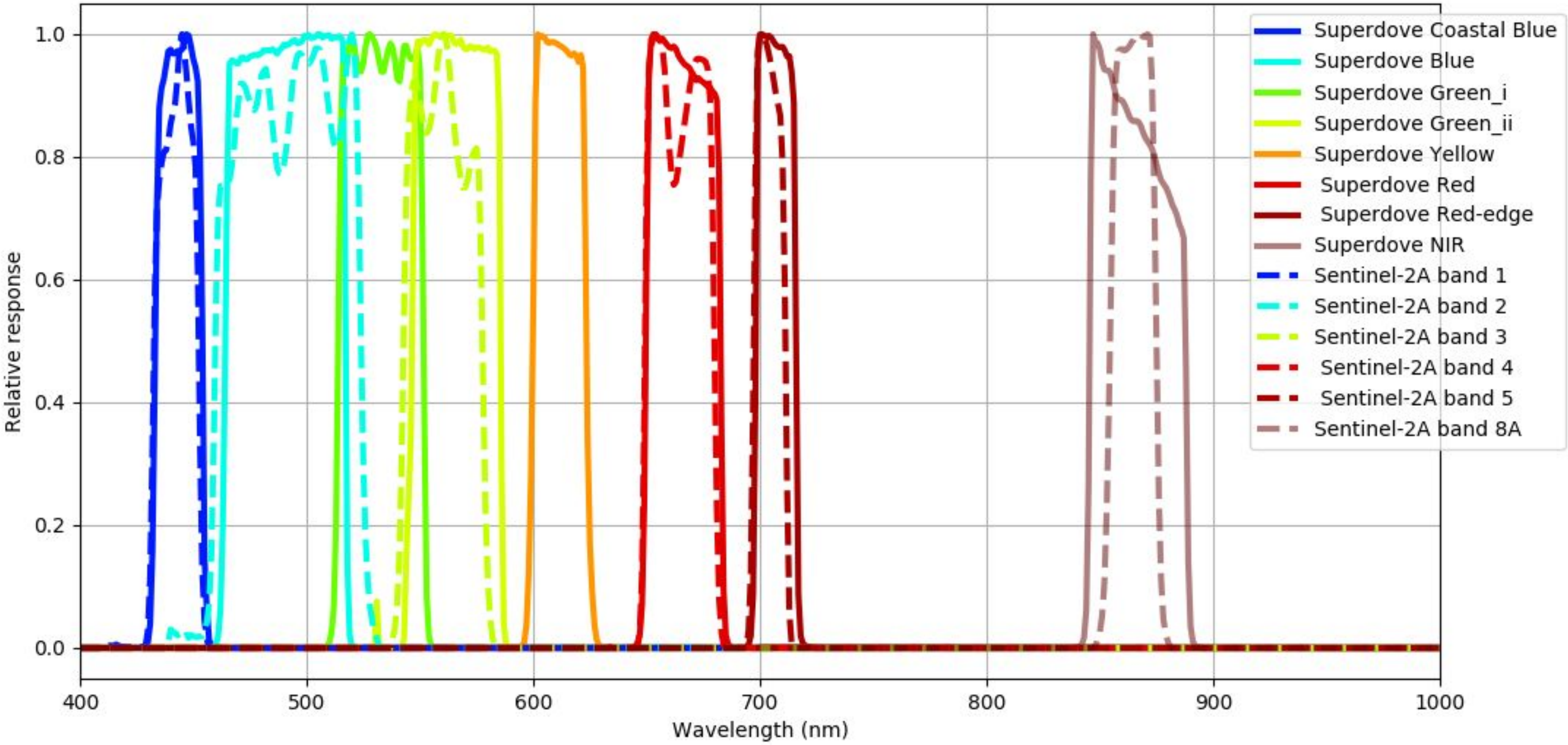
Band	Name	Notes	Wavelength (fwhm)	spatial sampling	GSD (m)	L_{ref} (W $sr^{-1}um^{-1}m^{-2}$)	SNR @ L_{ref} (t=10ms)*
1	Coastal Blue	core visible bands	443 (20)	**0.25x**	**12**	130	193
2	Blue		490 (50)	**1x**	**3**	130	170
3	Green I		531 (36)	**1x**	**3**	130	150
4	Green II		565 (36)	**1x**	**3**	130	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)	**1x**	**6**	70	57
13	NIR	narrow NIR	865 (40)	**0.5x**	**6**	130	137

Patent Pending (US20180098014A1)

Superdove RSR (from manufacturer data)



RSR comparison with Sentinel-2

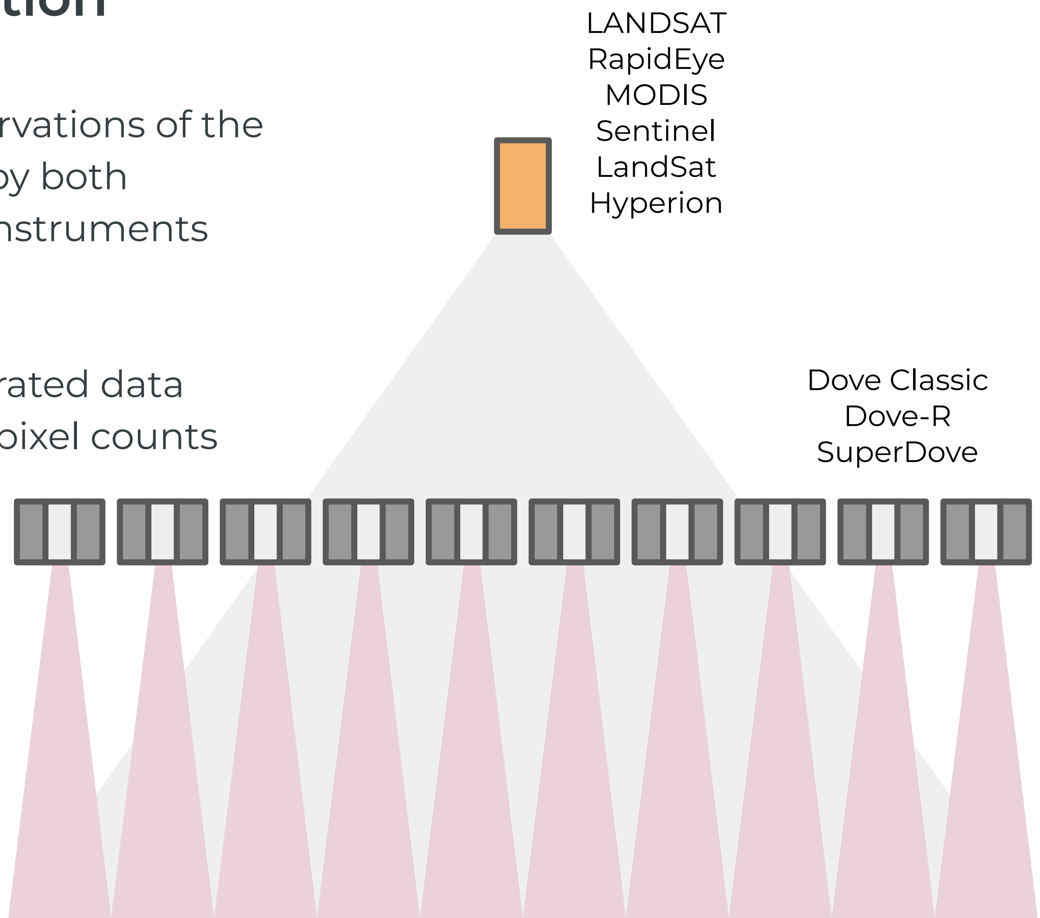


Radiometric Calibration

- Near-simultaneous observations of the same groundsite made by both PlanetScope and other instruments are collected

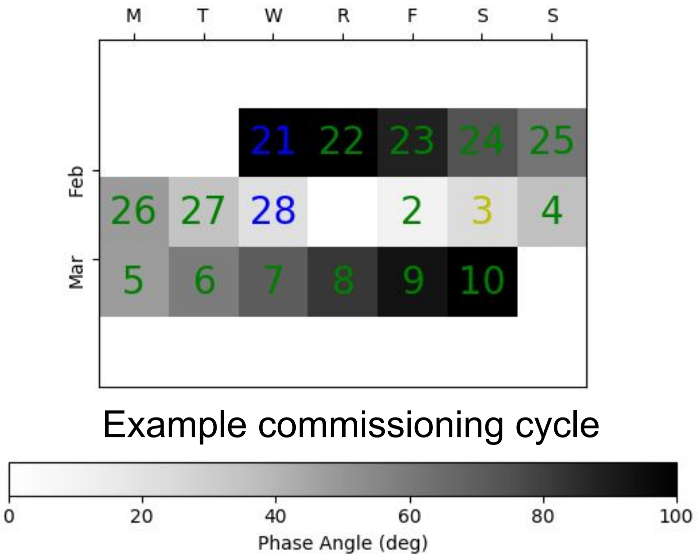
- Crossovers used to generated data products that make our pixel counts more in alignment with absolute truth

