Radiometric Flat Field Calibration Using Integration Time Dither

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Motivation for the work

- **Calibration has a tangible impact on sensor performance**
  - Uncorrected gain and dark offset nonuniformity becomes sensor noise
  - Detection performance of an area array imaging camera is optimal when correctable calibration error is less that the camera’s temporal noise floor
  - Sensor calibration attributes can change between ground calibration and launch, and over the mission lifetime in space
- **But not all sensors can afford to bring along flat field sources**
  - Calibration devices can be expensive, risky, prone to change, tricky to use and drive cost into the space sensor system
- **Time critical missions can not afford to take time off to calibrate**
  - Sensors that turn away to calibrate are not doing their primary mission
- **Commercial users may not have the time or know-how to calibrate**

Can integration time dither help to remove fixed pattern noise on the fly?

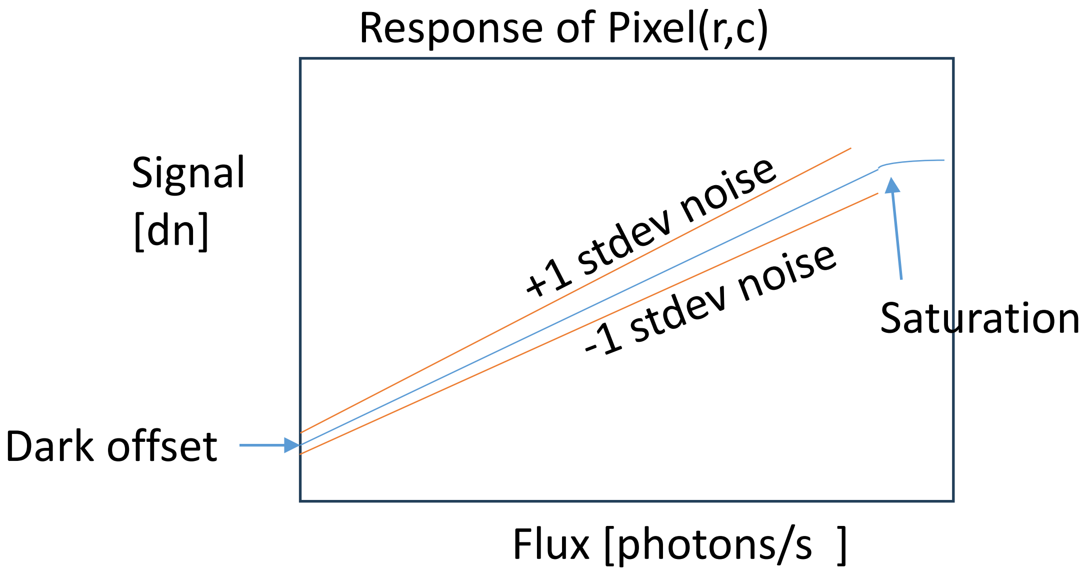
Calibration On-the-Fly Examples

- **Pointing Calibration**
  - A star camera may be used to detect resident space objects, and use the known stars as points of known RA/Dec reference
  - Earth viewing sensors may correlate a new image to an existing well geolocated image
- **Synthetic Dark Signal Correction**
  - Widenhorn developed synthetic dark signal correction methods for commercial cameras
    - Ralf Widenhorn, Armin Rest, Morley M. Blouke, Richard L. Berry, and Erik Bodegoma, "Computation of dark frames in digital imagers," Sensors, Cameras, and Systems for Scientific/Industrial Applications VIII, Morley M. Blouke, Editor, 650103, SPIE Proceedings Vol. 6501
  - Chrien showed that it was possible to continually update dark signal level in a star tracker or SSA sensor, by observing the dark between the stars while tracking detector temperature
    - Chrien and Pepe, “Synthetic Correction of Dark Signal Data in a Space Situational Awareness Sensor,” AMOS 2022
- **Absolute Radiometic Calibration**
  - Lockwood used regular passes over the Sahara to update the radiometric calibration of the ARTEMIS (TACSAT3) sensor
    - Lockwood, Ronald. On-Orbit Calibration and Focus of Responsive Space Remote Sensing Payloads
- **Scene-Based Non-Uniformity Correction**
  - Scribner used high pass temporal filter and artificial neural network
    - Non-uniformity correction for staring IR FPAs using scene-based techniques, SPIE Vol. 1308, (1990)
  - Tong Liu reports use of an adaptive progressive strategy base on Laplacian pyramids
    - Strong NUC algorithm based on spectral shaping statistics and LMS, Optical Express Vol 31 No. 19, (2023)

Can we use integration time dither for on-the-fly FPN?

