Calibration of a Multi-Spectral CubeSat with LandSat Filters

Sloane Wiktorowicz, Ray Russell, Dee Pack, Eric Herman, George Rossano, Christopher Coffman, Brian Hardy, & Bonnie Hattersley (The Aerospace Corporation)

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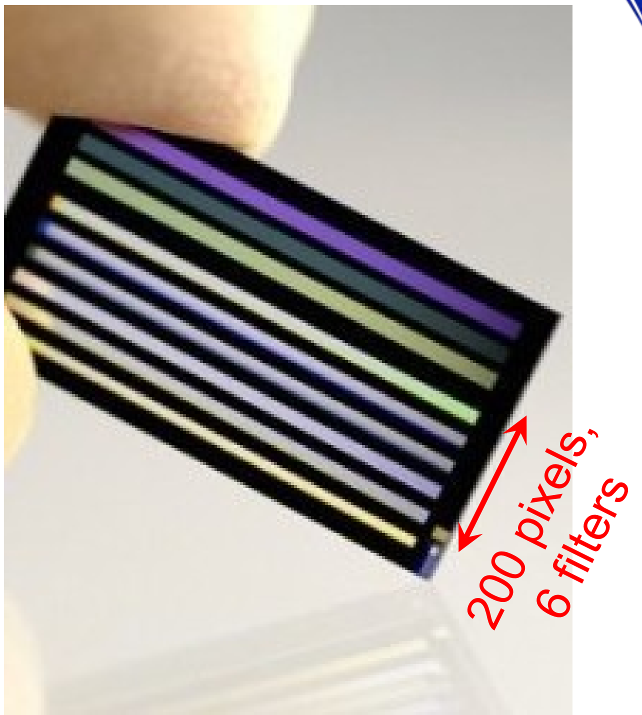
AeroCube 11 Spectral (AC-11 R3) Overview

- 3U CubeSat with six Landsat-8 Operational Land Imager (OLI) filters in butcher block configuration (nine filters comprise filter assembly, but pixels only under six filters are read out due to downlink limitations)
- TDI-in-software images constructed in each filter
- Goal: Demonstrate SNR within 10% of Landsat-8
- ON Semiconductor LUPA1300-2 CMOS sensor
  - *1024 x 1280 pixels, only 206 x 1280 are read out*
  - *14 μm pixel pitch*
- Performed all testing procedures on engineering model first
  - *Minimize risk of damage to flight focal plane array (FPA)*
  - *Optimize test procedure efficiency for flight FPA*
  - *Uncovered unforeseen need to tune flight FPA*



Spectral Response

Flight model

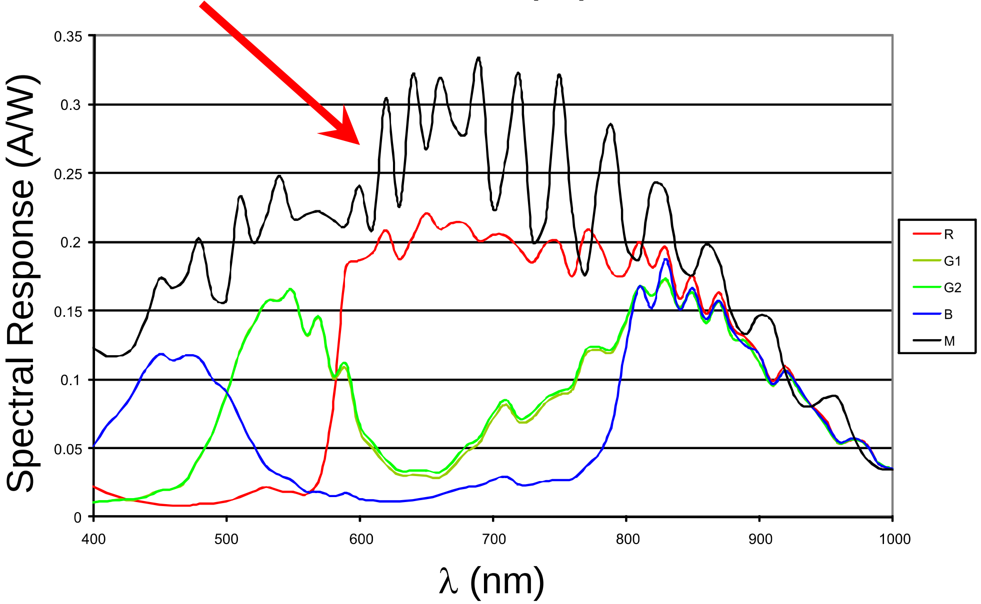
Landsat filters

- *Panchromatic:* *504-676 nm*
- *Blue:* *453-512 nm*
- *Coastal aerosol:* *435-451 nm*
- *NIR:* *850-880 nm*
- *Red:* *635-675 nm*
- *Green:* *533-592 nm*
- *SWIR2*:* *2,108-2,293 nm*
- *SWIR1*:* *1,567-1,654 nm*
- *Cirrus*:* *1,365-1,386 nm*

*Not read out

Figoski et al. 2009, SPIE, 7452, 74520T

LUPA, Monochromatic (M) model



Special thanks to Kevin Downing at Materion Precision Optics for providing the filter array used in the R3 payload. The filters provided are identical to those used on the OLI instrument on Landsat 8. Their assistance with this project was critical.