- Absolute references could take the place of relative calibration



Moon Monitoring
for Radiometric Calibration

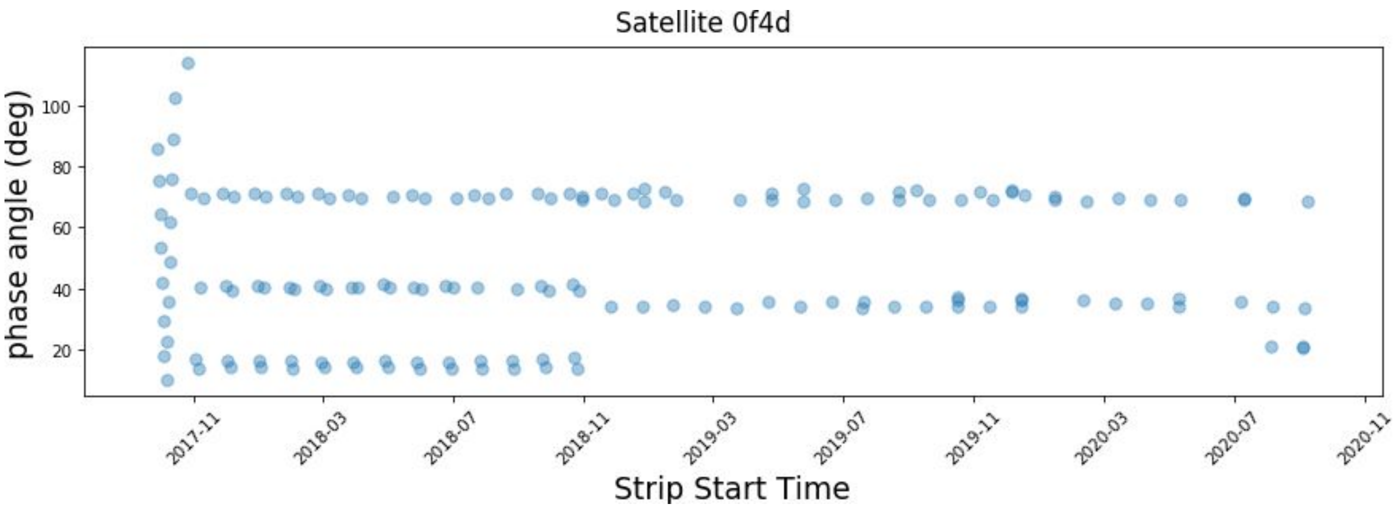
- Doves are maneuvered to point towards the moon through the range of the lunar cycle
- Allows for studies of different response ranges
- Full cycle of moon shots during the first full available lunar cycle after commissioning
  - Confirm normative operation
- Subsequent maneuvers executed at low, medium and high moon phases for the life of the satellite
  - Exposure to a ‘constant’ illumination source with no atmosphere useful for validation and calibration



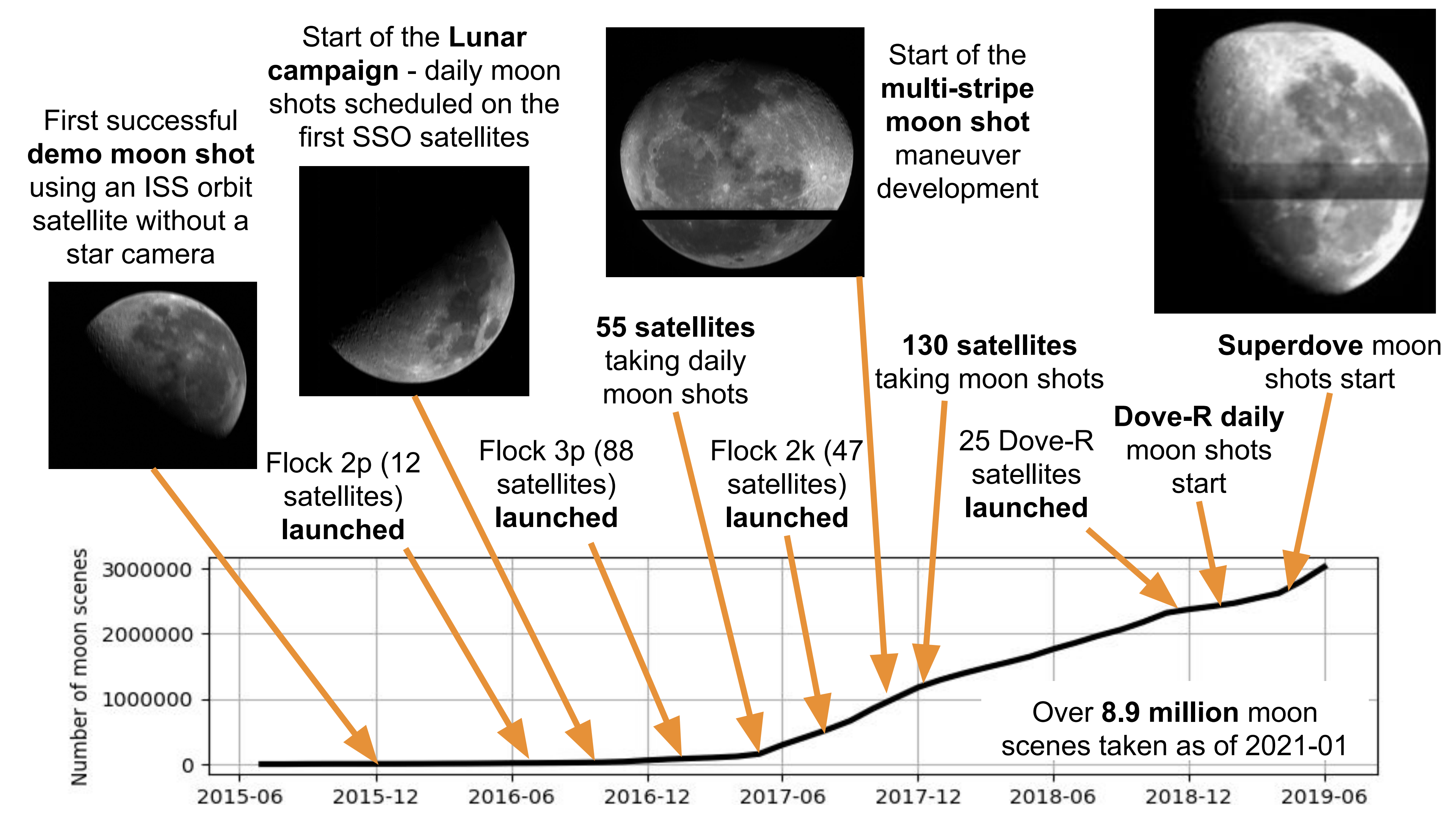
Example commissioning cycle

Moon Monitoring

Consistent Phase Angle Coverage



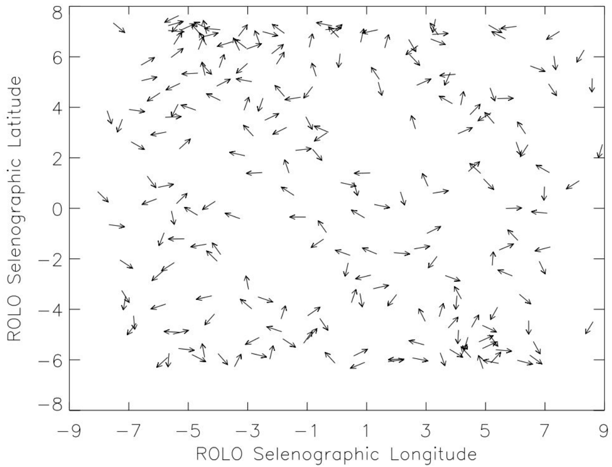
- Lunar maneuvers scheduled by Mission Control successfully captured as strips
- Initial commissioning phase, followed by ongoing monthly observations