Area Array Camera Model

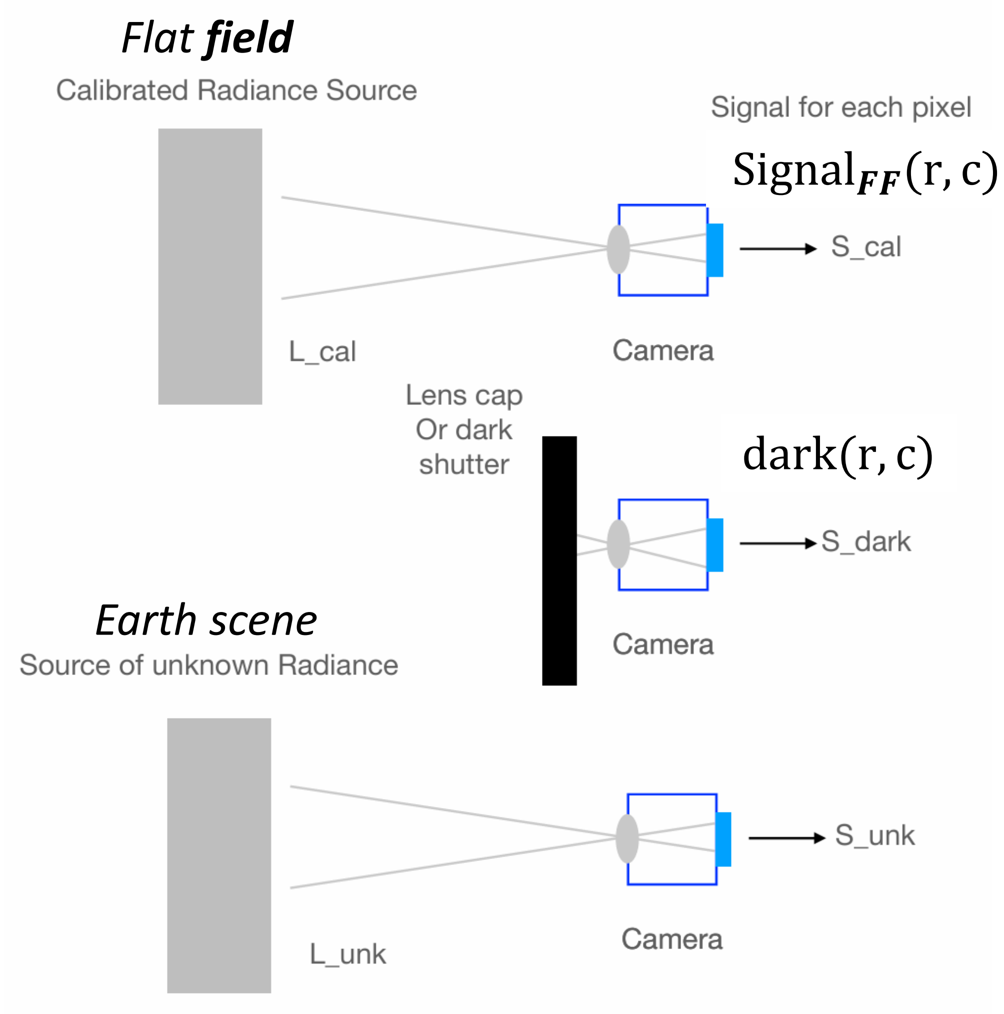
- **Camera consists of a 2-D array pixels in rows and columns pixel(r,c)**
- **Each pixel responds to input flux as shown on graph**
- **Offsets and gains vary on a pixel-to-pixel basis**
- **Each pixel has a read noise and photon noise contributions**
- **Int. time: t, det. Temp T**