Flight Model Tuning

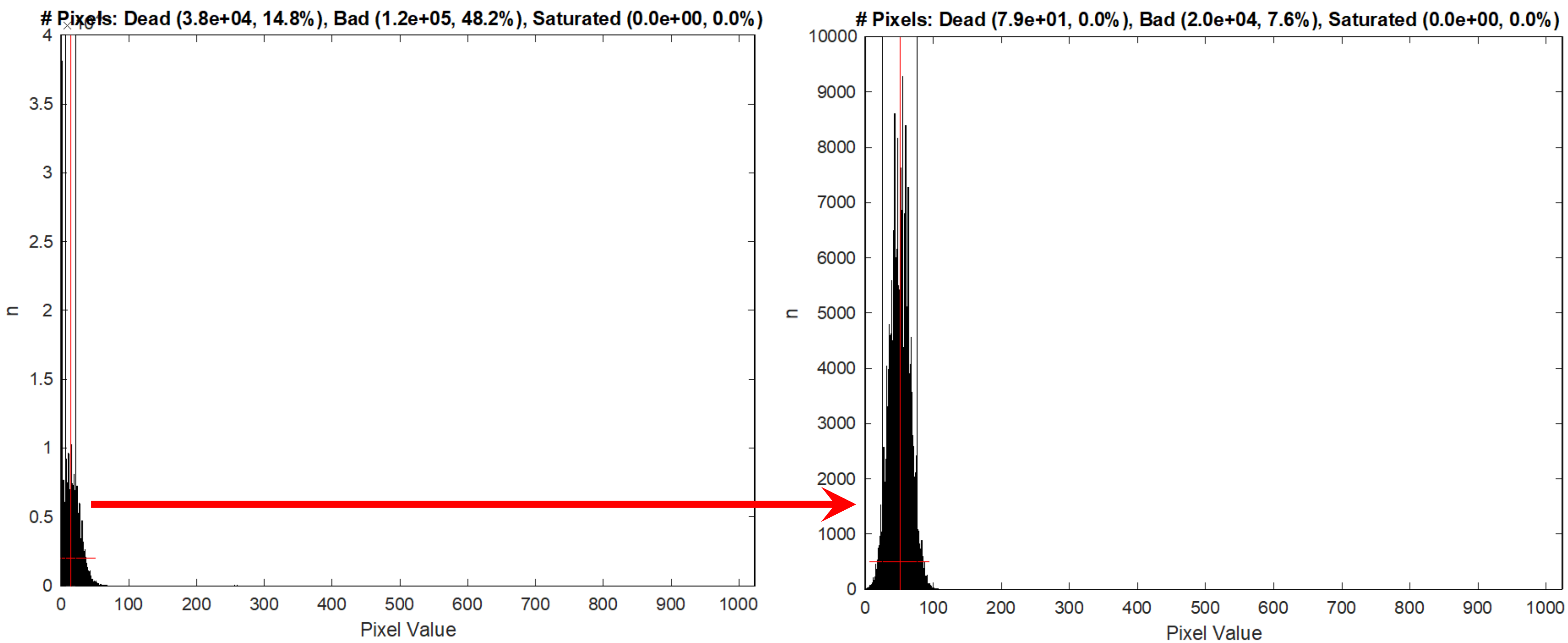
Bias

Problem

- Initial darks were essentially black (pixel values = 0) regardless of integration time (cannot measure noise floor)

Solution

- Send binary string to register to enable bias control, vary bias until histogram of pixel values > 0 out to 3 sigma from mean



Flight Model Tuning

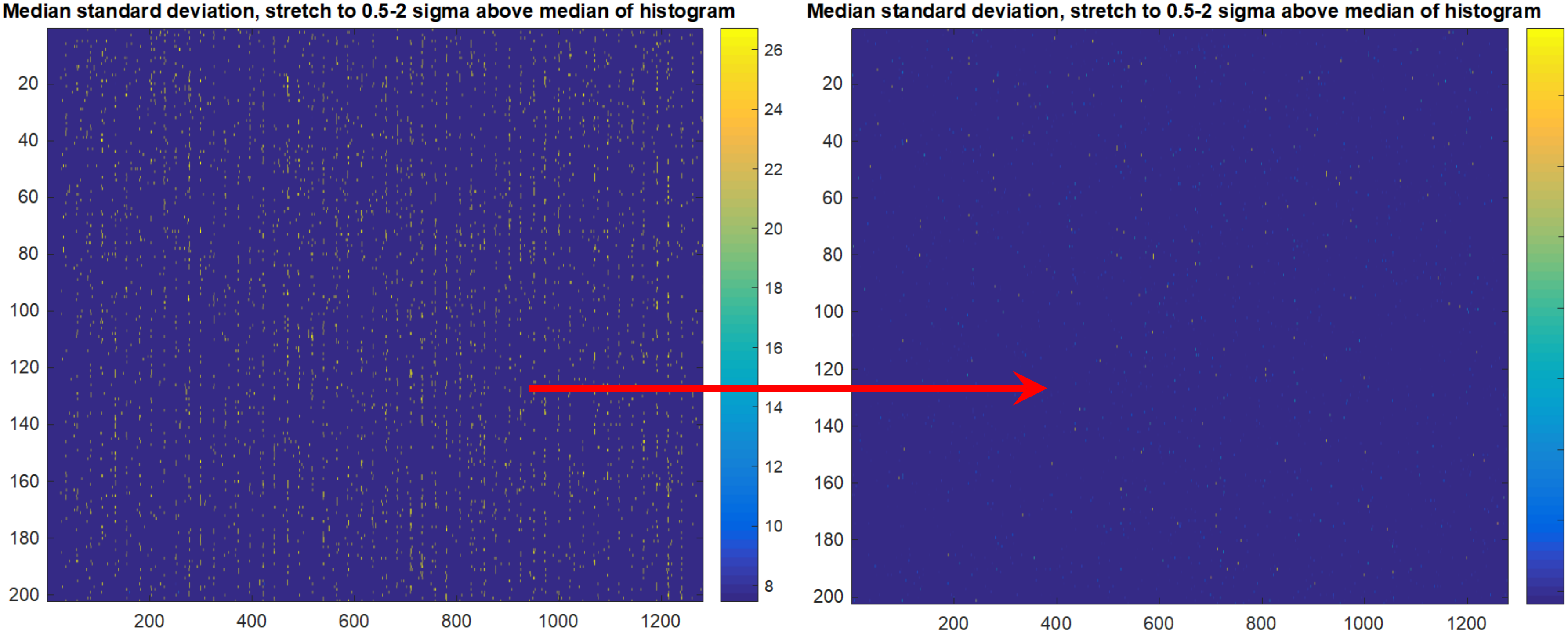
Skew

Problem

- Many FPA columns strongly temporally variable (large standard deviation from frame to frame) due to clocking offset

Solution

- Send binary string to register to vary skew until frame-to-frame standard deviation minimized



Noise reduction of 0.9 orders of magnitude ($\sigma \leq$ 27 counts improves to $\sigma \leq$ 3.2 counts)