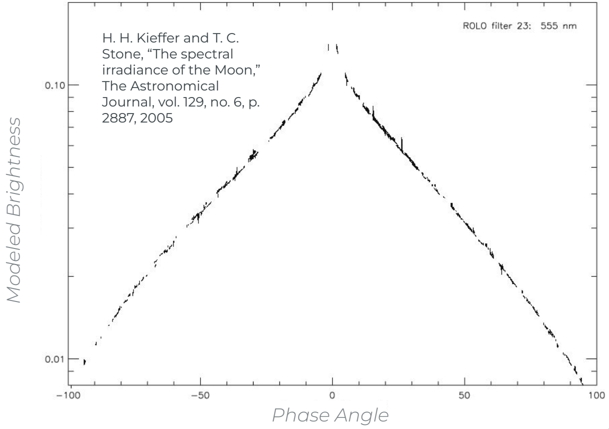


First successful **demo moon shot** using an ISS orbit satellite without a star camera
Start of the **Lunar campaign** - daily moon shots scheduled on the first SSO satellites
Start of the **multi-stripe moon shot** maneuver development
55 satellites taking daily moon shots
130 satellites taking moon shots
Superdove moon shots start
Flock 2p (12 satellites) **launched**
Flock 3p (88 satellites) **launched**
Flock 2k (47 satellites) **launched**
25 Dove-R satellites **launched**
Dove-R daily moon shots start
Over **8.9 million** moon scenes taken as of 2021-01
Number of moon scenes
3000000
2000000
1000000
0
2015-06
2015-12
2016-06
2016-12
2017-06
2017-12
2018-06
2018-12
2019-06

ROLO Model Brightness
for Moon Phases

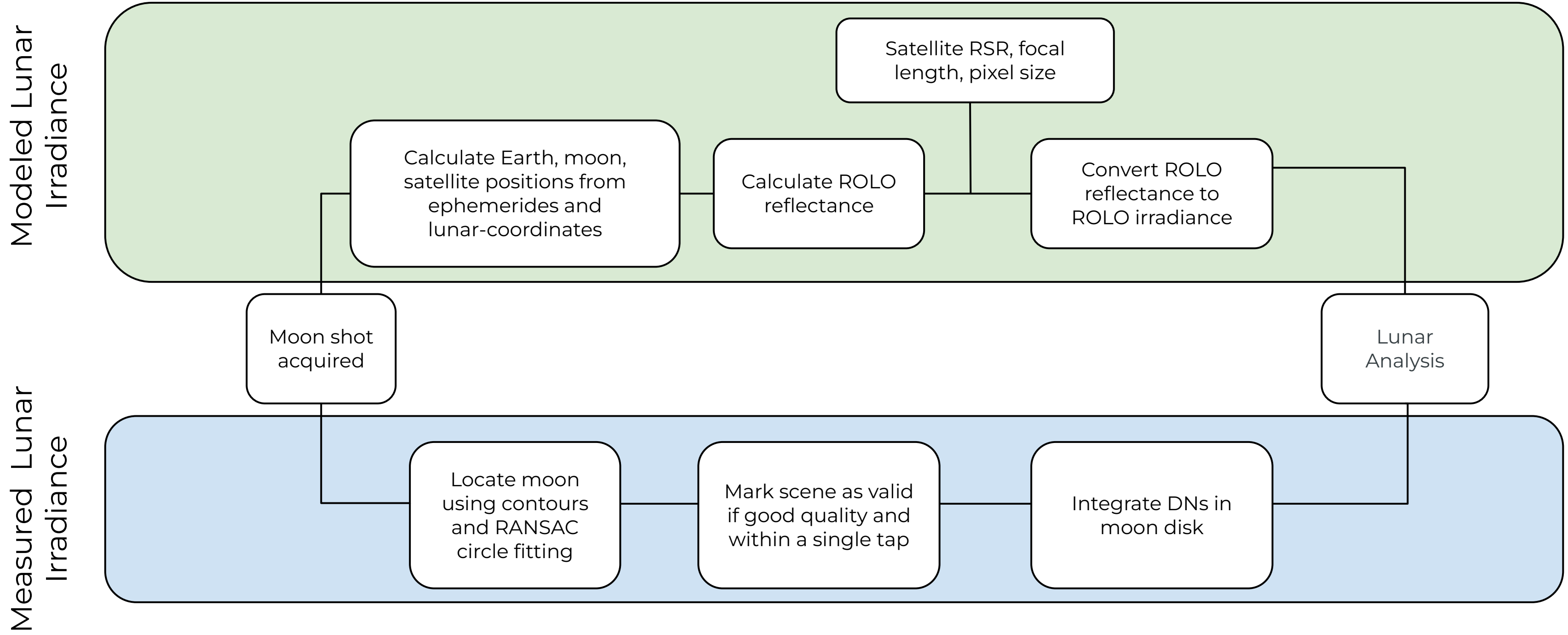
- Over 1000 images, each in 32 wavelengths, taken at a variety of selenographic longitude, latitude and phase angles
- ROLO model produces the moon's **full disc** brightness
  - 328 coefficients and position of the Earth, moon, and satellite yields a reflectance
  - Solar spectrum and satellite RSR yields a radiance
- Model is absolutely accurate to within ~10%, but relatively accurate to within sub-percent





H. H. Kieffer and T. C. Stone, "The spectral irradiance of the Moon," The Astronomical Journal, vol. 129, no. 6, p. 2887, 2005

Lunar Pipeline
for Dove Classic



Dove Classic

Moon shot maneuver

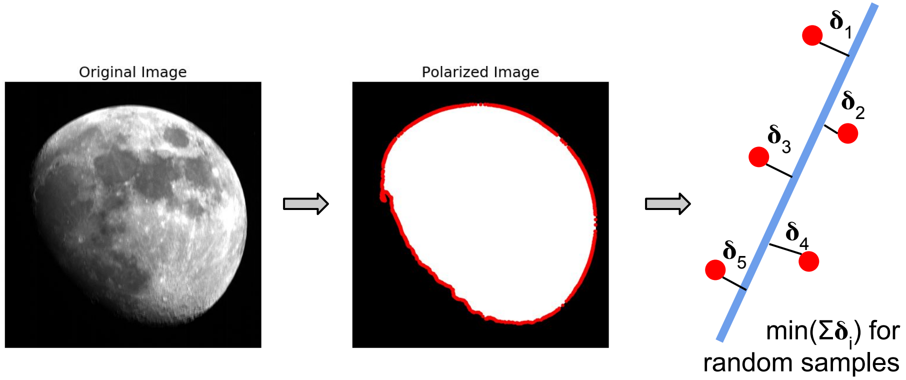
- Maneuver designed to cover the four taps of Dove Classic

- Computer vision tracks the location of the moon disc to:
  - Mark scenes as within a single tap
  - Provide template for measuring the moon's irradiance

- Takes ~5 minutes when satellites is in eclipse

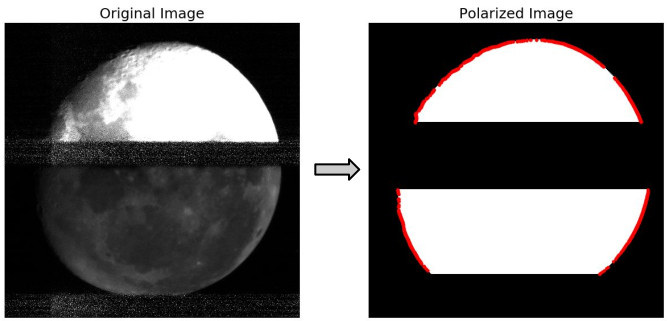
Dove Classic
Moon detection

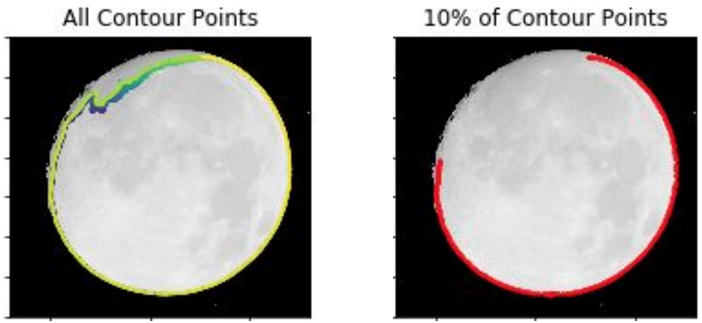
1. Polarizing images
2. Drawing contours around contiguous regions
3. Fitting circles through contour edge points with RANSAC algorithm



Polarize each filter separately to increase inlier contour points for RANSAC selection