- **Dark Offset(r,c,t,T) = Fat Zero + Dark current(r,c,T)*t + nearfield(r, c)*t**
- **Signal(r,c,t) = Gain(r,c)*Flux*t + offset(r, c)**

Modern detector arrays can change integration time frame-by-frame

Classic Determination of Flat Field Gain and Offset



- **Calibrated Radiance (Flat field source) consists of a uniformly illuminated screen**
- **Dark signal (with lens cap on)**
- **Gain(r,c,t) =** $\dfrac{\text{Signal\_}\boldsymbol{ave}_{\boldsymbol{FF}}(\text{r,c}) - \text{dark\_}\boldsymbol{ave}(\text{r,c})}{\boldsymbol{FF}_{\boldsymbol{Flux}} * \boldsymbol{time}}$
- **Flux(r,c,t) =** $\dfrac{\boldsymbol{Signal}(\boldsymbol{r},\boldsymbol{c}) - \boldsymbol{dark}(\boldsymbol{r},\boldsymbol{c})}{\boldsymbol{Gain}(\boldsymbol{r},\boldsymbol{c}) * \boldsymbol{t}}$
- **Many frames of flat field signal and dark are collected and averaged to suppress calibration noise**

CMOS Camera

- **MT9P031 Sensor Chip**
- **DMK27BUP031 Camera**
- **SharpCap 4.1 Image Capture Software**
  - Enables control of:
    - Frame rate
    - Integration time
    - Bit depth
    - Fat Zero offset
    - Window regions
    - File Format

Table 1. KEY PERFORMANCE PARAMETERS

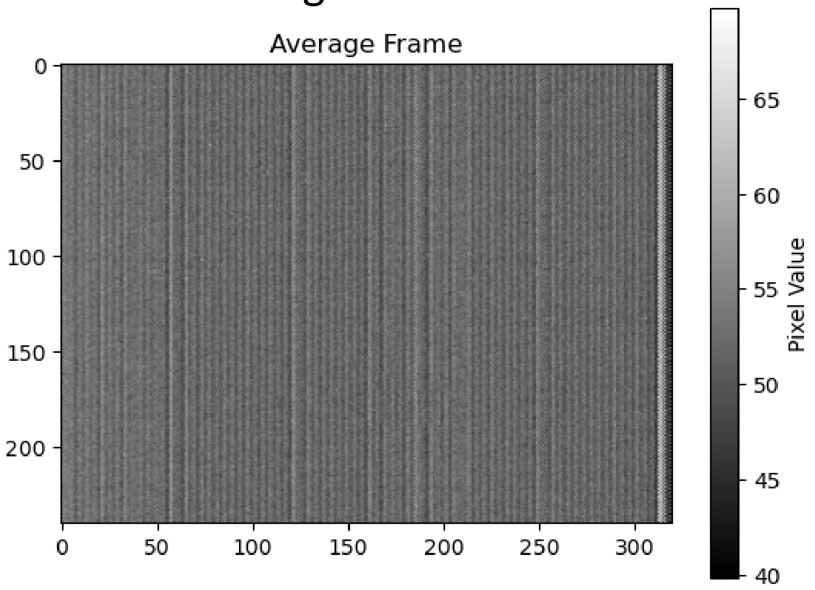
Parameter		Value
Optical Format		1/2.5-inch (4:3)
Active Imager Size		5.70 mm (H) x 4.28 mm (V) 7.13 mm Diagonal
Active Pixels		2592 H x 1944 V
Pixel Size		2.2 x 2.2 μm
Color Filter Array		RGB Bayer Pattern
Shutter Type		Global Reset Release (GRR), Snapshot Only Electronic Rolling Shutter (ERS)
Maximum Data Rate / Pixel Clock		96 Mp/s at 96 MHz (2.8 V I/O) 48 Mp/s at 48 MHz (1.8 V I/O)
Frame Rate	Full Resolution	Programmable up to 14 fps
	HDTV (640 x 480, with binning)	Programmable up to 53 fps
ADC Resolution		12-bit, On-chip
Responsivity		1.4 V/lux-sec (550 nm)
Pixel Dynamic Range		70.1 dB
SNR_{MAX}		38.1 dB
Supply Voltage	I/O	1.7–3.1 V
	Digital	1.7–1.9 V (1.8 V Nominal)
	Analog	2.6–3.1 V (2.8 V Nominal)
Power Consumption		381 mW at 14 fps Full Resolution
Operating Temperature		–30°C to +70°C
Packaging		48-pin iLCC, Die

