Focus characterization of SuperDoves: On-ground and on-orbit first light

Juan Fernandez-Saldivar, Caroline Pritchett, Kenji Ozawa, Ignacio Zuleta

South Passage, Australia – October 1, 2015

CALCON 2020

calcon
www.calcon.sdl.usu.edu

First Light Results

https://www.planet.com/pulse/flock-4v-captivating-first-light-imagery/

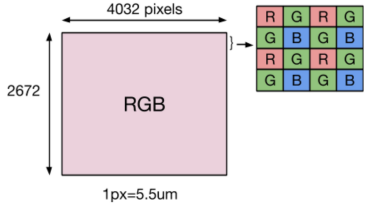
Planet SuperDove first light image of the Amu Darya River, Turkmenistan (left) Uzbekistan (right) © 2020, Planet Labs Inc. All Rights Reserved

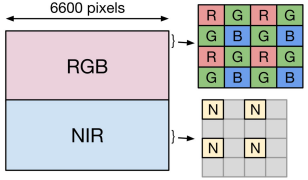
Overview

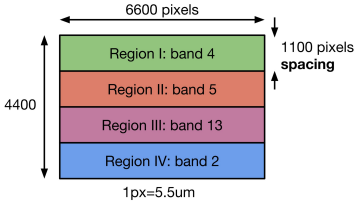
- SuperDove introduction
- How to maintain and improve image quality in a flock globally ?
  - Optical Testing: Characterization of telescopes and satellites
    - Metrics: What do we measure ?
      - Modulation Transfer Function and MTF50
      - Through focus MTF
    - Methods: How to test many SupeDoves ?
      - Collimator projecting Edge target object
      - Induce gradients in telescope to refocus
      - Testing at scale scopes and satellites
- First light
  - Initial assessment vs Ground Measurements
- Conclusions

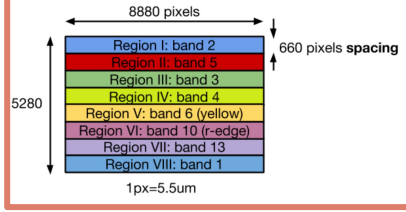
London Array Wind Farm, United Kingdom – April 17, 2016

Planet payloads over the years



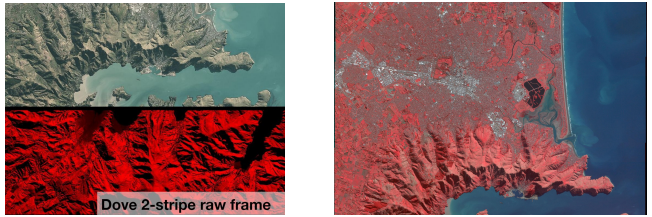




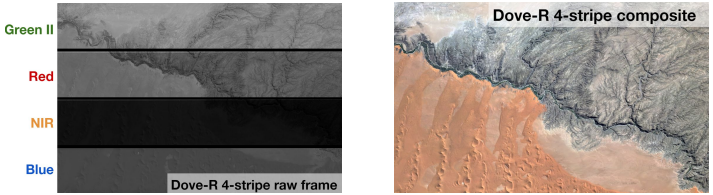


Dove Pilot (~50 satellites)

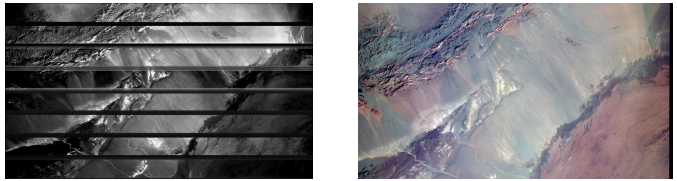
Dove (~150 satellites)



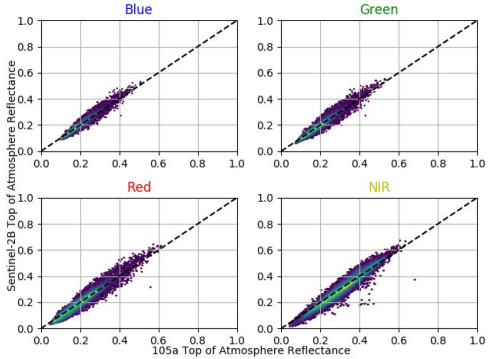
Dove-R (24 satellites)



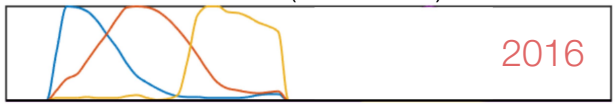
SuperDove (~64 satellites)



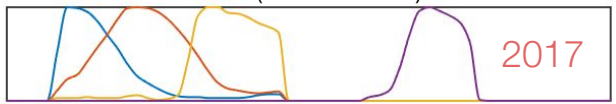
Dove-R versus Sentinel-2



Dove Pilot (~36 satellites)

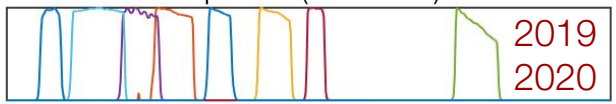


Dove (~150 satellites)



Dove-R (24 satellites)

SuperDove (36 satellites)