Flight Model Tuning

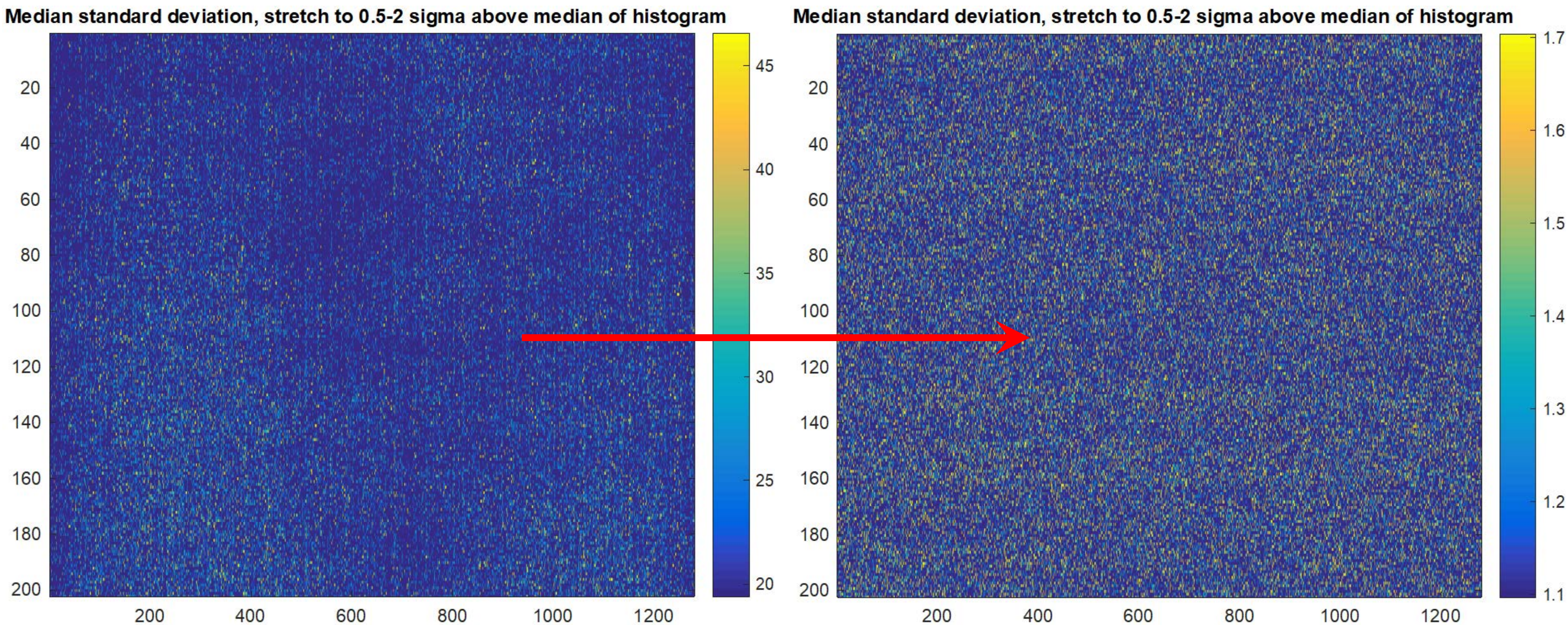
LVDS offset

Problem

- Many FPA pixels still strongly temporally variable (large standard deviation from frame to frame)

Solution

- Send binary string to register to vary LVDS offset until frame-to-frame standard deviation minimized

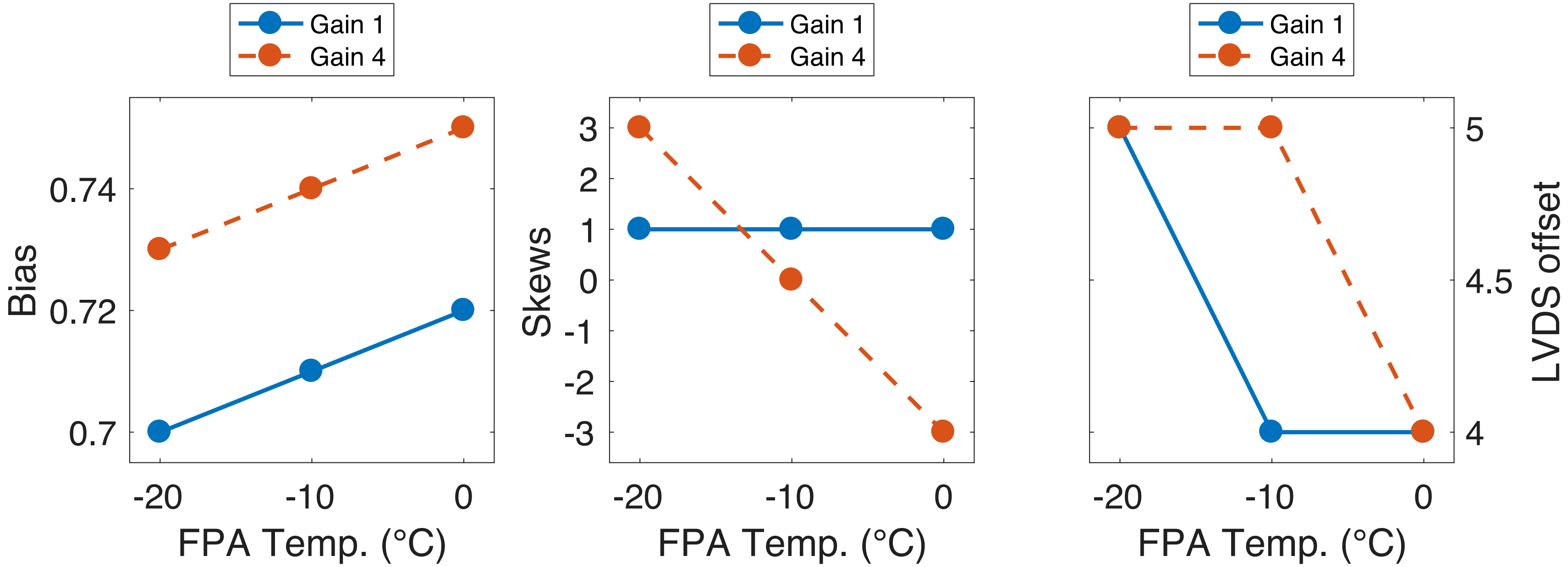


Noise reduction of 1.4 orders of magnitude ($\sigma \leq$ 46 counts improves to $\sigma \leq$ 1.7 counts)

Flight Model Tuning

FPA temperature effects

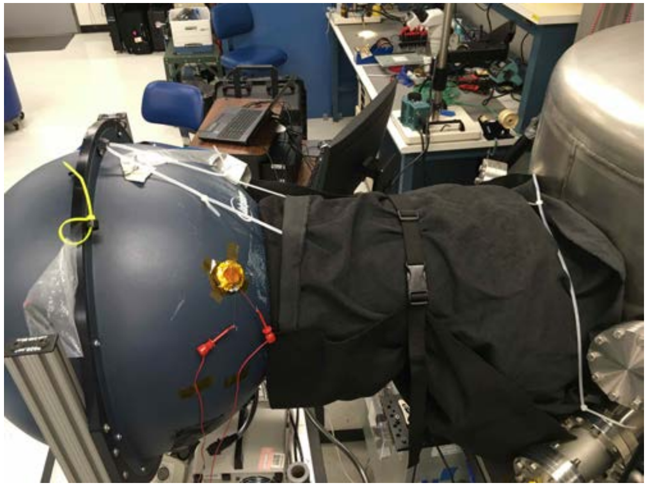
- Generated look-up table of bias, skew, LVDS offset values vs. FPA temperature and gain
- This table to be applied each time the satellite is powered on