We used these cameras in teaching PHYS3440/A -Applied Optics at CPP

Example Dark Offset From CMOS Camera

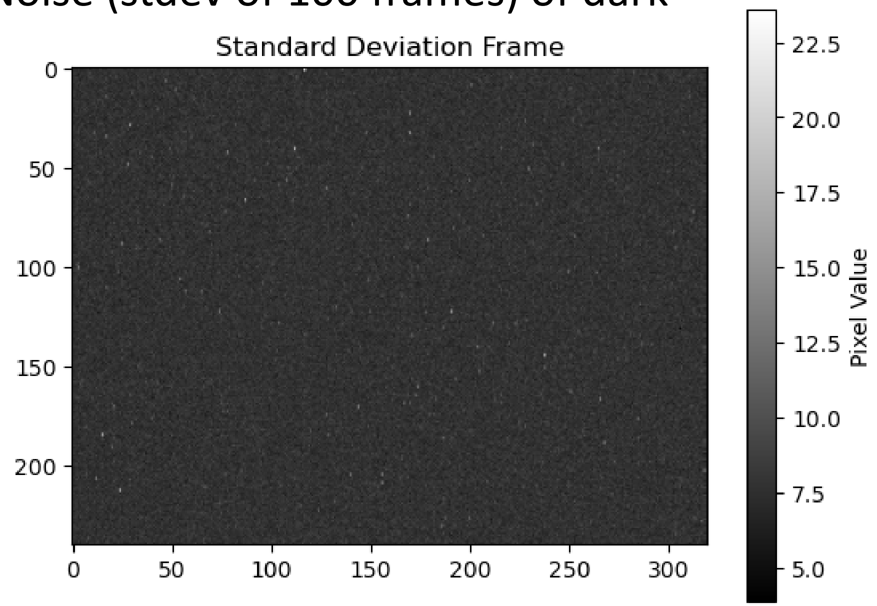
Fat Zero = 50 dn