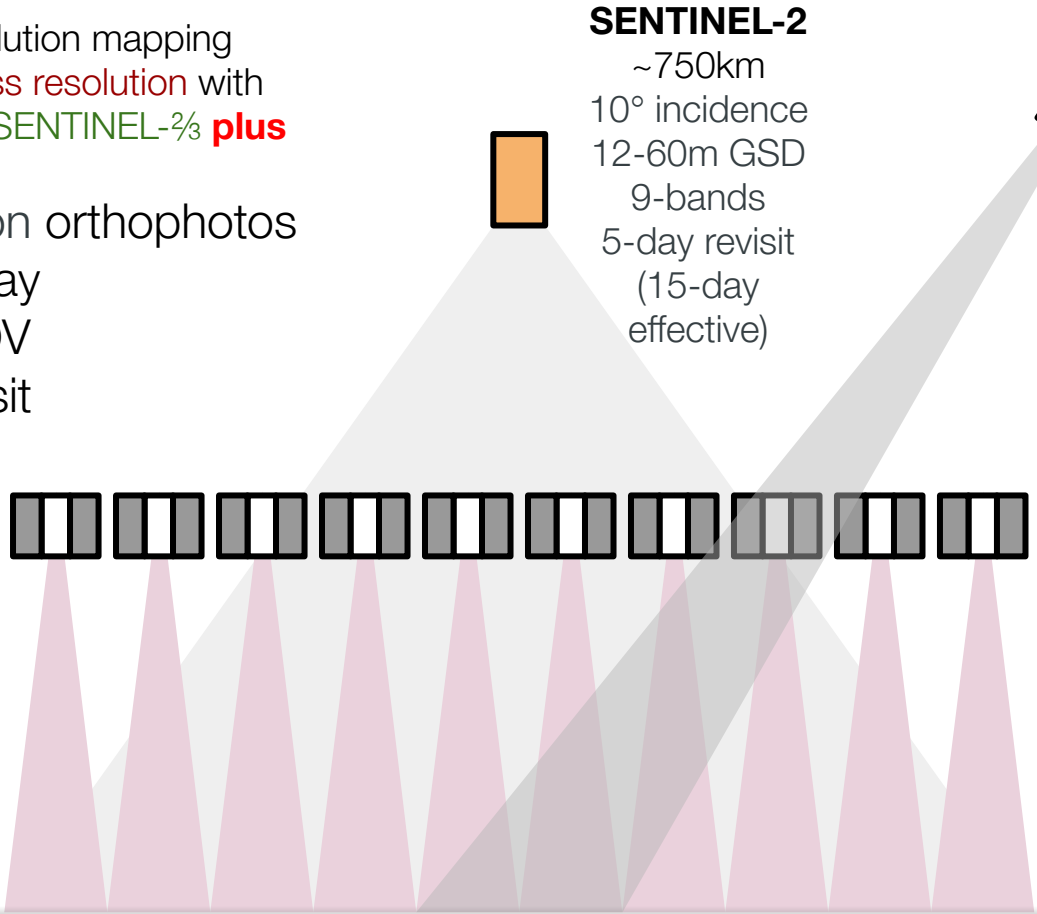


wavelength (nm)

Why SuperDoves?

SuperDove is a high resolution mapping mission with SPOT-5-class resolution with the spectral coverage of SENTINEL-2⁄3 **plus**

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

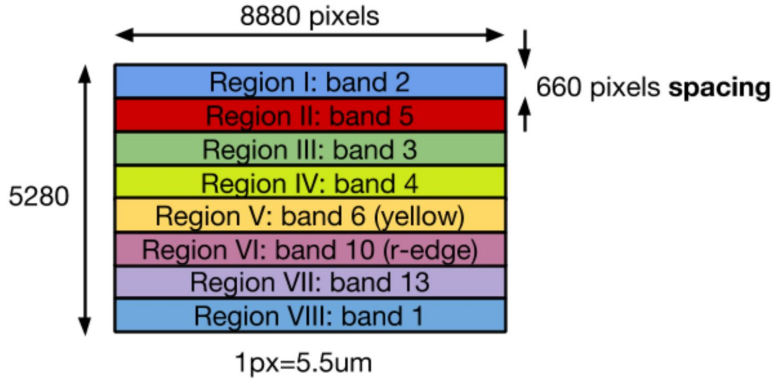


SENTINEL-2
~750km
10° incidence
12-60m GSD
9-bands
5-day revisit
(15-day effective)

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

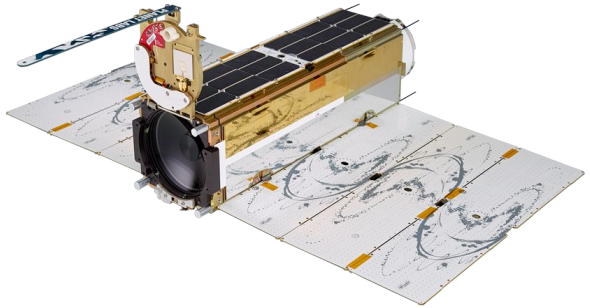
SuperDove	**Dove-R**
~500km	~500km
2° incidence	1.5° incidence
3-12m GSD	3m GSD
8-bands	4-bands
1-day revisit	1-day revisit

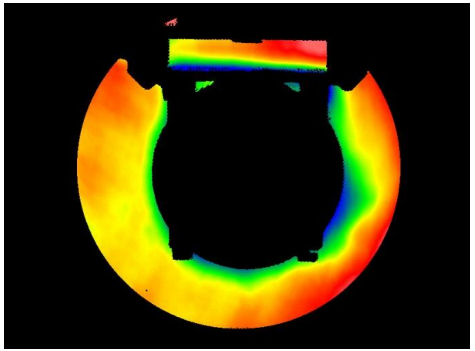
SuperDove sensor layout



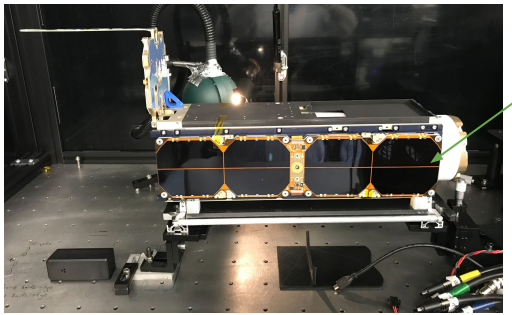
Band	Name	Notes	Wavelength (fwhm)	spatial sampling	GSD (m)	L_{ref} (W $sr^{-1}um^{-1}$ m^{-2})	SNR @ L_{ref} (t=10ms)*
1	Coastal Blue	core visible bands	443 (20)	**0.25x**	**12**	130	193
2	Blue		490 (50)	**1x**	**3**	130	170
3	Green I		531 (36)	**1x**	**3**	130	150
4	Green II		565 (36)	**1x**	**3**	130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

The SuperDoves: Optical Testing Introduction





SuperDove Optical Testing. Interferometry footprint for telescope testing



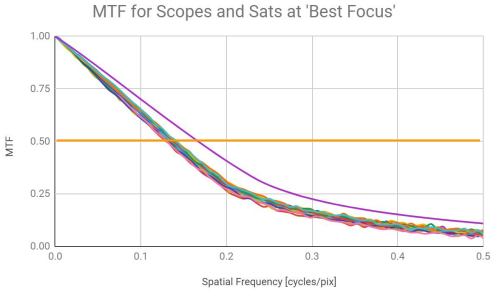
Superdove in Focus Testing. Positioning in collimator

Doves Optical Testing

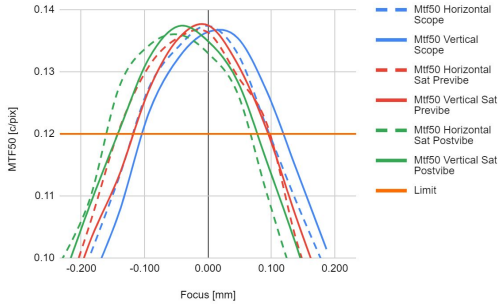
TEST	MTF50	FOCUS
Through Focus MTF	**> 0.12 c/pix**	**+/- 0.05 mm**

FIELD	SPECTRAL BANDS
Center	**Green-II**

Overview of Doves optical testing. A series of measurements to ensure the optical performance is maintained from ground to orbit.