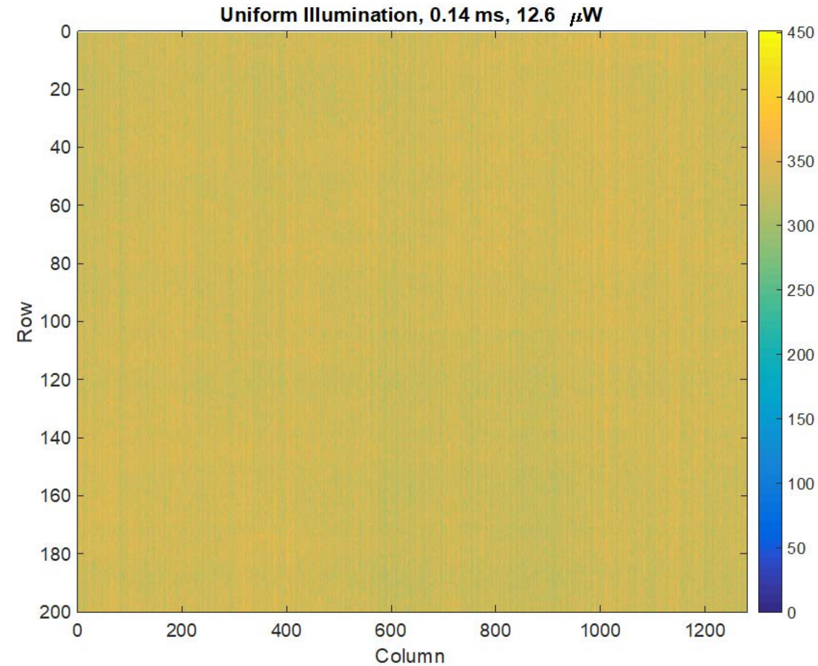


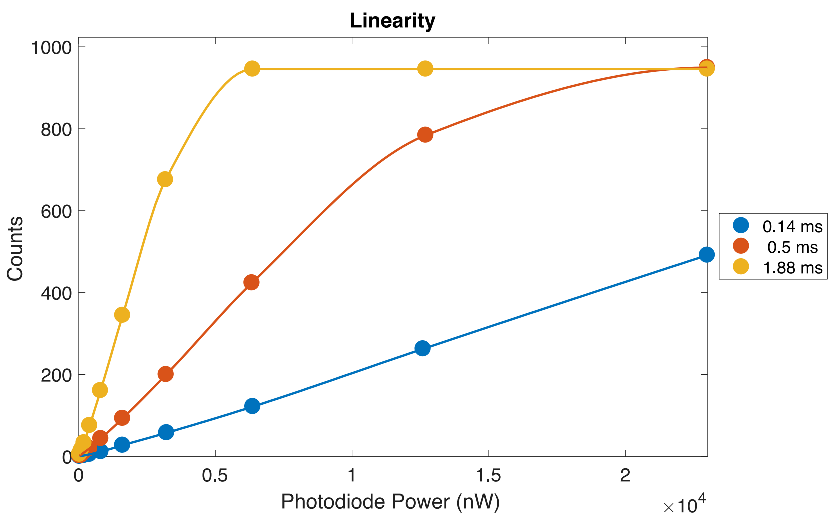
Now calibration may begin

Flight Model Testing

Darks, linearity, flat fields, reciprocity, spectral response





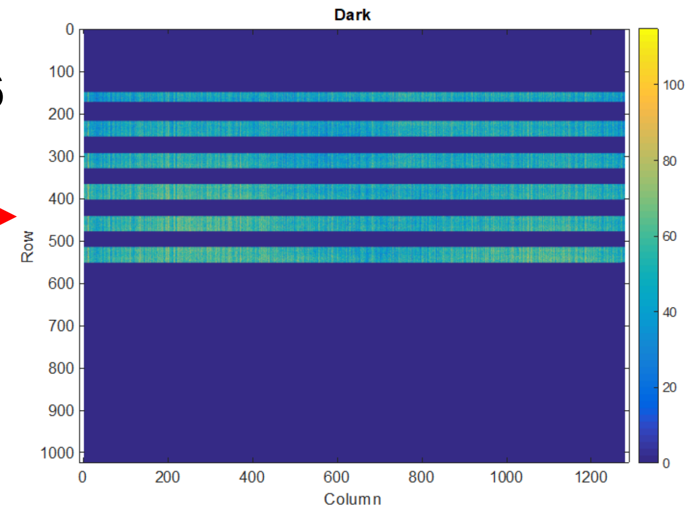


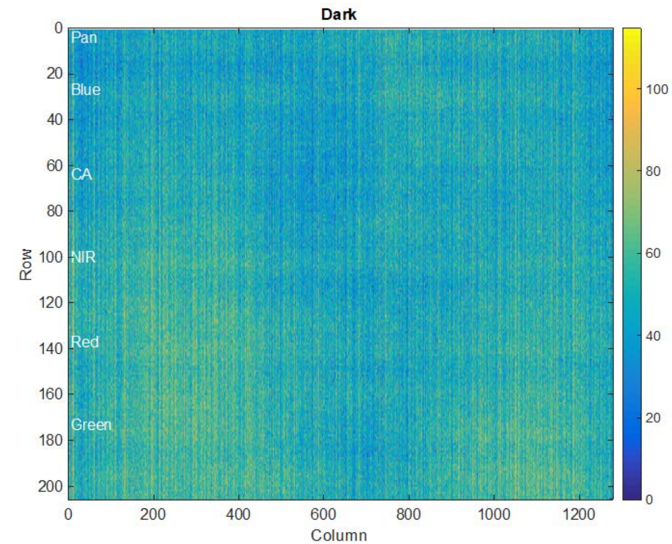
Perform calibration tests with engineering model to minimize risk to flight payload