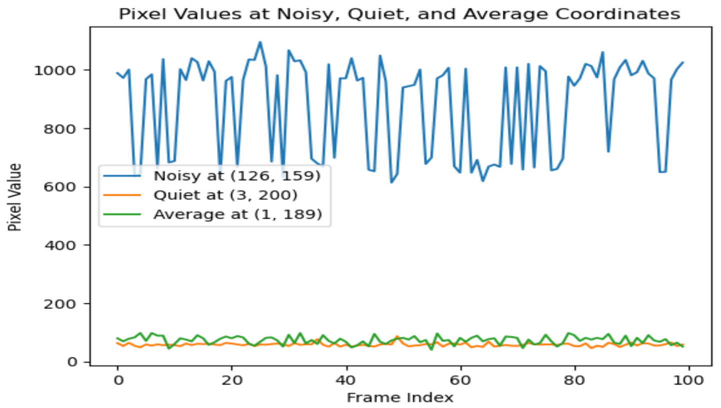
Dark Offset Signal



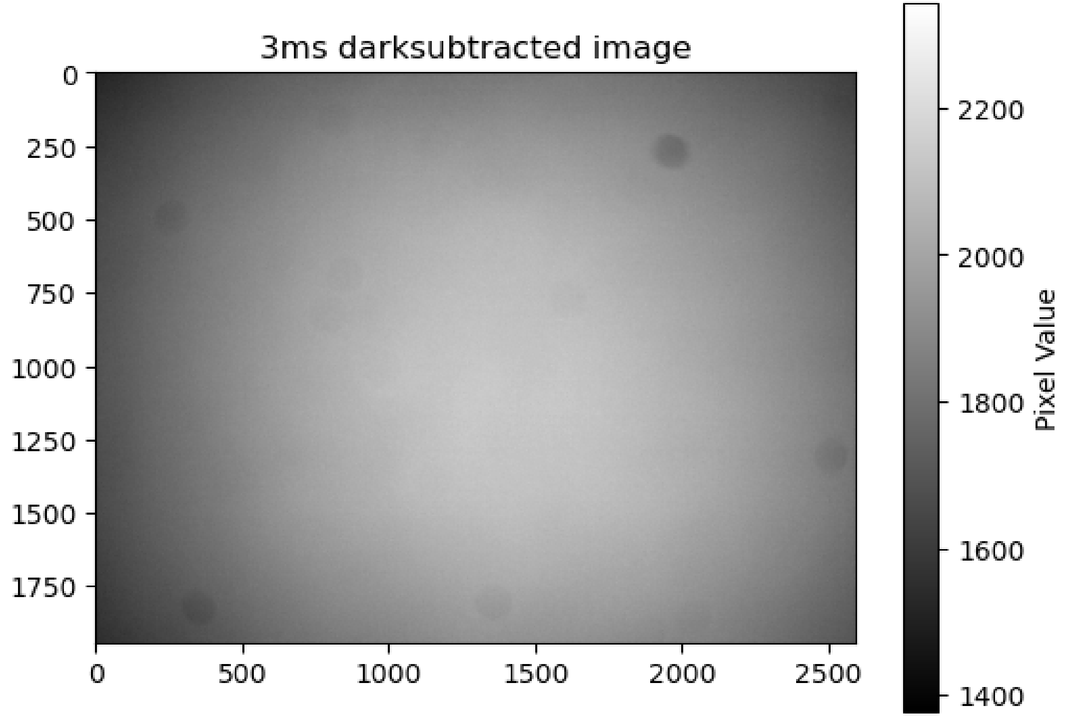
Dark Current Signal
After 2 sec, max dark current signal is < 4 dn at room temperature