Filter contour points to remove extraneous outliers from Moon's terminator region

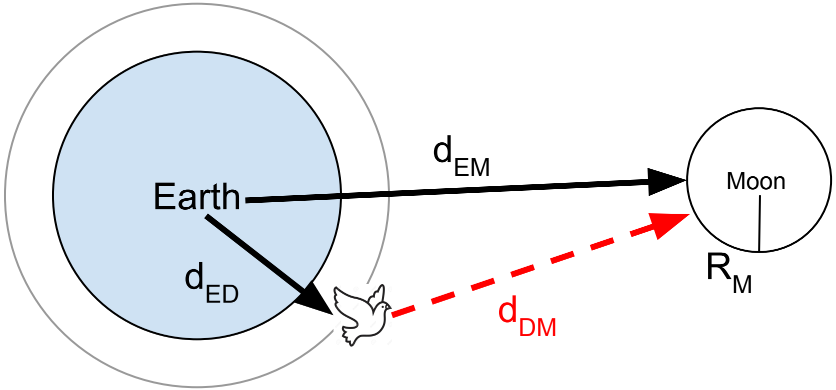


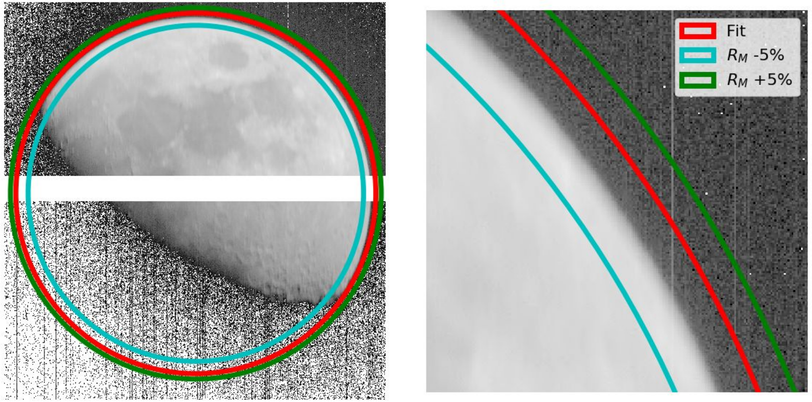


Dove Classic

Implementing Physical Limitations

- Position of the satellite, Earth and Moon can be used to calculate the angular size of the Moon
- Combined with the pixel scale of the camera gives a pixel size of the moon





Moon detections are tested against Moon’s true radius within 5% range to account for uncertainty in the pixel scale.

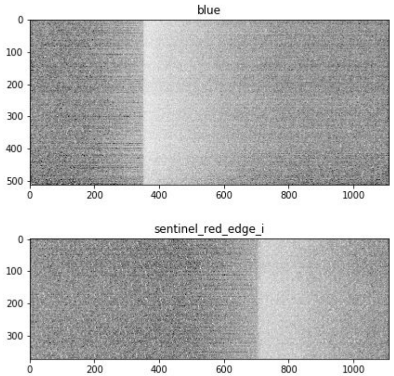
Dove Classic

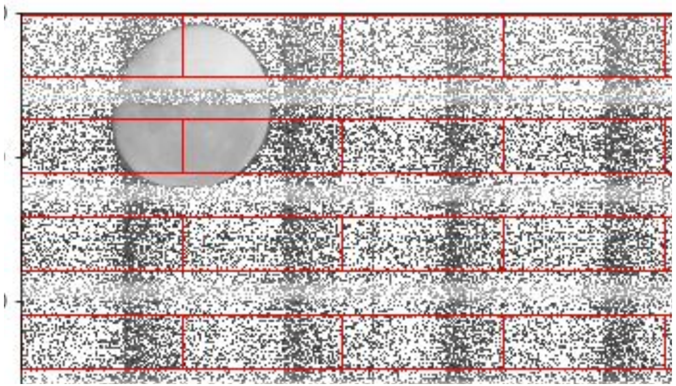
“Per-scene” Dark Frame Subtraction

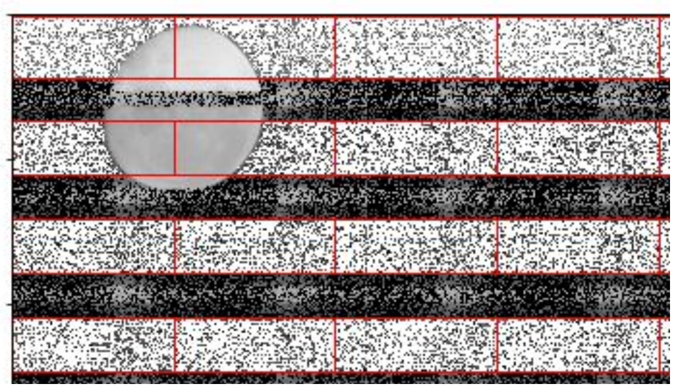
- Images taken in eclipse are at temperatures far below lab conditions
- Dark frames extrapolated from lab models contain residual noise
- “Dark taps” generated for each filter by taking median of all taps down-sampled with an averaging kernel

“Dark tap” subtraction from lunar scenes increases signal-to-noise of lunar measurement by several percent