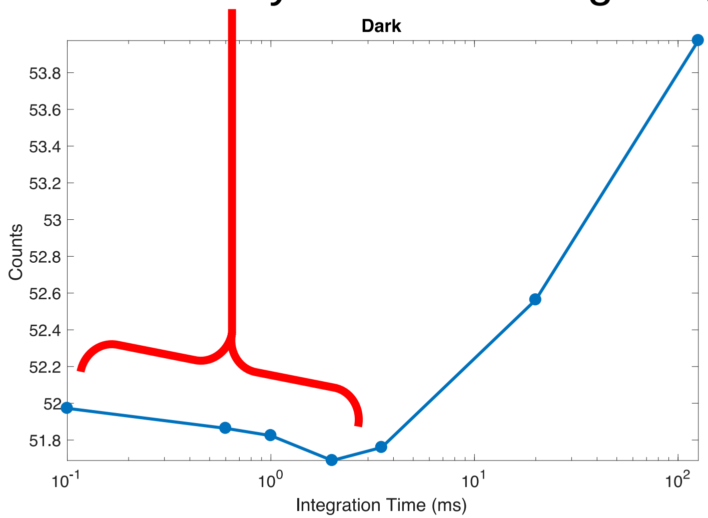
Flight Model Testing

Darks

- While the FPA has 1024 x 1280 pixels, only 206 x 1280 are read out under six spectral filters
- Bands are not contiguous on the FPA
- Dark signal vs. integration time nonlinear for short integration times due to electronic noise source related to pixel reset time (integration time and framerate independent up to a point, pixel reset is delay before starting integration)



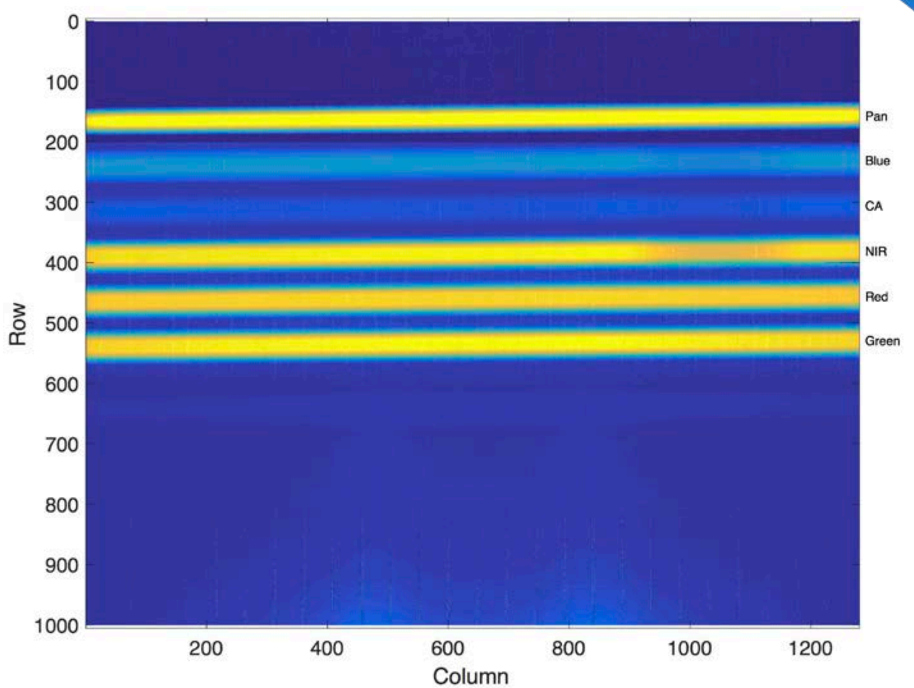


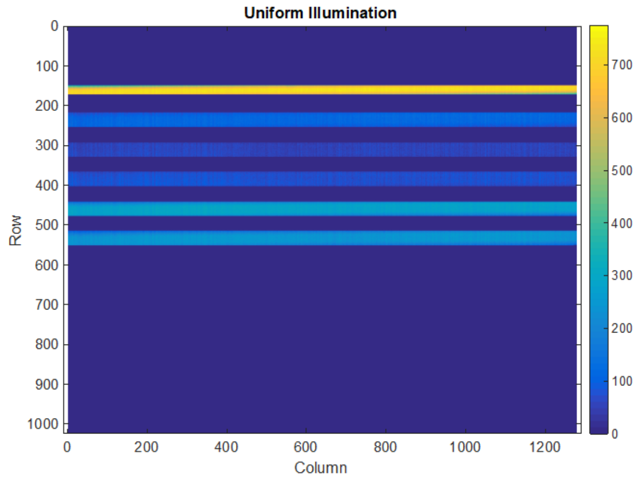


Flight Model Testing

Full frame mosaic

- Mosaic of 5 images (200 x 1280 pixels each) stitched together to create full-frame image
- Required 5 firmware updates to ground software to read out pixels 1-200, 201-400, 401-600, 601-800, 801-1000 in successive images
- Reveals anomalies for mitigation
  - *Stray light source in region of unread pixels due to unplugged through holes for mounting*
  - *Out of band leakage through SWIR2 filter (around row 650)*
  - *0.5° tilt of filter assembly with respect to FPA pixels (11 pixels over 1280 or 156 μm over 18 mm)*