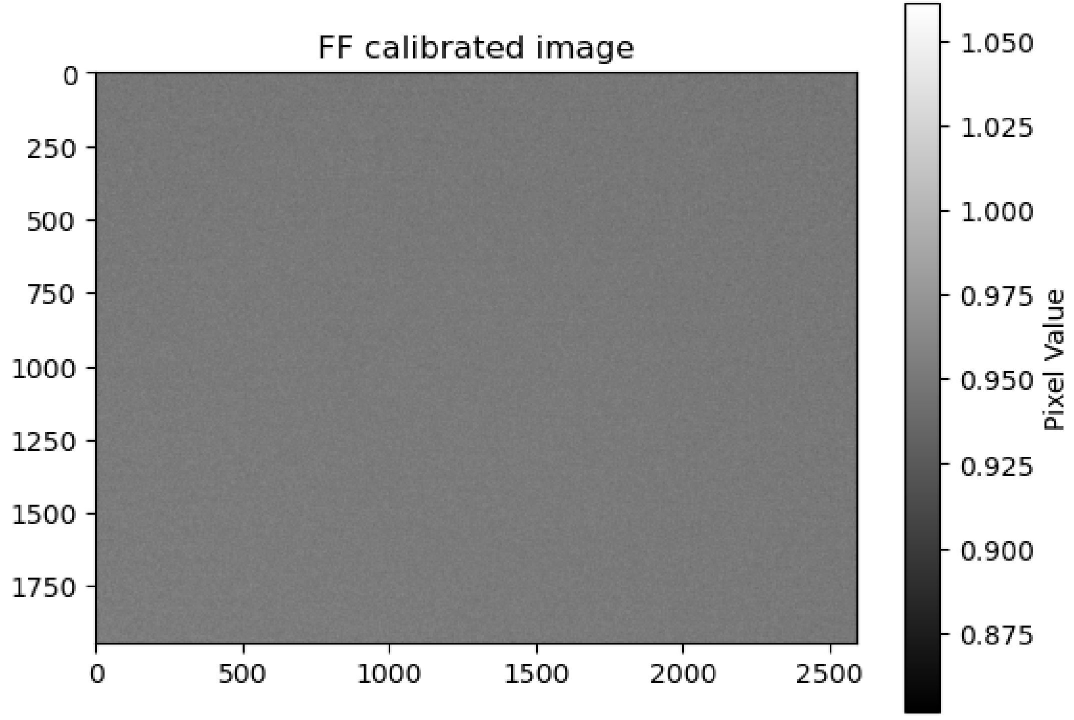
Noise (stdev of 100 frames) of dark





Flat Field Calibration Example

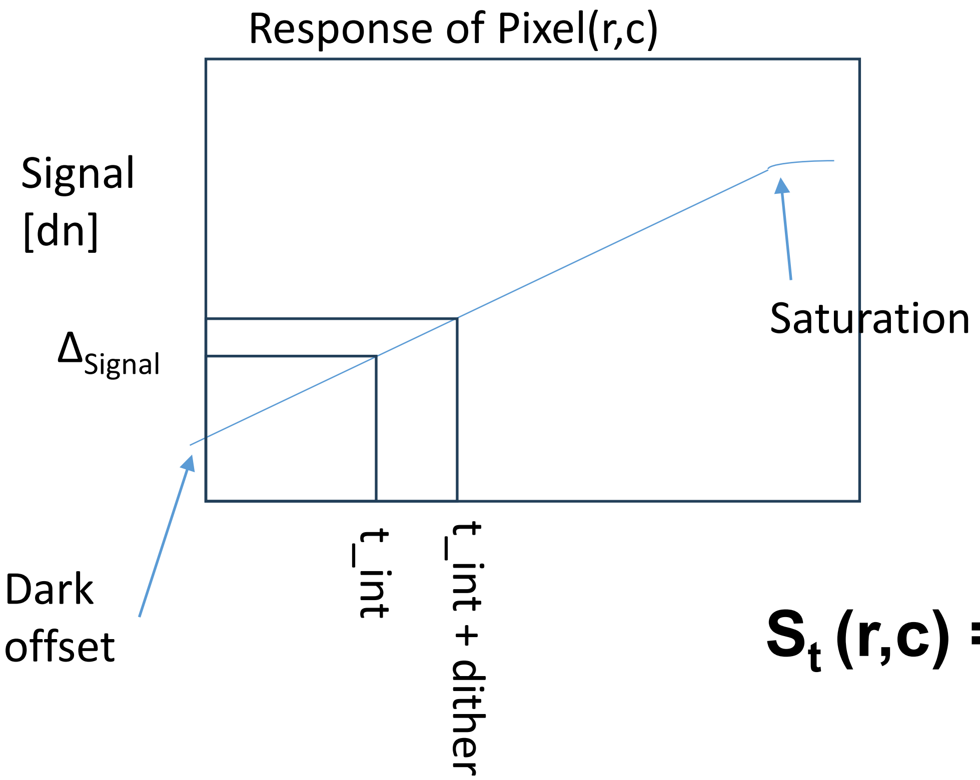




- **Single Frame collected at 3 ms, dark subtracted**
- **Percent noise: 7.36%**

- **Flat Fielded (4 ms gain)**
- **Percent noise: 2.03%**
- **(~temporal noise floor)**

Can Integration Time Dither Be Used Recover Offset?