“dark tap” model for each filter

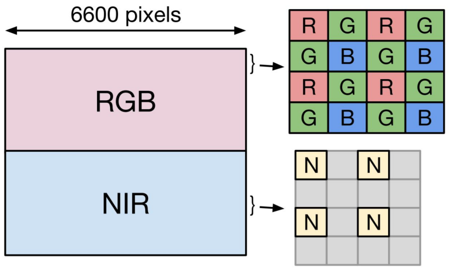


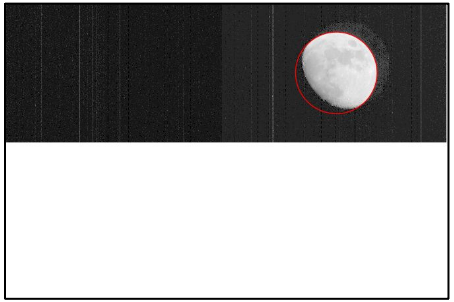




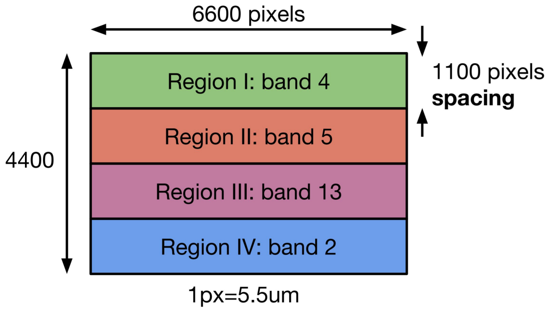
Multi-Stripe Doves

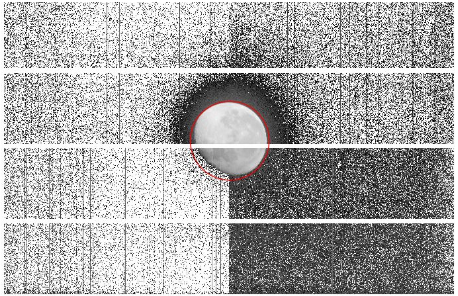
Dove Classic



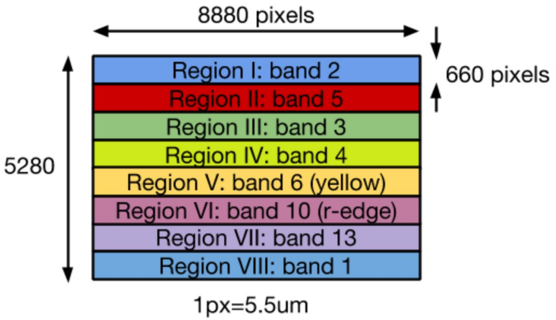


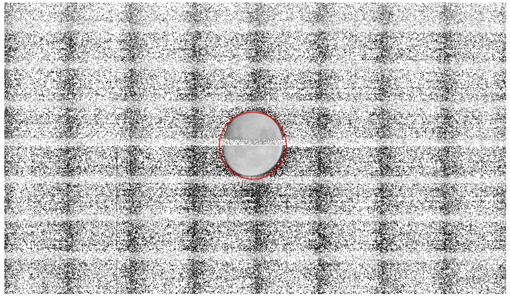
Dove-R





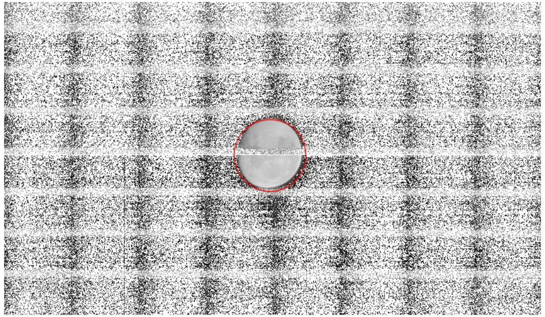
SuperDove





Multi-Stripe Moon Measurements

Requires Registration



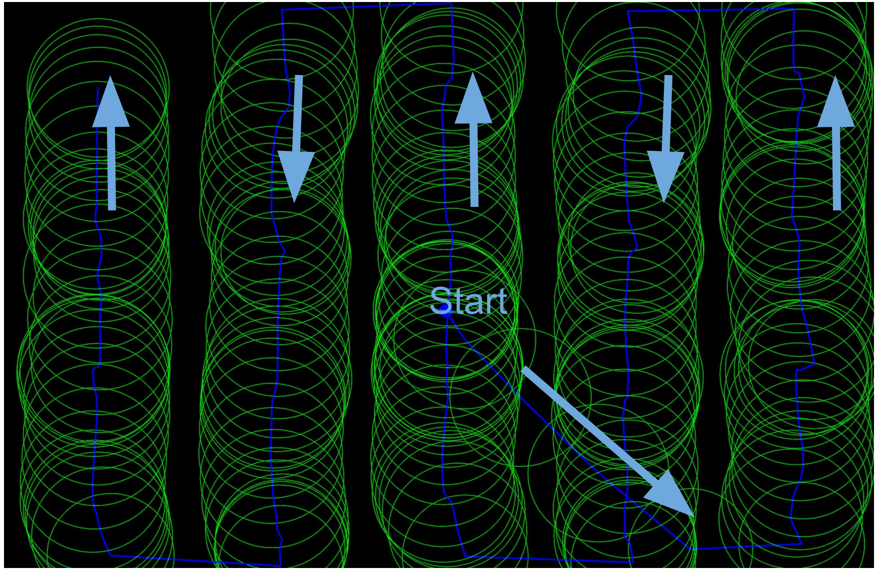
- ROLO model only calculates unresolved irradiance of entire moon disc
- SuperDove filter heights are not large enough to contain the entire moon disc
  - Multiple scenes must be registered together to create a single moon disc

Two main problems to solve to construct Moon discs

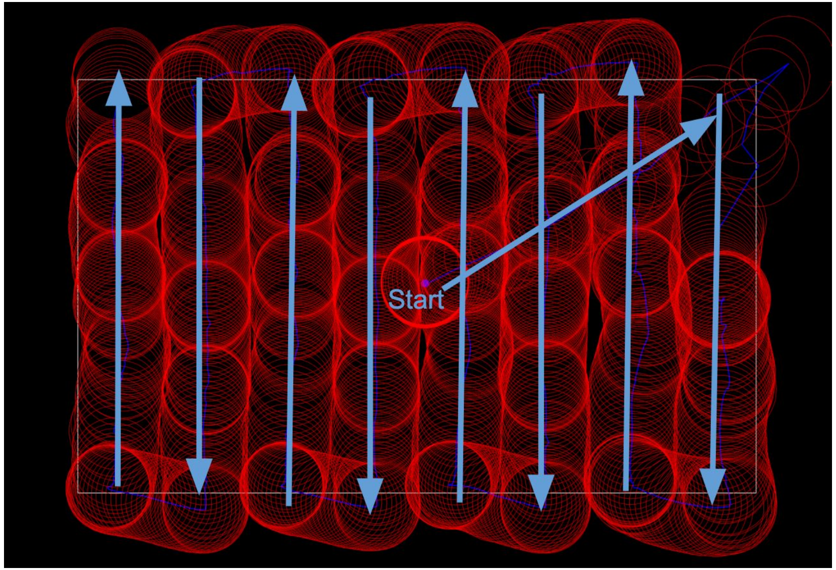
1. Which scenes to include to construct each filtered observation of the moon?	2. What algorithm to use to register multiple lunar scenes together?

Multi-Stripe Moon Maneuver

Dove-R (~500 scenes)



SuperDove (~1400 scenes)

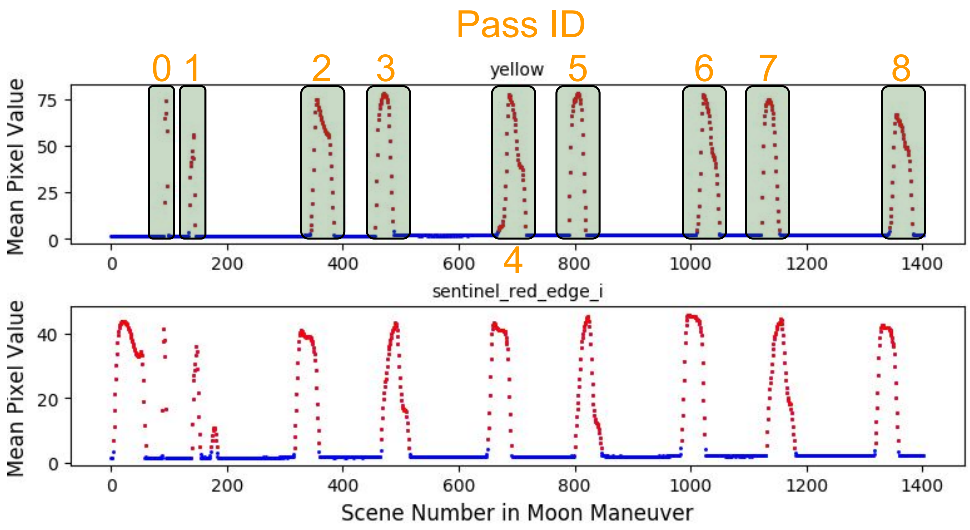


Scene selection requires knowing which scenes have the moon on which filters, ideally without loading every scene

Multi-Stripe Moon Registration

Scene Selection

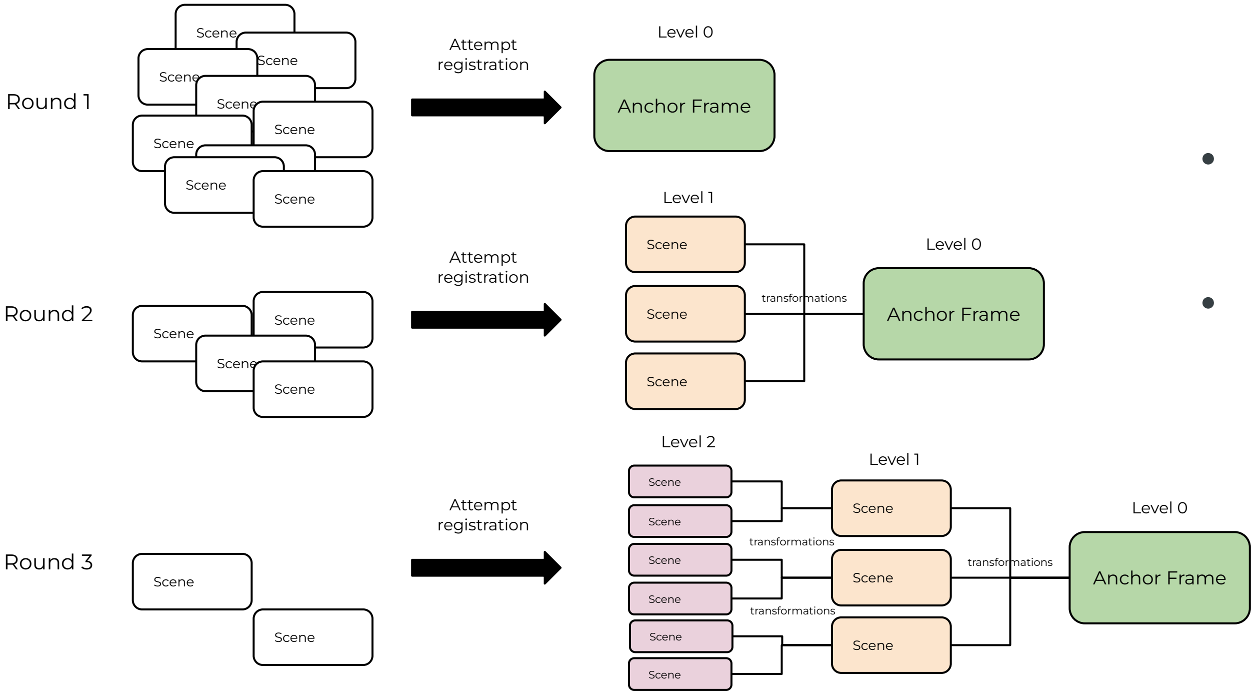
- Metadata *stats_by_filters* contains statistics for each scene broken out by filter
- Iterative asymmetric sigma clipping for each scene mean pixel value (on each filter) can separate out scenes which contain the moon
- Separates moon maneuver into ‘passes’ for scene registration and combination



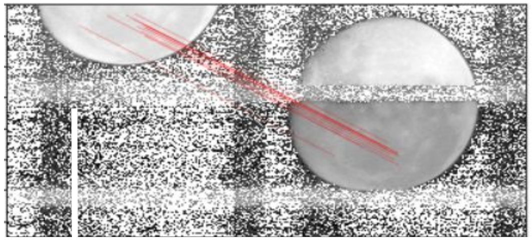
Scene selection using metadata is more computationally and memory efficient, naturally defines “passes” for scene registration.