MTF curves. For various scopes and sats, arrows indicate MTF50 and its corresponding frequency

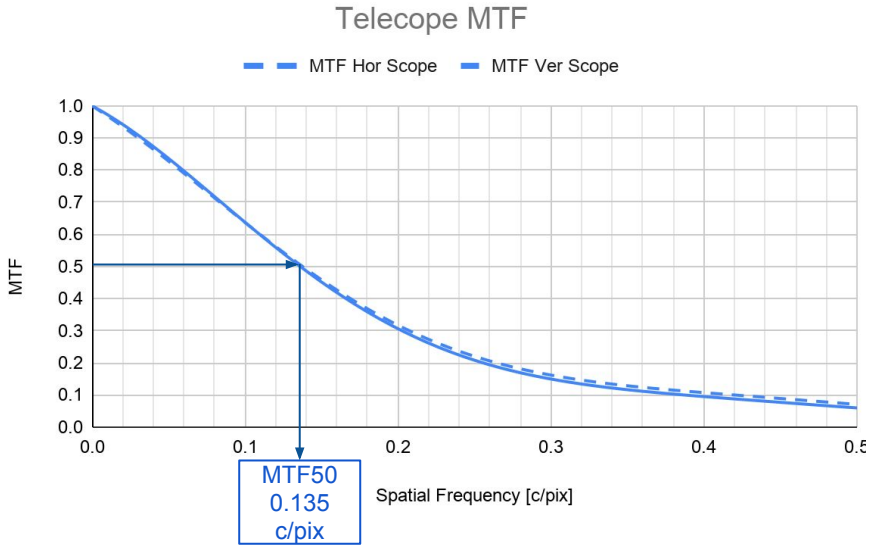


MTF50 through focus. At scope level and satellite pre/post vibe

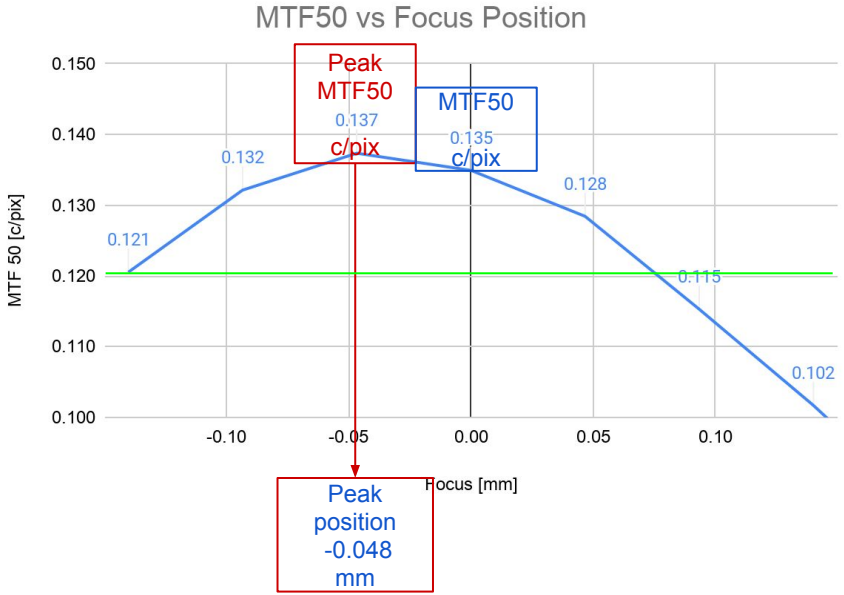
Metrics: MTF, MTF50 and ‘focus peak’

Modulation Transfer Function is a standard image performance metric

- The frequency for MTF50 is used as the pass criteria for scopes/satellites
- This frequency must be > 0.12 c/pix and located +/- 0.05 mm from ‘best focus’



Example MTF curve for a telescope. Center of field, Green II band.

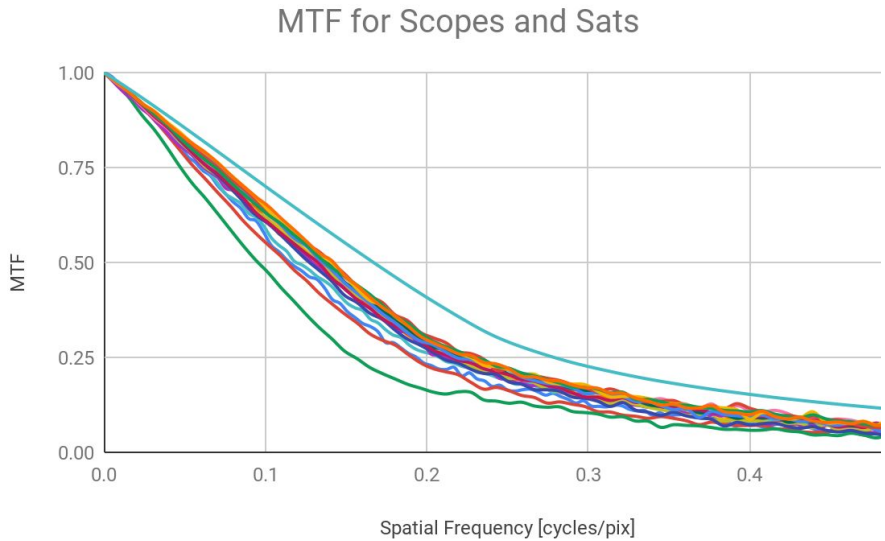


Right: Through focus MTF50 for a SuperDove. Center of field, Green II band.

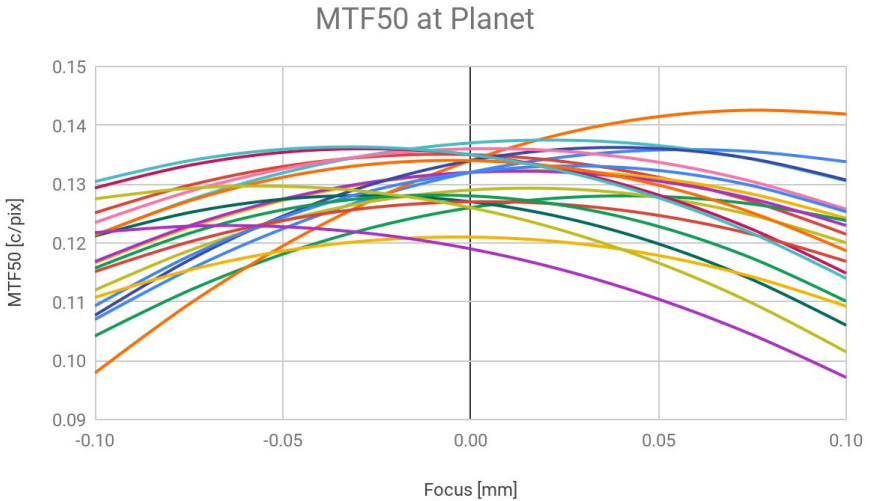
Metrics: MTF, MTF50 and ‘focus peak’

Examples of on-ground testing:

- (Left) Complete MTF curve up to Nyquist
- (Right) Though focus curves at MTF50

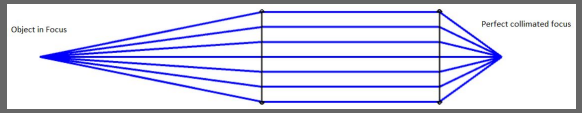


MTF for a sample of telescopes. Good scopes and anomalies



Through focus MTF50 for multiple telescopes. Ground testing

Optical Ground Support Equipment



Focus Bench Layout

Integrating Sphere

Corner Target on moving stage

Flat Mirror

+Z….0….-Z

Satellite/Telescope

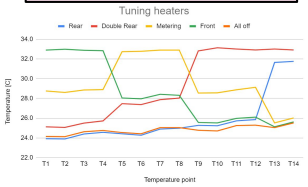
Image for Analysis

Horizontal Edge

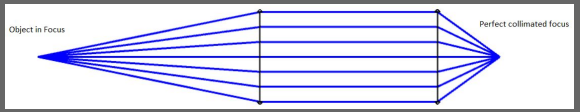
Vertical Edge

Measure and/or apply Thermal Gradients

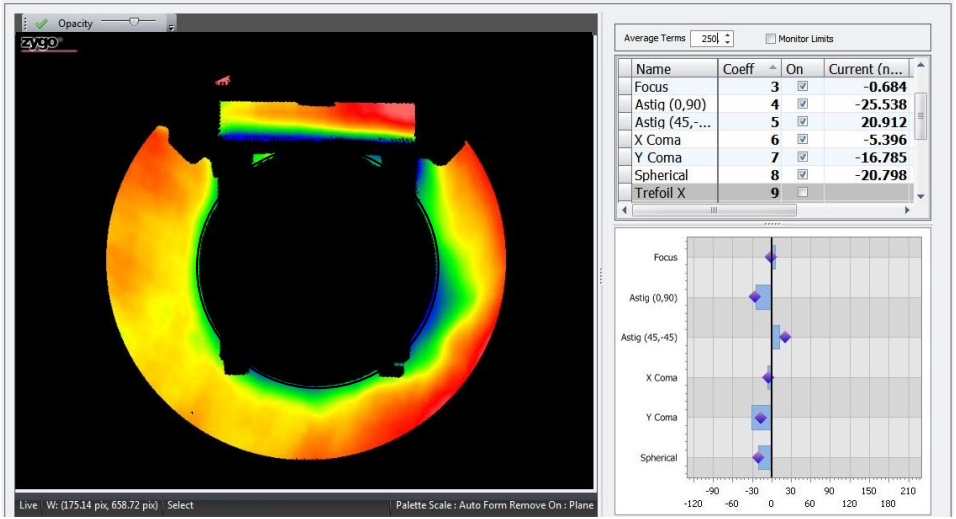
OAP
Φ=200mm

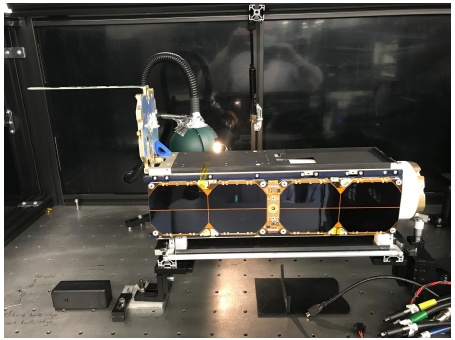


Ground Testing: Collimator



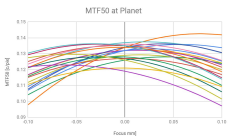
- Collimator focal length > 3x scope:
  - WFE < 50 nm RMS
- Collimator at vendor facilities for camera assembly
- There are two collimators at Planet for testing scopes:
  - Production
  - R&D
- We ensure our collimators have low WFE and are suitable for testing satellites.





Top: Telescope in the collimated beam. WFE (270 nm PV 40nm RMS) over much larger aperture than supedove telescope.
Bottom: Satellite in collimated beam. Ready for through focus tests

Pre-Launch Testing

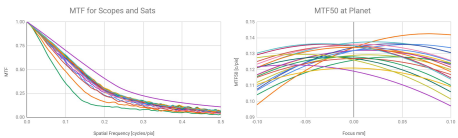


- Single focus position was measured in the past at center (not through focus)
- Currently through focus tests of a single spectral band are performed at:
  - Center
  - Edge of field
- Full MTF and through focus curves at:
  - Scope level
  - Satellite level
    - Pre and Post environmental tests (delta in performance)
    - Using thermal profiles (for refocus estimates)
- We use on-orbit data to improve next-launch production
    - Applying focus biases if required during assembly
    - Reducing variance of testing with process control
- Test duration has increased during implementation (but)
    - Implementation was tested during production and then optimized

Ground Testing

Iguazú National Park, Brazil – September 23, 2016

Focus Tests (Normal):

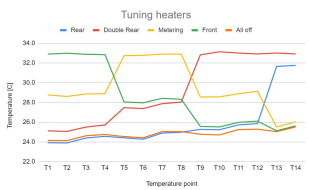


Data Collection:

1. Payload at room temperature ~22.5 C
   - Cooling approaches
     - Scope
     - Sat
2. Position corner target in center Green II band (for data continuity previous Doves)
   - Use liveview and move the target
3. Start collecting 5 images at each of 9 focus positions
   - Step size ~ 50 um image space
4. Repeat collection
   - 3x times
5. Camera off
   - Analysis and upload images

Normal Focus Tests	
Test time (Scope and Sat)	15 to 30 min
Focus steps	9
Equiv step size (image)	50 um

Focus Test (Thermal):



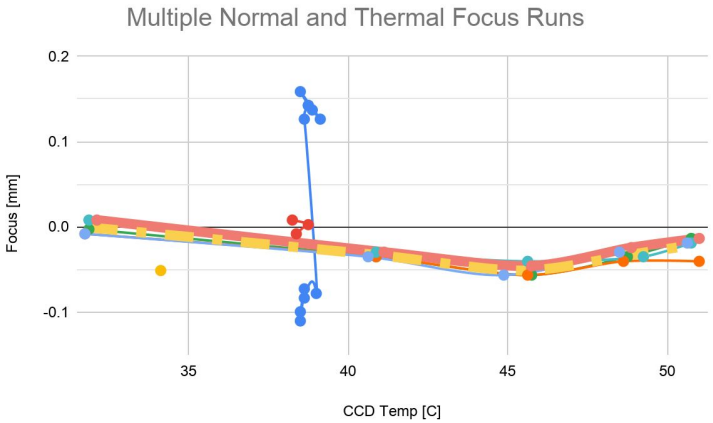
Data Collection:

1. Position corner target
    - Liveview alignment
2. Apply these gradients (one at the time) and wait 5 minutes
    - Telescope heater groups
        - Front group
        - Mid group
        - Rear group
        - Back
3. Start collecting 5 images for 9 focus positions
    - Step size ~ 50 um image space
4. Camera off
    - Analysis and upload images

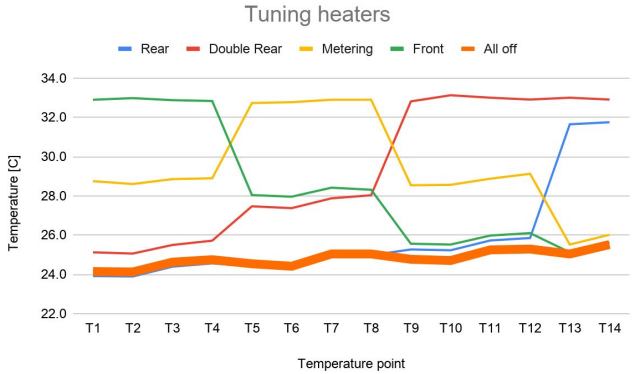
Thermal Focus Tests	
Avg Test Duration	5 min to apply thermal config 20 min per thermal config 2hr wait in between
Thermal focus range	~ +/- 100 um
Delta Temperature	Currently 9 C