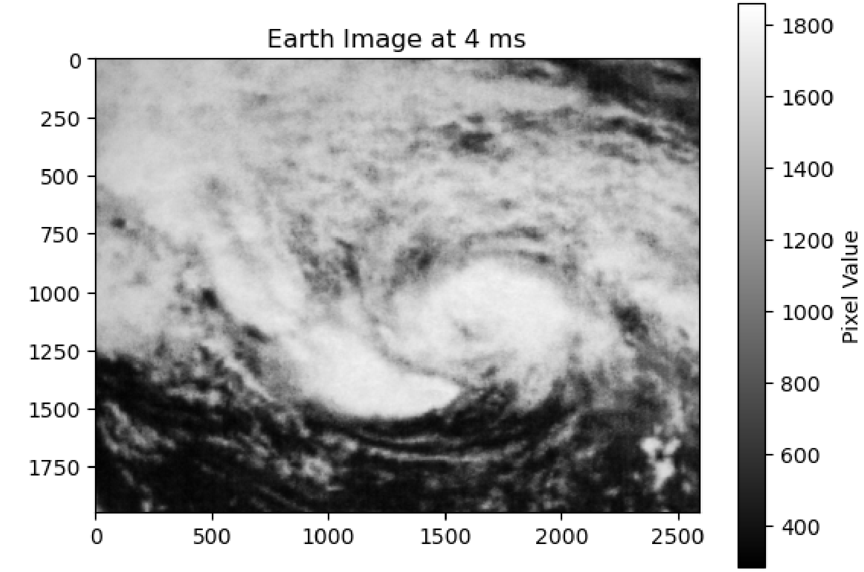
- **Heterogenous Earth scene flux and gain fall out of the equation for offset**

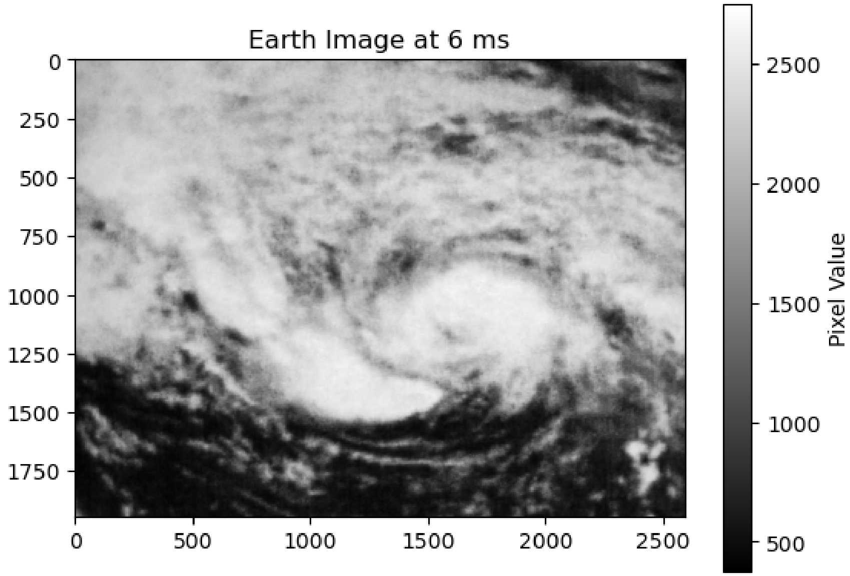
$$S_t\,(r,c) = Gain(r,c)*Flux(r,c)*t - Offset(r,c)$$

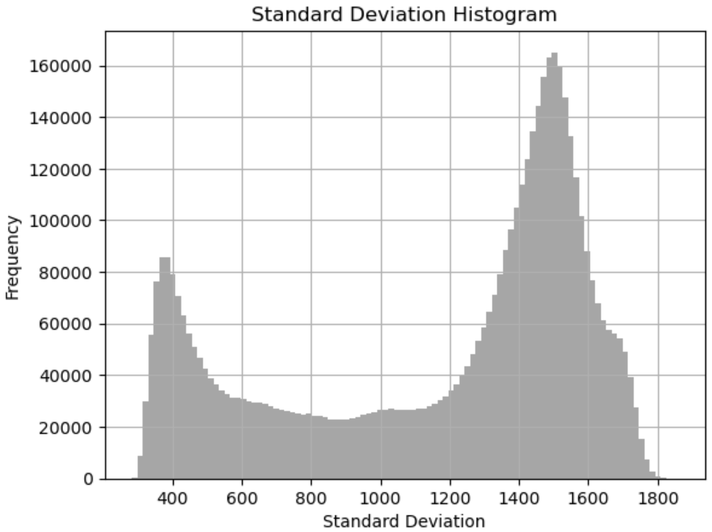
$$S_{t+\Delta t}(r,c) = Gain(r,c)*Flux(r,c)*(t+\Delta t) - Offset(r,c)$$