Multi-Stripe Moon Registration

Via Recursive Nested Sampling



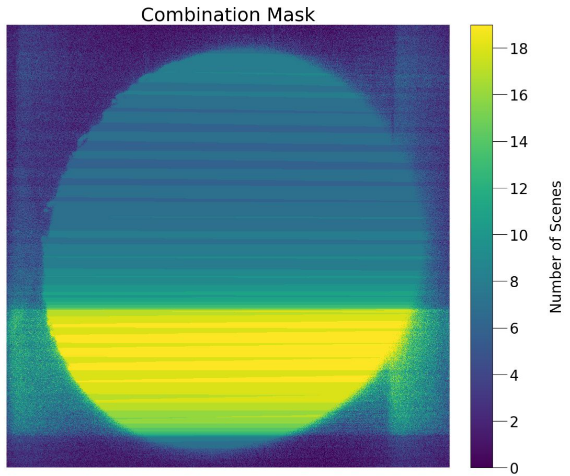
- Registration features identified on all images within moon ellipse mask
  - Each filter separately contour stretched
- An image with the most number of feature is named the Anchor Frame
- Recursive algorithm run to attempt to transform each image to the anchor

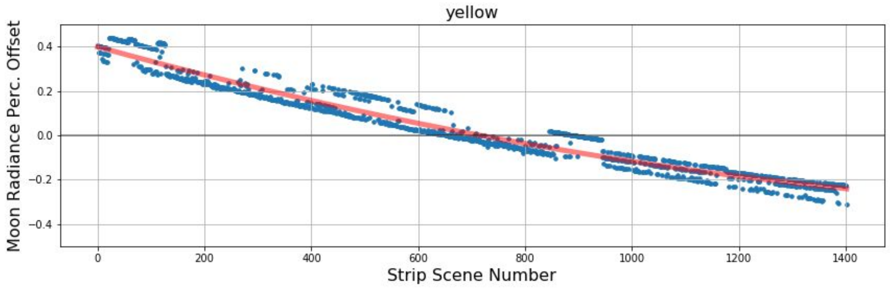


Multi-Stripe Moon Registration

Increasing SNR

- Combination masks constructed by counting the number of scenes that are added to each pixel
- Moon co-addition is divided by this combination mask, resulting in an average resolved moon disc
    - Increases signal-to-noise of measurement

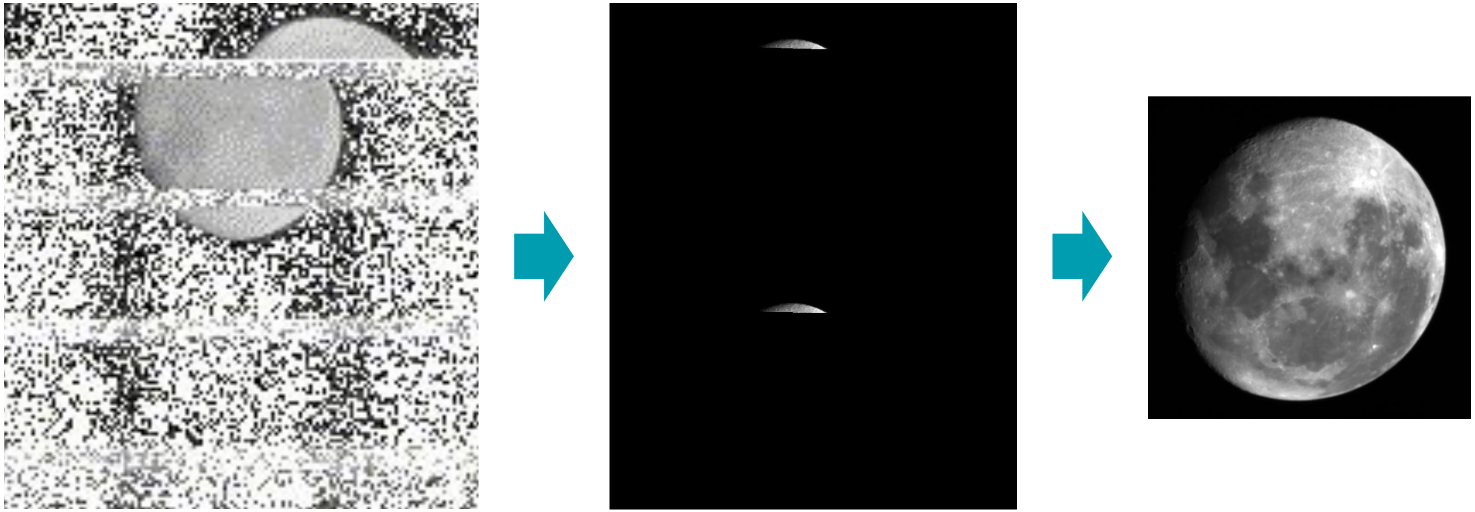




- Moon brightness from the ROLO model for each scene in the filter-pass provides a scaling factor
- Each scene must be multiplied by this scaling factor before combination

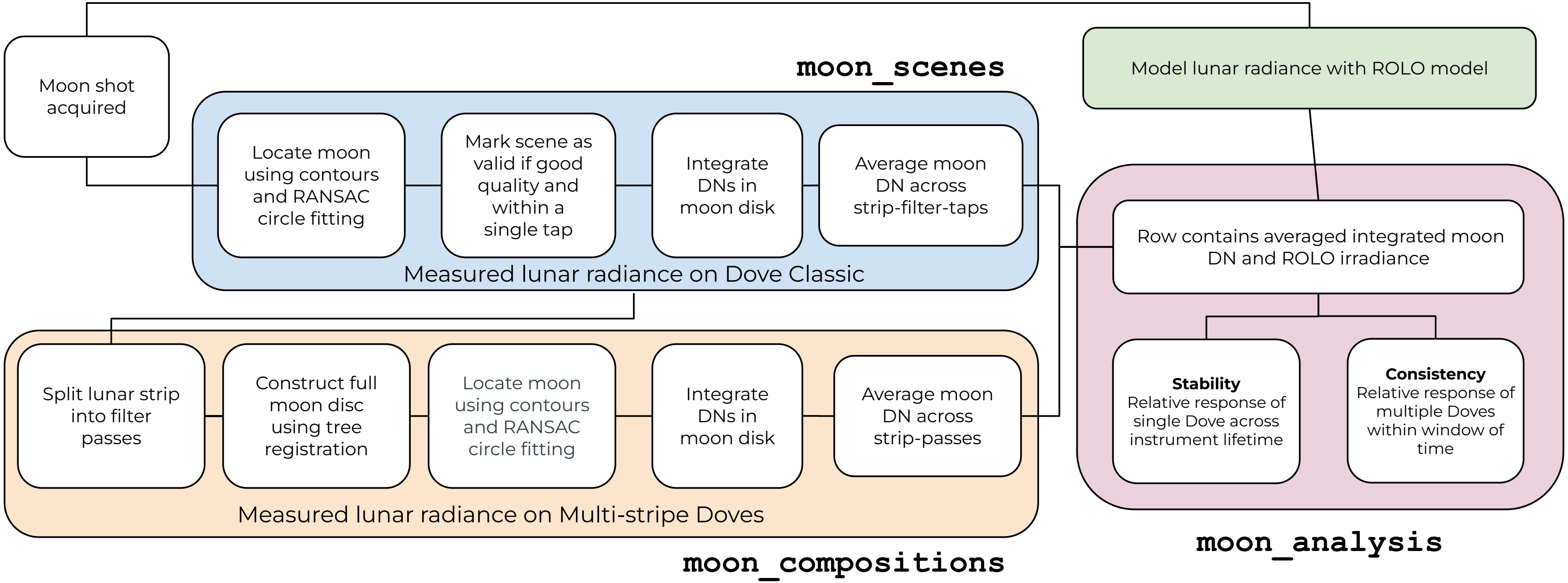
Multi-Stripe Moon Registration

Lunar images in single filter-pass
registered and combined to produce moon disc for comparison with ROLO model