Thermal test variations

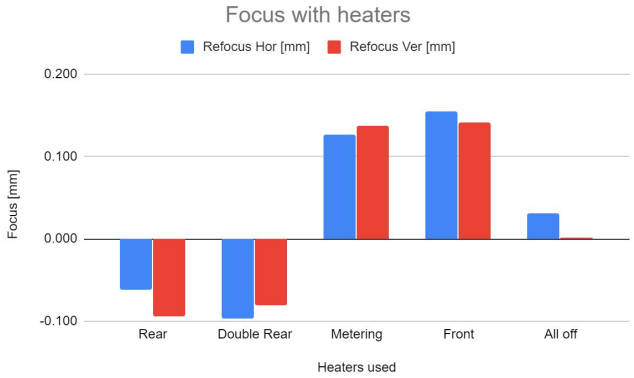
- During a focus test temperature changes
  - CCD Temp
  - Telescope gradients
    - These can be introduced to change focus of satellites



Multiple normal and thermal runs. Single sat 5 repeats



Normal and Thermal Profiles

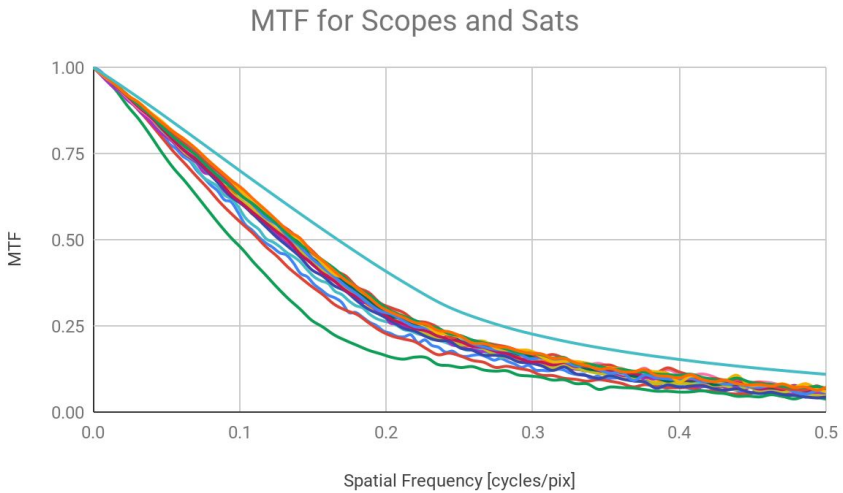


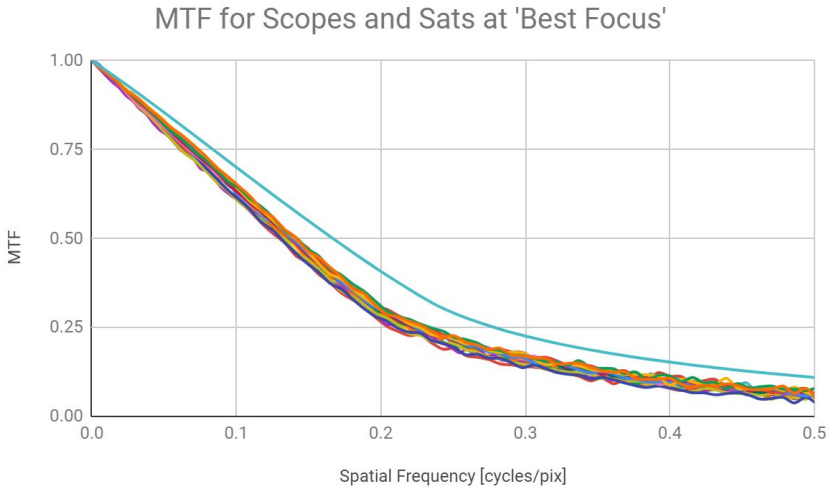
Thermal refocus ranges

Thermal test refocus

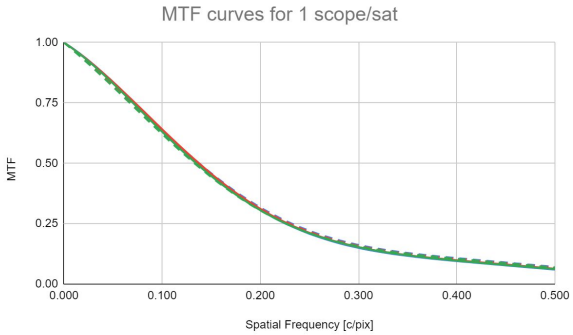
- For satellites with a slight focus bias
  - (~ +/- 0.100 mm)
- It is possible to recover the optical performance using thermal heaters

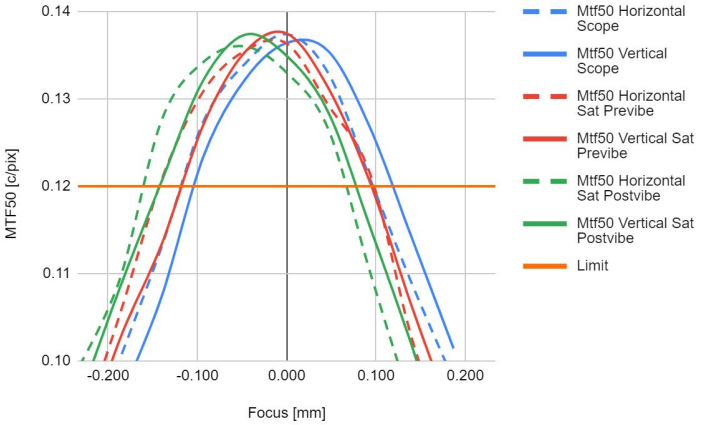
- Once the satellites are refocused, their spread on the MTF curve will be less to reflect the real average optical performance after focus tuning





Pre-Launch Testing: Scope and Satellite





MTF50 Peak [c/pix]	Horizontal	Vertical
Scope	0.137	0.136
Previbe	0.136	0.138
Postvibe	0.136	0.137
MTF50 [c/pix]		
Scope	0.137	0.136
Previbe	0.136	0.138
Postvibe	0.133	0.135
MTF 50 focus Peak [mm]		
Scope	-0.010	0.008
Previbe	-0.025	-0.012
Postvibe	-0.052	-0.032

Scope level

Subresults

Name	Comment	Value	Units	Limits	Result
mtf50_horizontal		0.1374000000000012	cycles/pixel	> 0.12 <= 0.15	Passed
mtf50_vertical		0.1364200000000013	cycles/pixel	> 0.12 <= 0.15	Passed

Satellite Previbe

Subresults

Name	Comment	Value	Units	Limits	Result
mtf50_horizontal		0.1363400000000013	cycles/pixel	> 0.1 <= 0.15	Passed
mtf50_vertical		0.13750000000000118	cycles/pixel	> 0.1 <= 0.15	Passed

Satellite Postvibe

Subresults

Name	Comment	Value	Units	Limits	Result
mtf50_horizontal	Horizontal MTF is good at neutral focus	0.13300000000000167	cycles/pixel	> 0.1 <= 0.15	Passed
mtf50_vertical	Vertical MTF is good at neutral	0.13494000000000145	cycles/pixel	> 0.1 <= 0.15	Passed

Pre-Launch Testing: New test outputs

- New metrics and methods are interleaved during production.
- With minimal downtime we can implement our new metrics for testing and tracking:

Name	Comment	Value	Units	Limits	Result
mtf50_calculated_peak_horizontal	Median horizontal calculated peak MTF is good	0.13489175722799143	cycles/pixel	> 0.1 <= 0.15	Passed
mtf50_calculated_peak_vertical	Median vertical calculated peak MTF is good	0.13448867613408289	cycles/pixel	> 0.1 <= 0.15	Passed
mtf50_horizontal	Median horizontal MTF is good at neutral focus	0.13322000000000164	cycles/pixel	> 0.1 <= 0.15	Passed
mtf50_vertical	Median vertical MTF is good at neutral focus	0.13440000000000152	cycles/pixel	> 0.1 <= 0.15	Passed
peak_deviation_horizontal	Median camera horizontal focal plane distance fit is good	0.03490731273315592	mm	>= -0.05 <= 0.05	Passed
peak_deviation_vertical	Median camera vertical focal plane distance fit is good	0.002685177902550462	mm	>= -0.05 <= 0.05	Passed

Ground testing: Flock

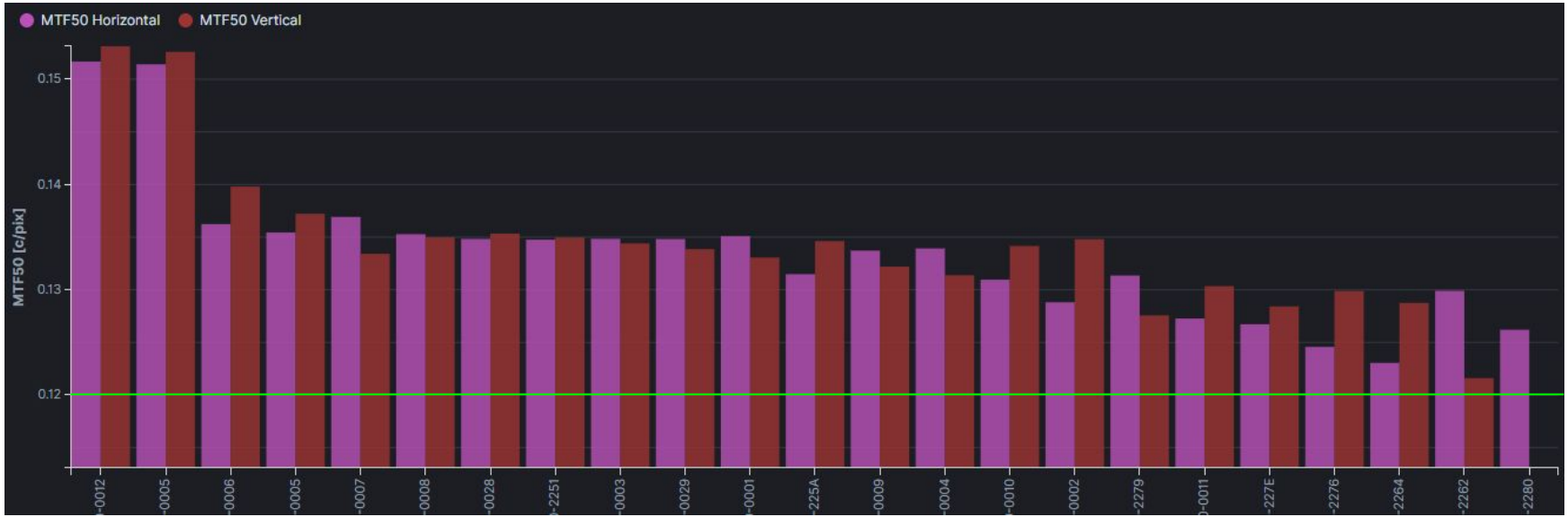
https://www.planet.com/pulse/flock-4v-captivating-first-light-imagery/

Focus Peak Position: Flock

- At scope and sat level
  - Depth of focus is ~ 0.16 mm
  - Automatic pass at +/- 0.05 mm
- Satellites outside of this range will require some ‘thermal refocus’

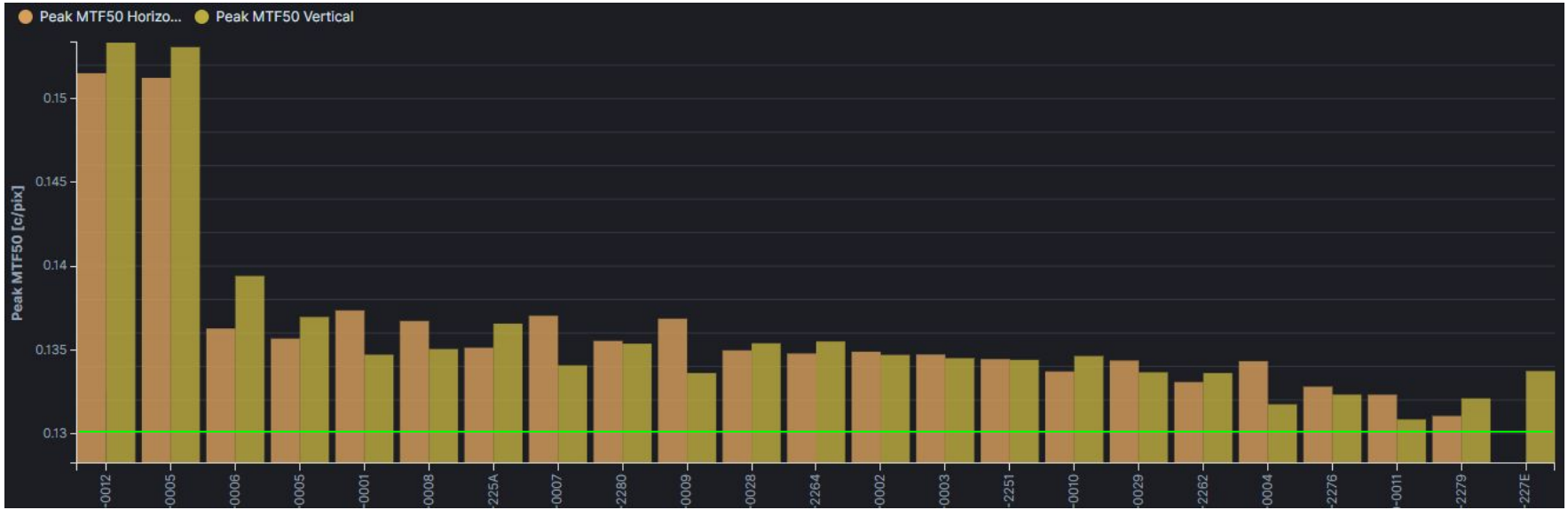
MTF50 at collimated position: Flock

- Ground based criteria
  - MTF50 > 0.12 c/pix
- Tech demos can achieve
  - MTF50 > 0.15 c/pix