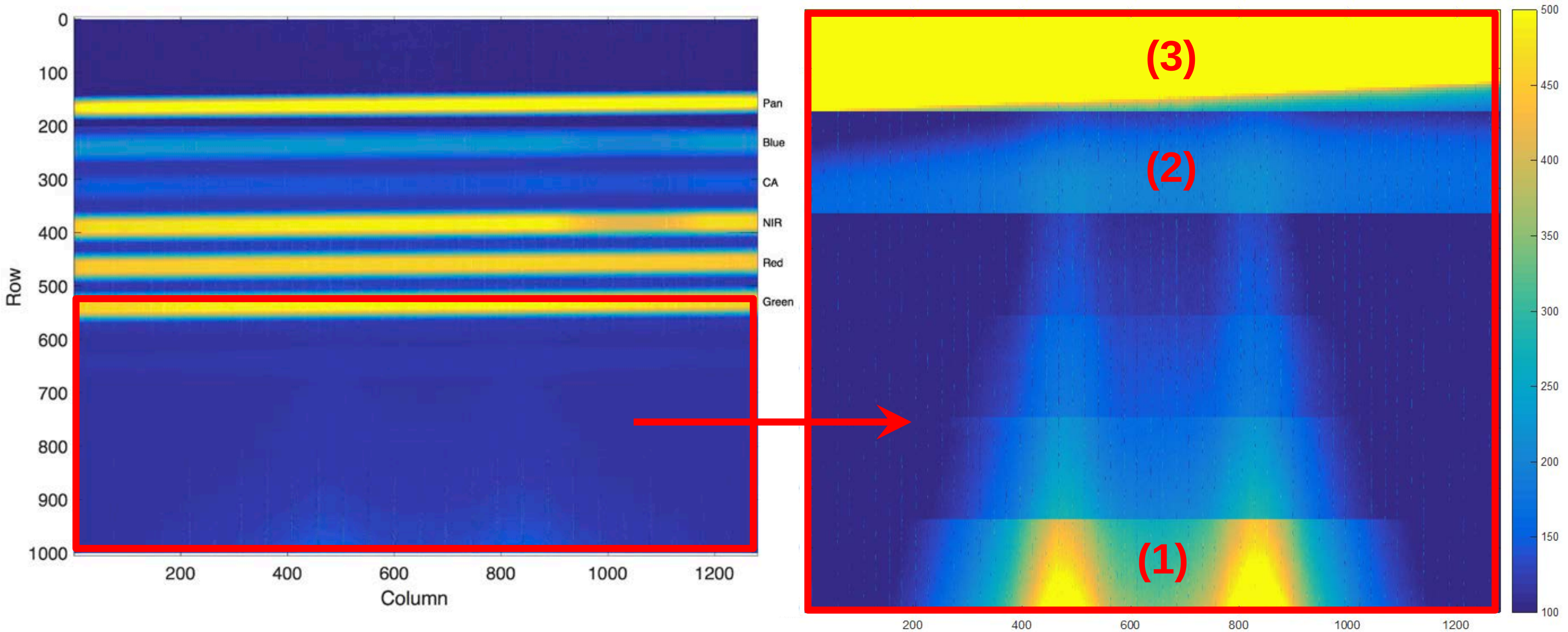




Flight Model Testing

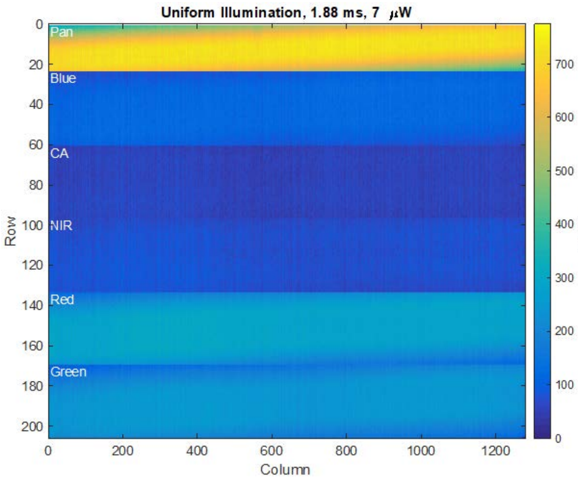
Anomalies

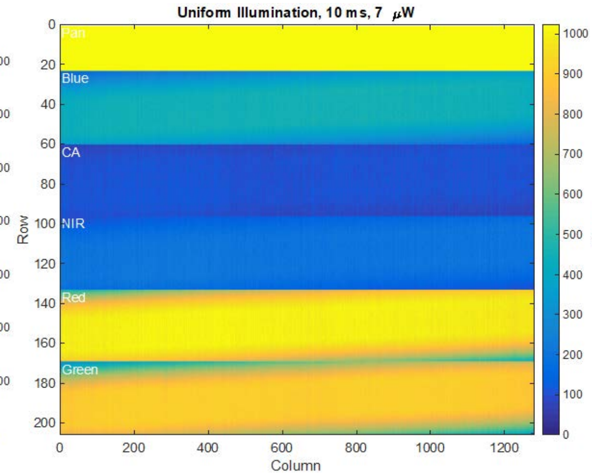
1) Stray light source: plugged
2) Out of band leakage: only affects unread SWIR2 filter
3) 0.5° tilt of filter assembly: read 206 rows instead of 200