Lunar Pipeline

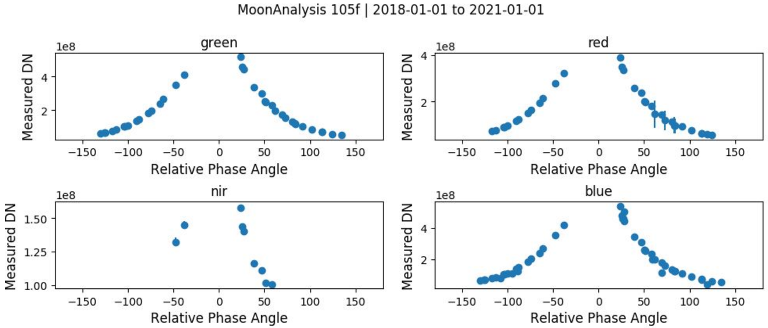
for Dove Classic and Multi-Stripe Doves



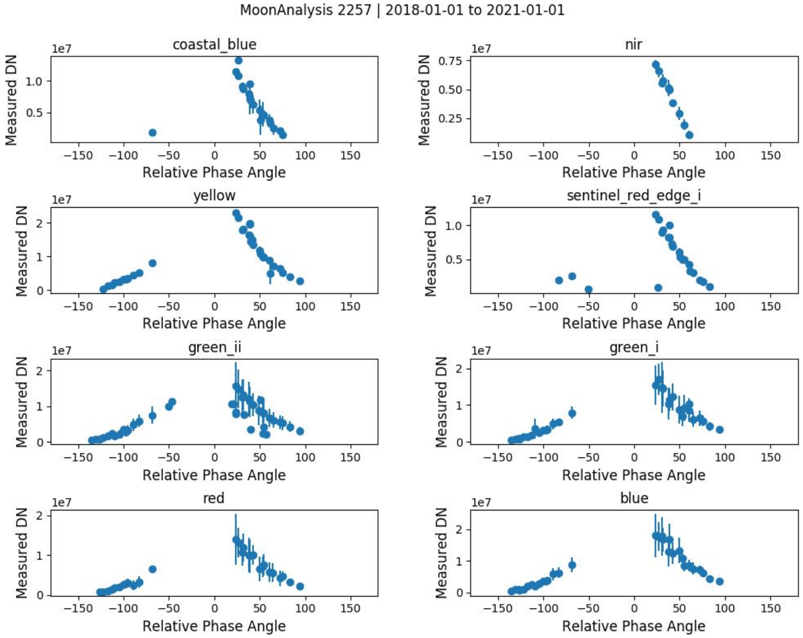
Measured Lunar DN

Correlates with Phase Angle

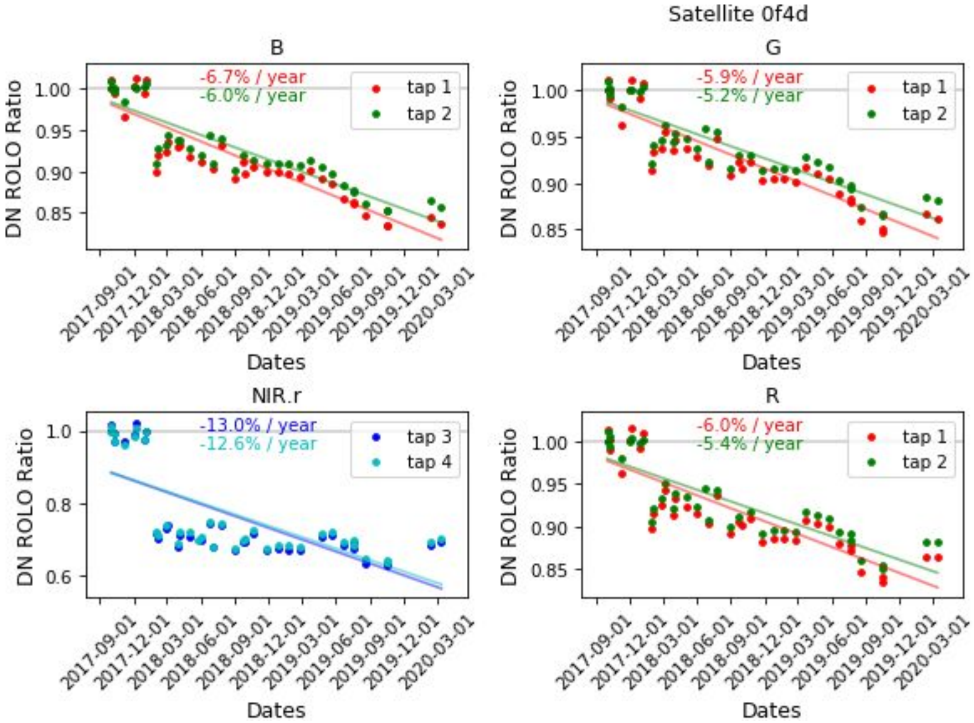
Dove-R



SuperDove

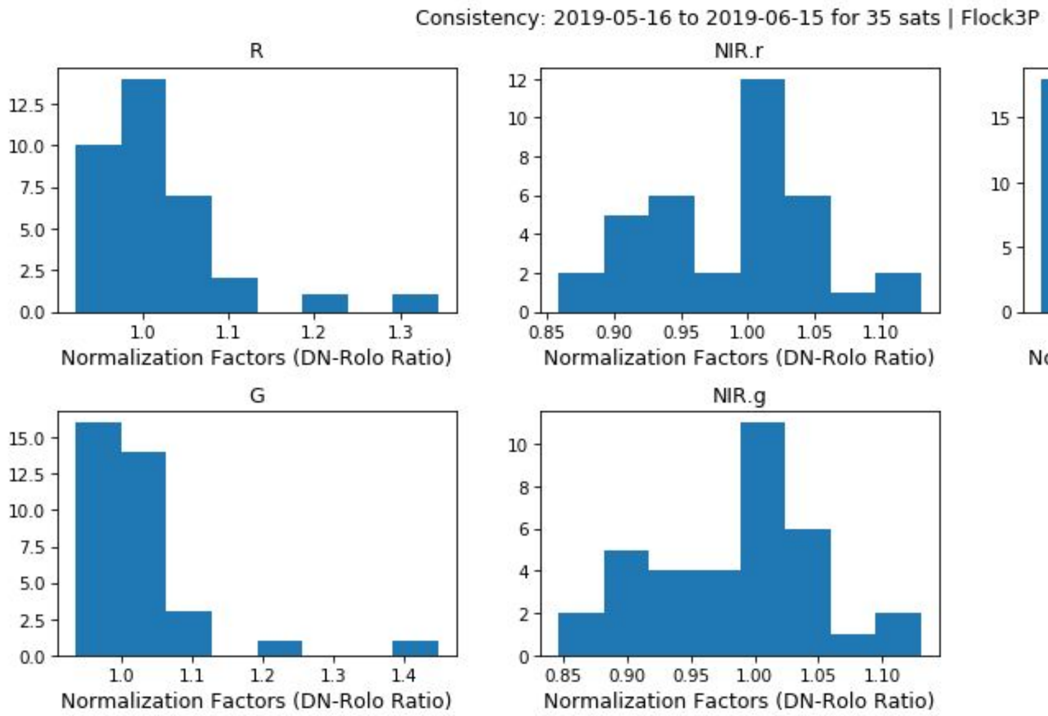


Instrument Stability



- Ratio of DN to ROLO radiance
  - normalized by median of first three observations
- No significant differences between tap performance seen for nearly every Dove Classic
- Decay rates in the range of 5-15% decline in throughput per year