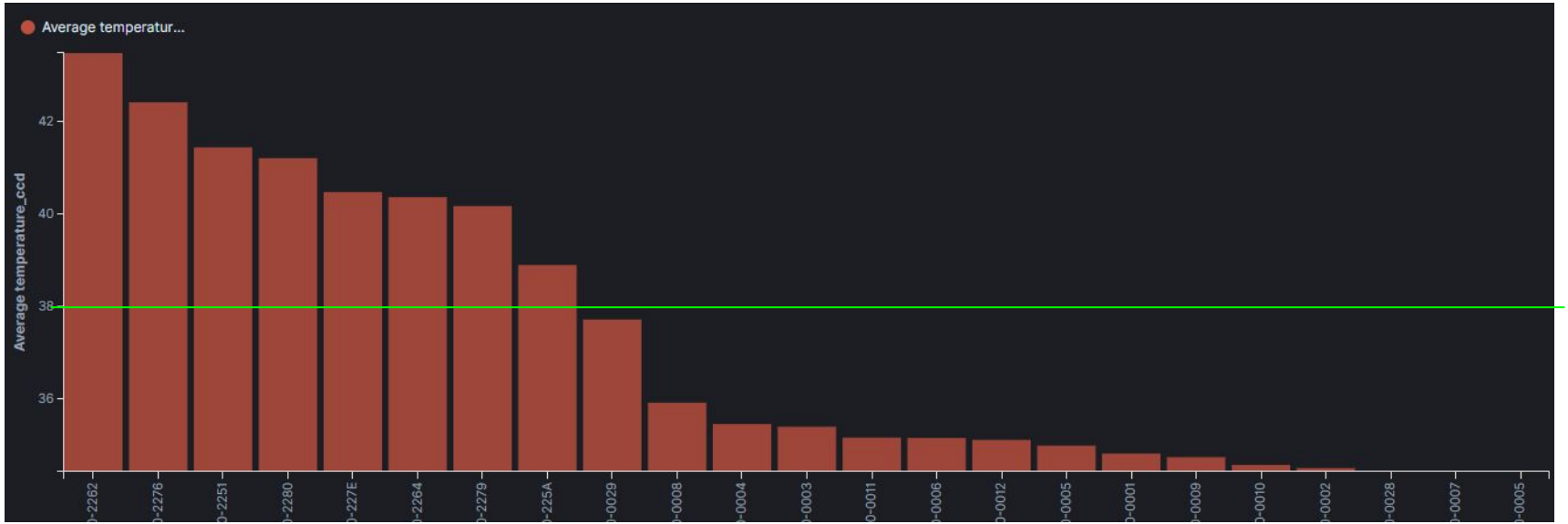
MTF50 Peak [c/pix]: Flock and Tech Demos

- Current design MTF50 @ Peak > 0.13 c/pix
  - Current Tech Demos > 0.15 c/pix
- Peak can be achieved with
  - Thermal focus

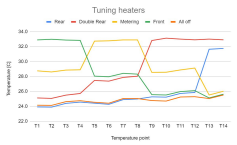


CCD Temp [C]: Scopes and Sats

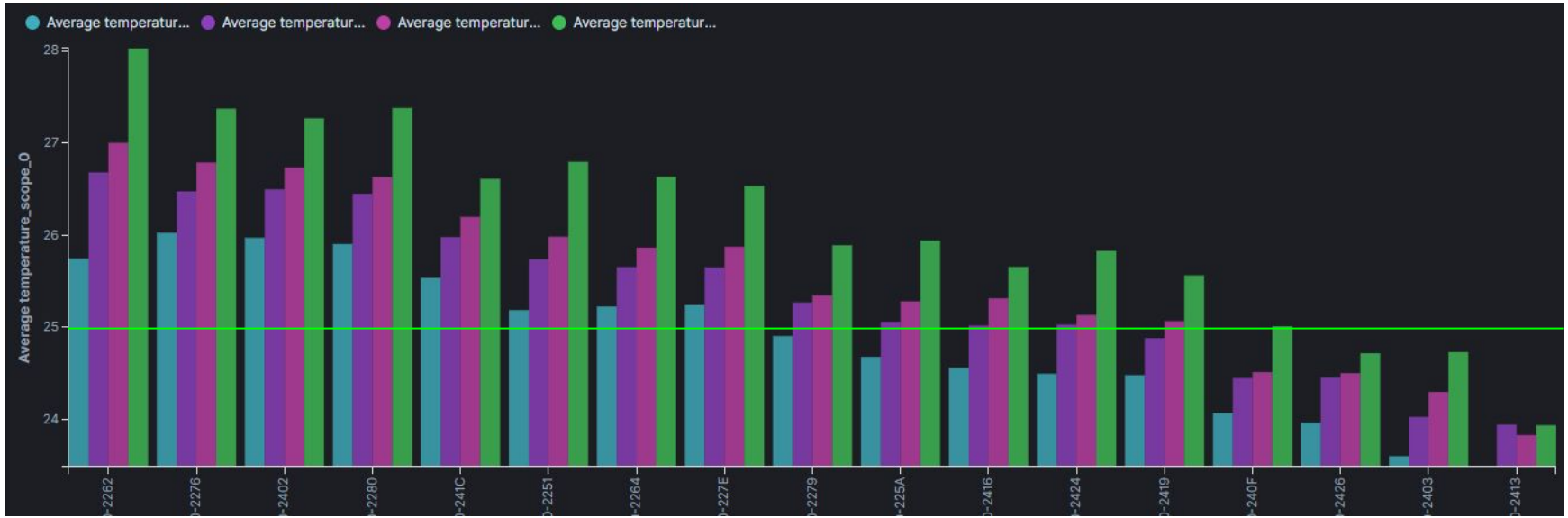
- At scope level current test are < 38 [C]
  - More stable test conditions
- At satellite level CCD Temp is > 38 [C]
  - Gradients from previous tests build up



Telescope Gradients [C]: Flock



- There are 4 main thermal groups on the satellite
- The average temp of the scope is ~ 25 C
- The max allowed gradient for testing is 2 C

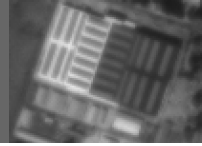


First Light Results

Preliminary Analysis

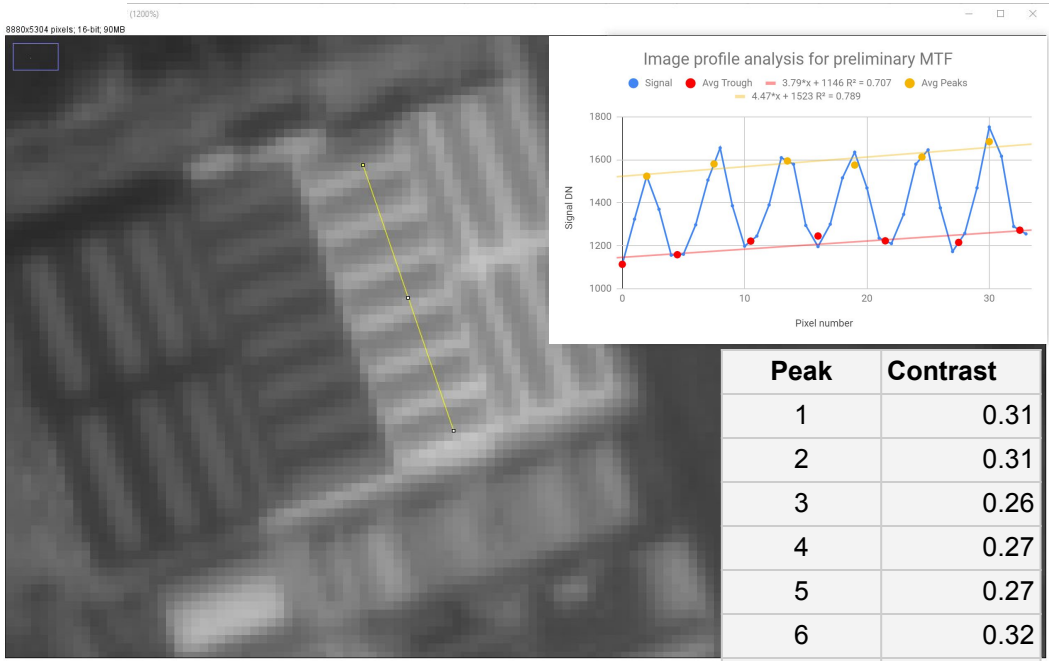
https://www.planet.com/pulse/flock-4v-capturing-first-light-imagery/