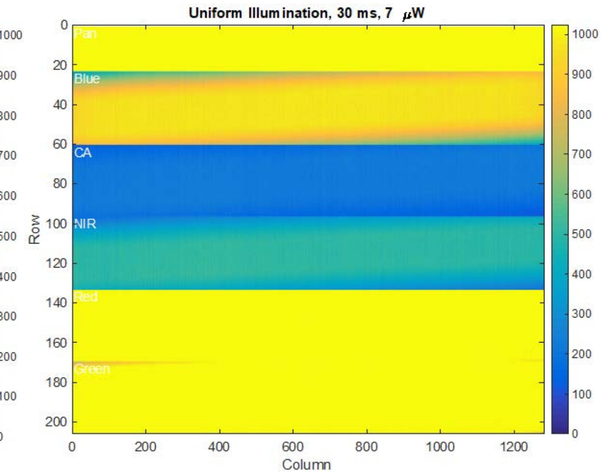


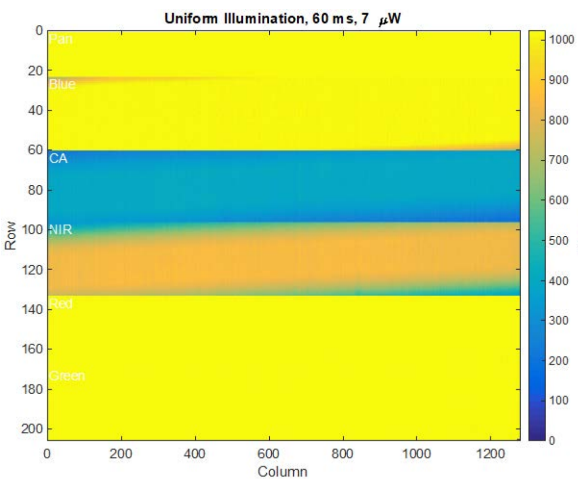
Flight Model Testing

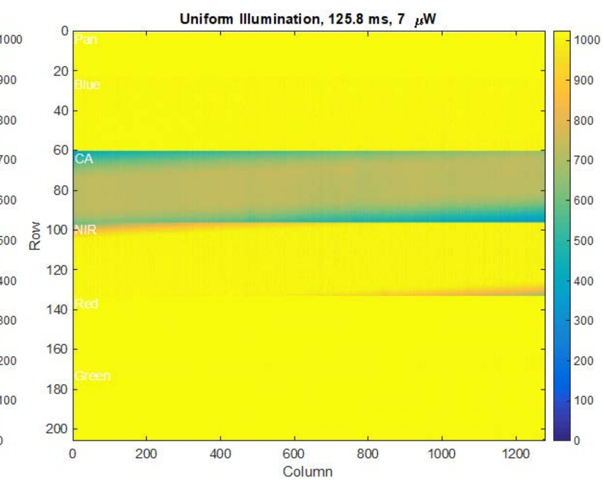
Linearity / flat fields

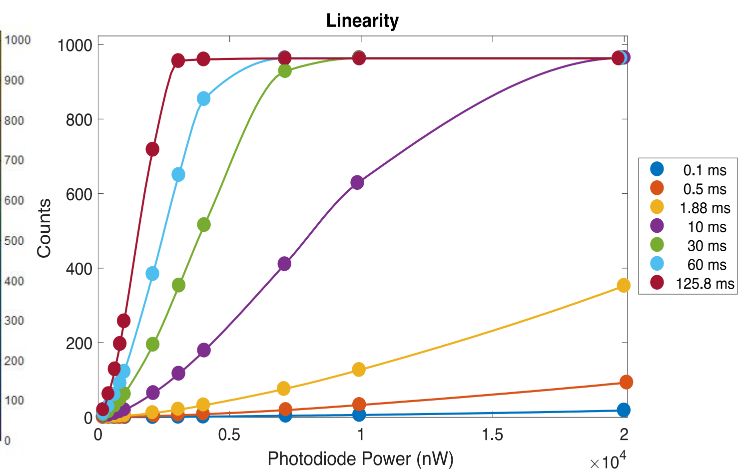








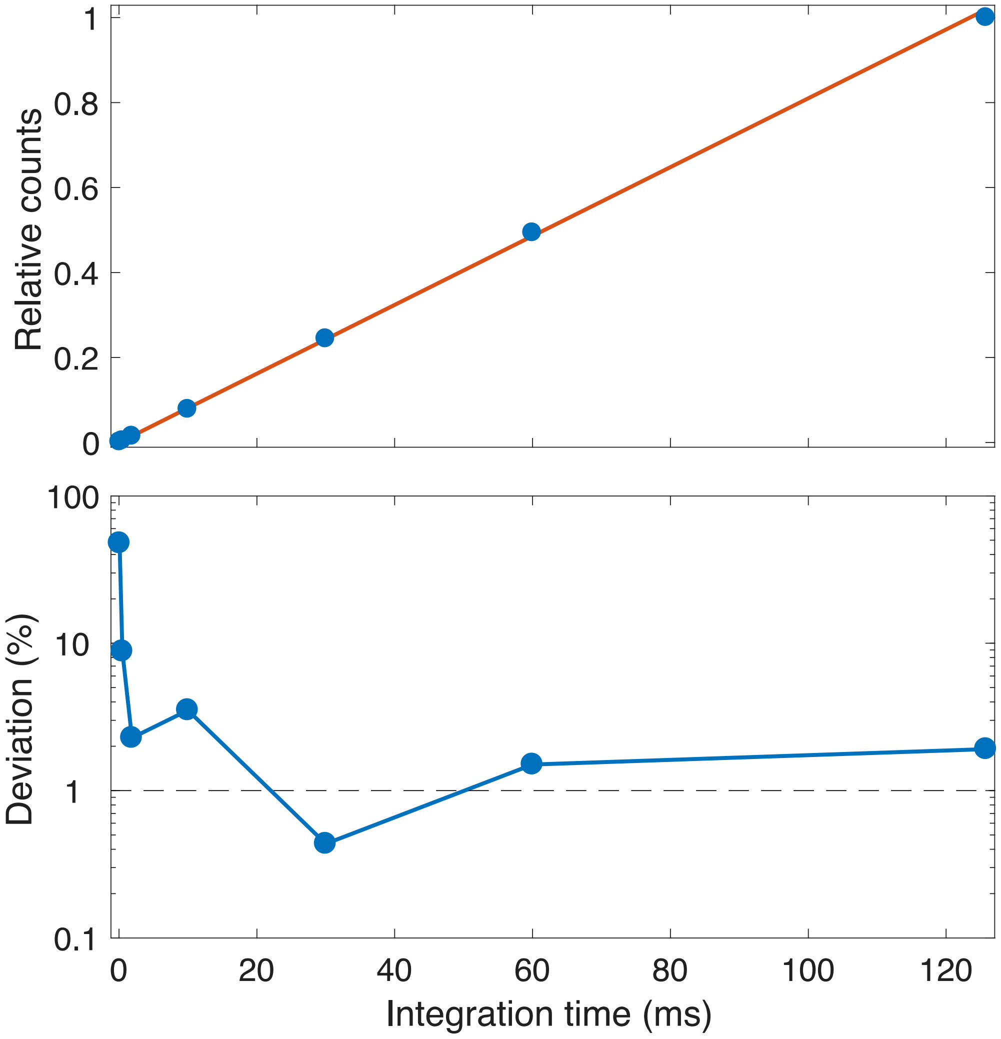




Flight Model Testing

Reciprocity

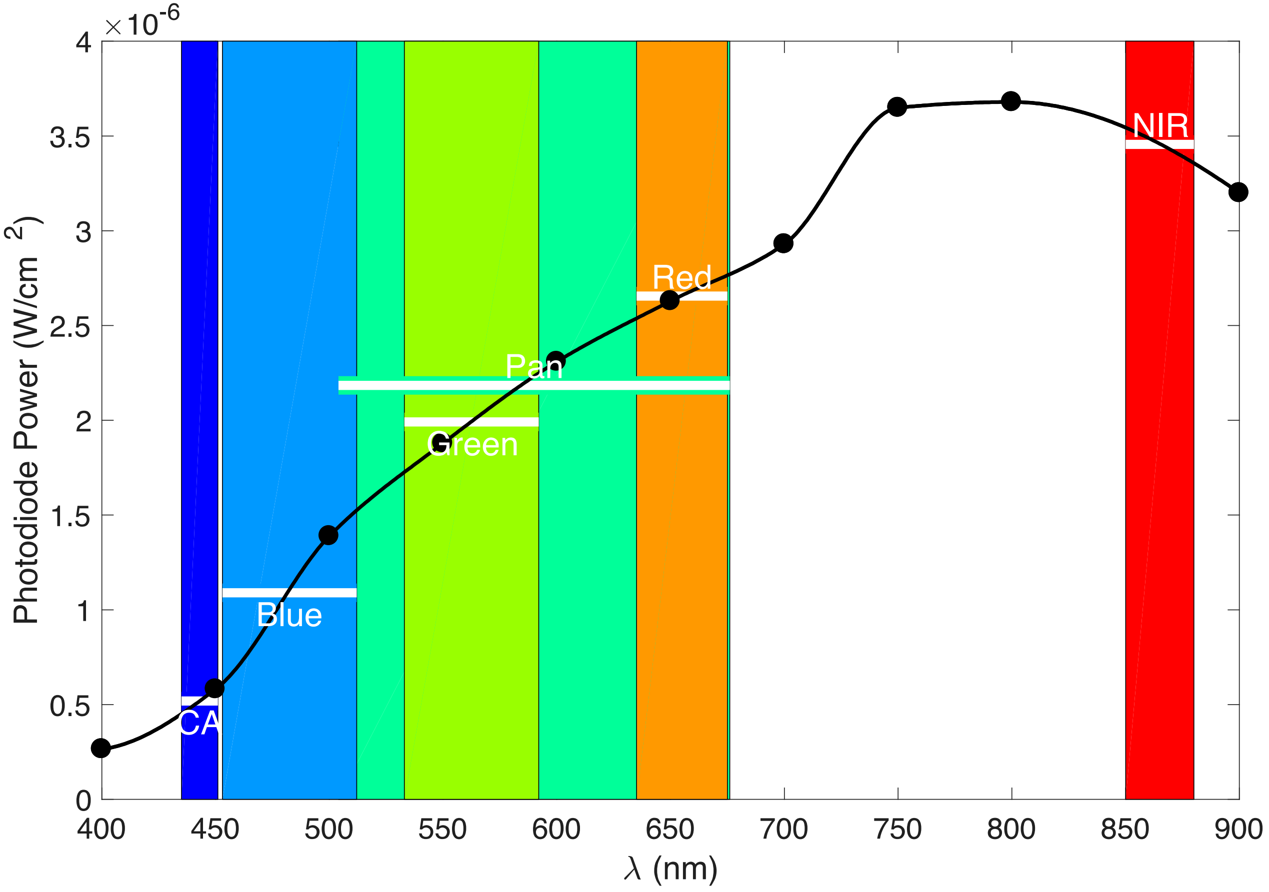
- Counts ≈ illumination x time
- Vary integration time for given light level as opposed to varying light level for given integration time
- Reciprocity holds to 2% across all bands