Flock Consistency



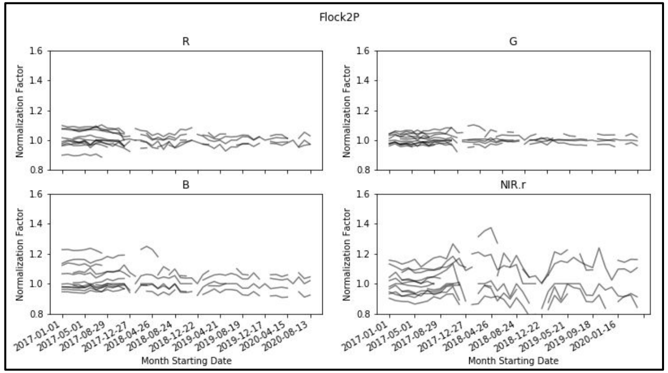
- Relative response of a set of satellites within a window of time
- Normalization factor:

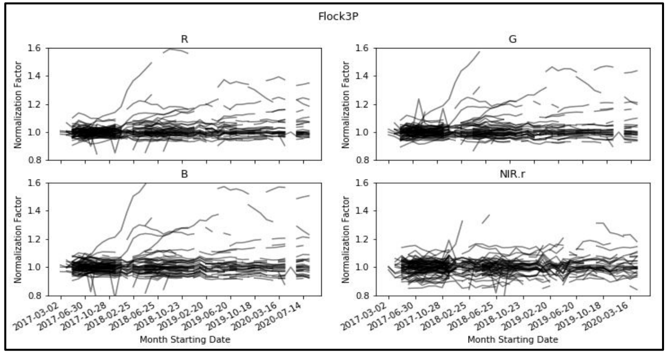
$$\eta_i = \left(\frac{(F_{DN,i}/F_{ROLO,i})}{med(F_{DN}/F_{ROLO})} \right)^{-1}$$

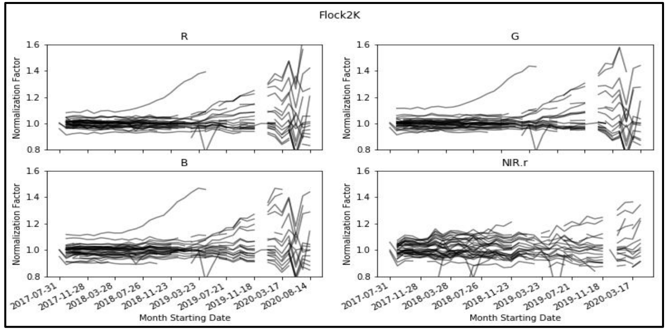
- Now used in the Dove Classic calibration pipeline to reduce scatter

Flock Consistency
Over Time

- Normalization factor is the relative response of a set of satellites within a window of time
- Consistency for each satellite remains fairly stable across time, as seen by the “smooth flow” of lines
- Flock 2P: Variance in consistency remains fairly stable
- Flock 3P: Variance in consistency remains fairly stable
- Flock 2K: Variance in consistency remains fairly stable for the first ~2 years, then rapidly spreads out

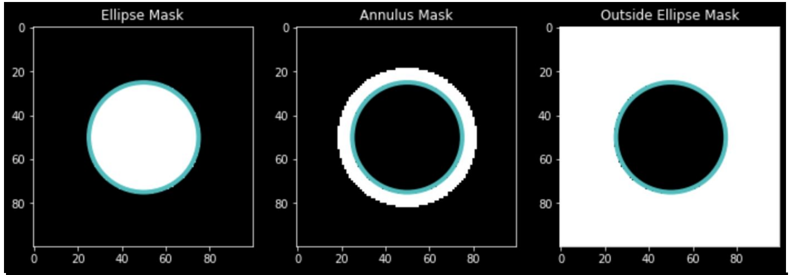


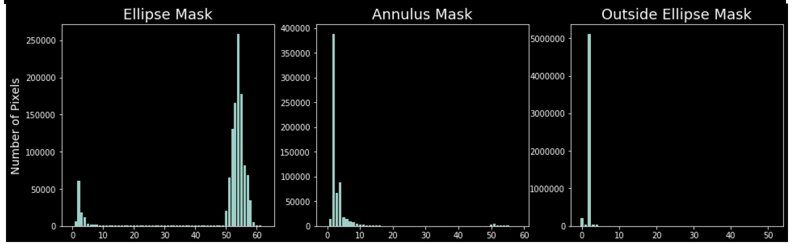


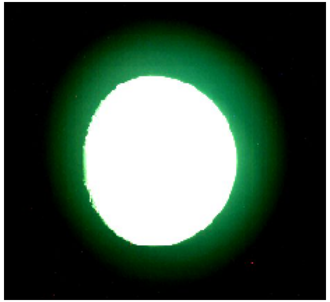


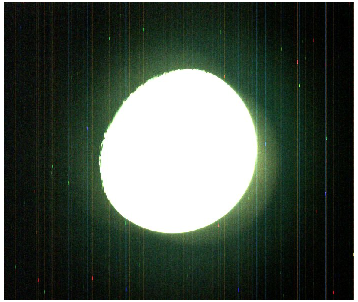
Identifying Image Haze

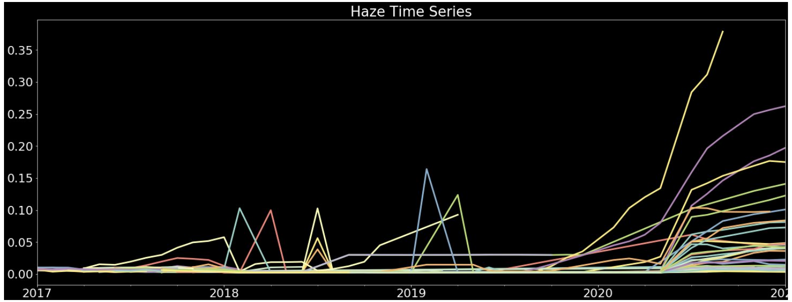
- Aging satellites can begin to suffer from haze due to deteriorating electronics
- Calculating the average brightness in the annulus surrounding the moon can alert operators to satellites that need to be inspected and/or decommissioned





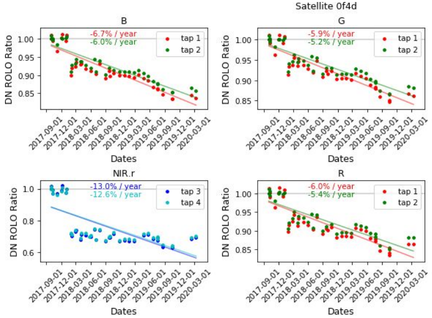


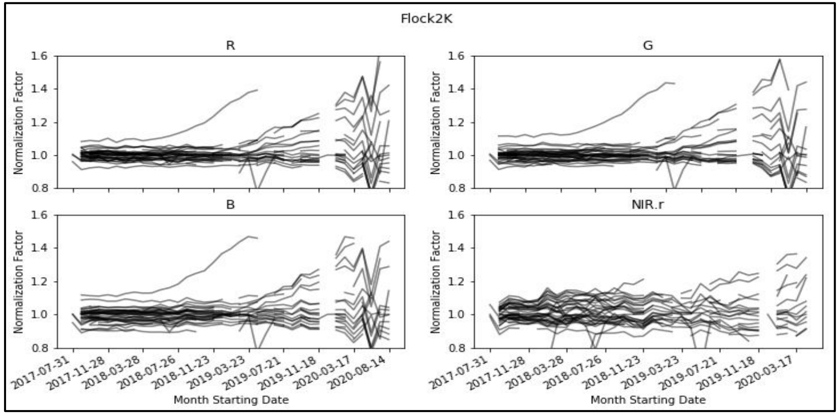


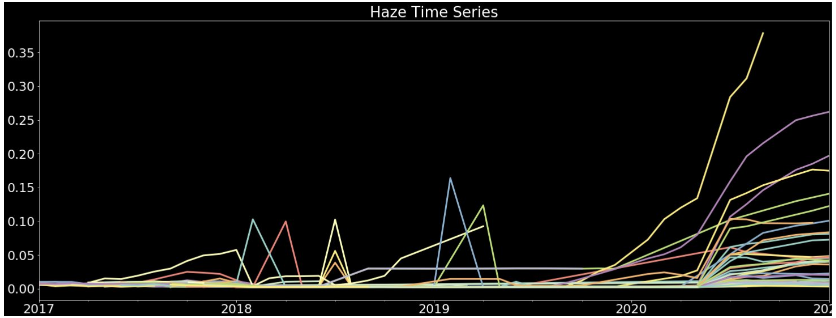


In Summary

- Lunar database provides valuable insight into the health of our growing heterogeneous fleet
- More insights to come!







For more information, you may find us here:

Official Website

@planet-labs

Great Barrier Reef, Australia – July 8, 2016