SuperDove F4V first light results



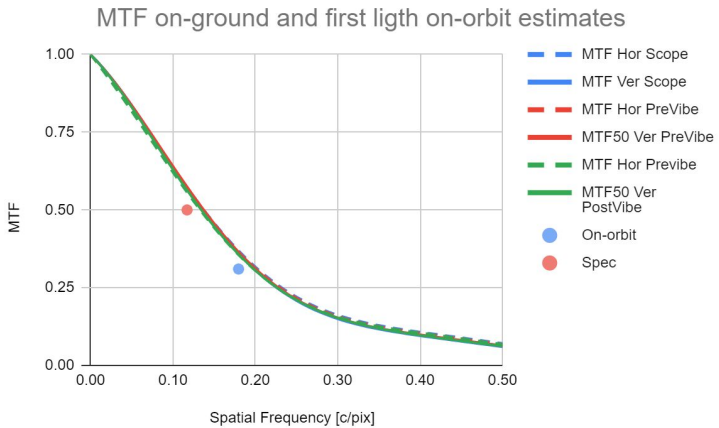
- Launch on Vega postponed our original plans (wait)
- Then RocketLab launch was unsuccessful (wait)
- 12 sats launched saw first light (as of 9-14-2020)
- Very early comparisons between ground tests vs on-orbit results
  - Currently in focus characterization prior to thermal refocusing if required
- Early days to draw conclusions, results look in good agreement
  - Further analysis is required before focus corrections

SuperDove F4V first light results (Green II @565nm)

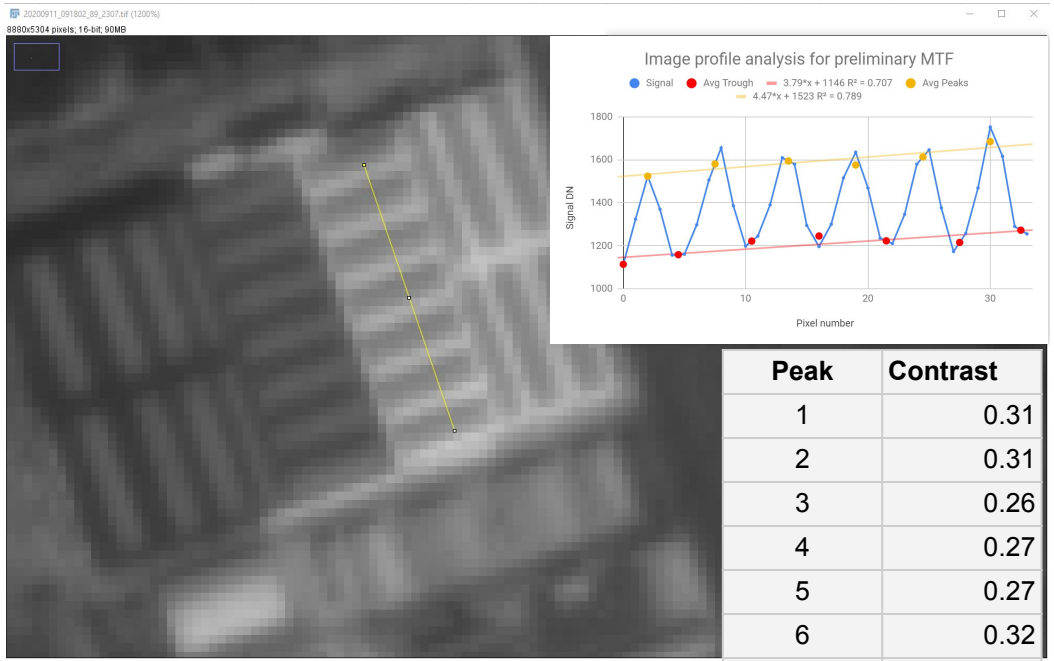


Peak	Contrast
1	0.31
2	0.31
3	0.26
4	0.27
5	0.27
6	0.32
Average	**0.29**

- Target is ~6 cycles in 33 pix
  - Freq ~ 0.18 c/pix
- Contrast is ~ 370/1270 DN
  - Contrast is ~ 0.29
- Ground measurements
- On-orbit quick estimate from image

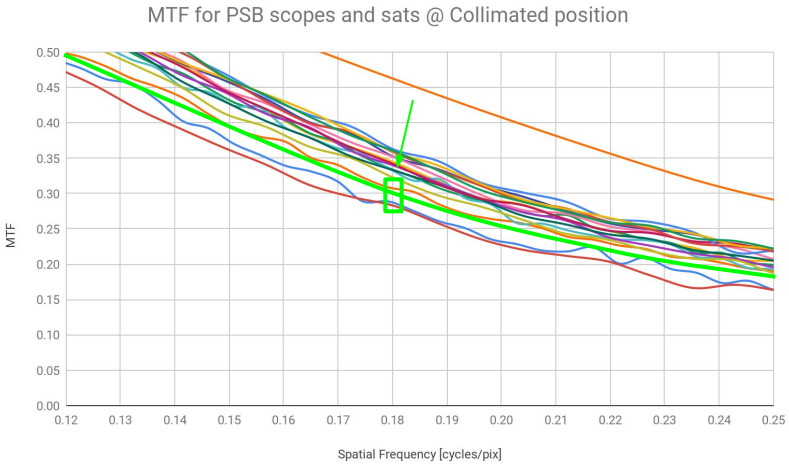


SuperDove F4V first light results (Green II @565nm)



Peak	Contrast
1	0.31
2	0.31
3	0.26
4	0.27
5	0.27
6	0.32
Average	**0.29**

- Estimated contrast for a sample is in good agreement with ground measurements
- Refined measurements will determine if tuning if required



Conclusions

- Image quality is needed everywhere everyday
- Demonstration of agile implementation of new methods and metrics in a production environment:
  - Ground Based Testing
    - Scope and satellite level
    - Thermal refocus (provides some freedom to tune focus)
  - Testing at scale (Dashboards for production)
  - Preliminary on-orbit results look positive
    - Less than 1 week since first light
    - In good agreement with on-ground measurements
- We are flexible to iterate and improve our test methods and incorporate changes quickly

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

Questions?

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