Flight Model Testing

Spectral response

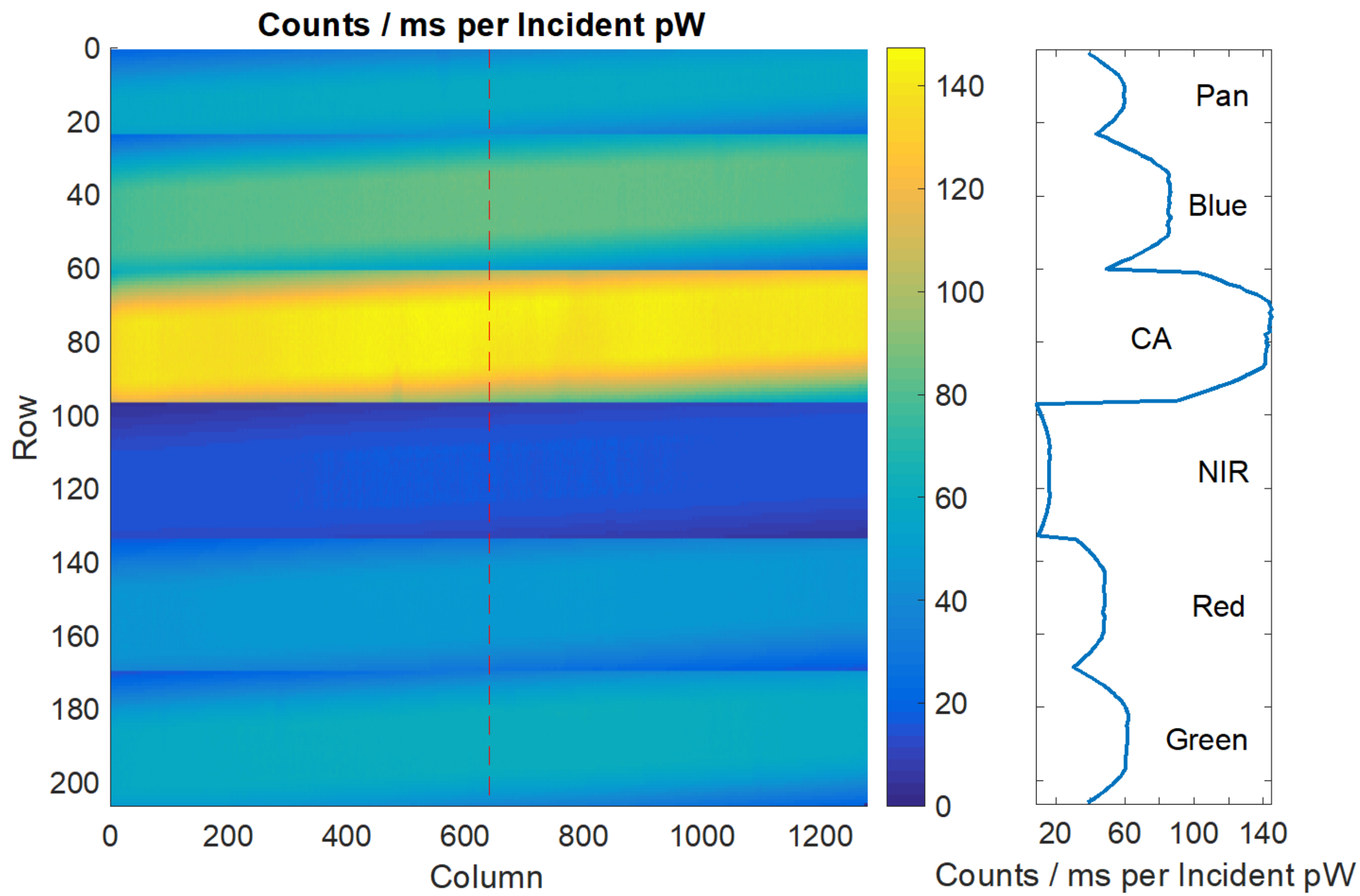
- Calibrated photodiode and narrowband filters used to calibrate illumination source



Flight Model Testing

Spectral response

- Filter spectral response used to determine count rate vs. incident power



Conclusion

- AC-11 R3 is intended to demonstrate the performance of a CubeSat (with a COTS sensor) for a mission typically performed by larger satellites: simultaneous, multi-spectral TDI imaging of the Earth's surface
- Thorough understanding and tuning of the COTS sensor is necessary in order to minimize electronic noise sources and to enable true radiometric calibration
- Anomalies were mitigated by constructing full-frame mosaic: reading out the entire FPA was key for anomaly resolution
- Low-light level performance dominated not by dark current but by unknown electronic noise source: on-orbit observation of dark voids in space may be necessary to generate dark frames for integration times not in look-up table
- Transmission varies by 100x from CA to Pan bands: will either saturate or have little signal in certain filters for all images
- Calibration tests show linearity and reciprocity reasonable for COTS sensor
- Spectral response tests enable radiance to be calculated in each spectral band for each image and improves accuracy of resulting data