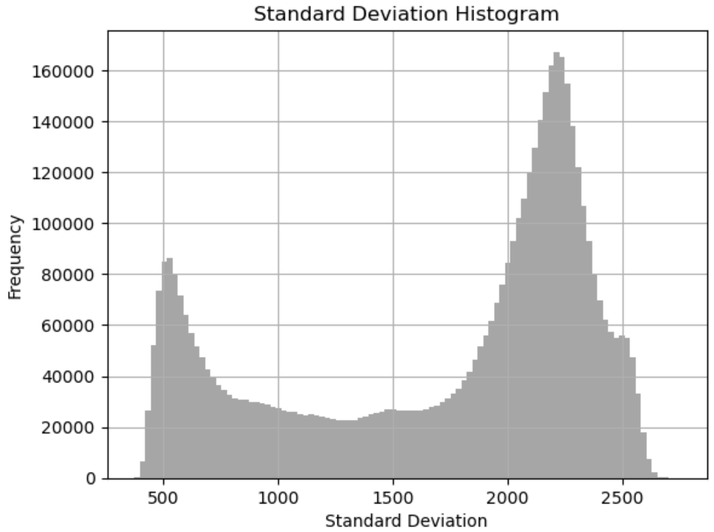
$$Offset(r,c) = S_t\,(r,c) - \{\Delta S(r,c)*/\Delta t\}*t$$

Calibration Using a Complex Cloud Image



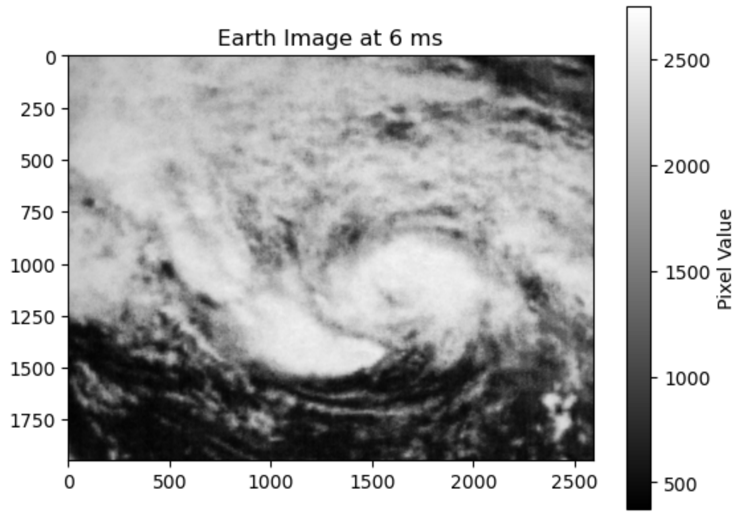


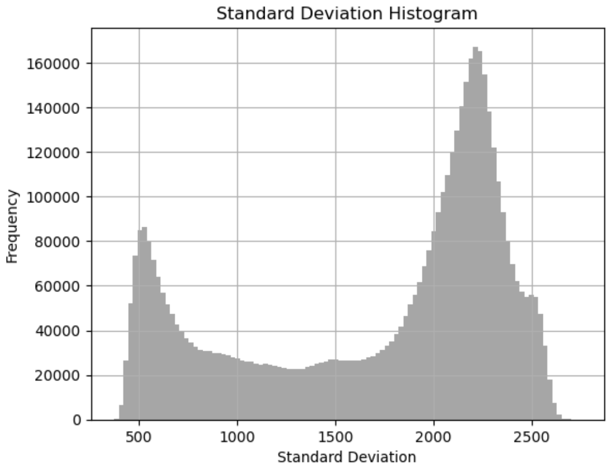


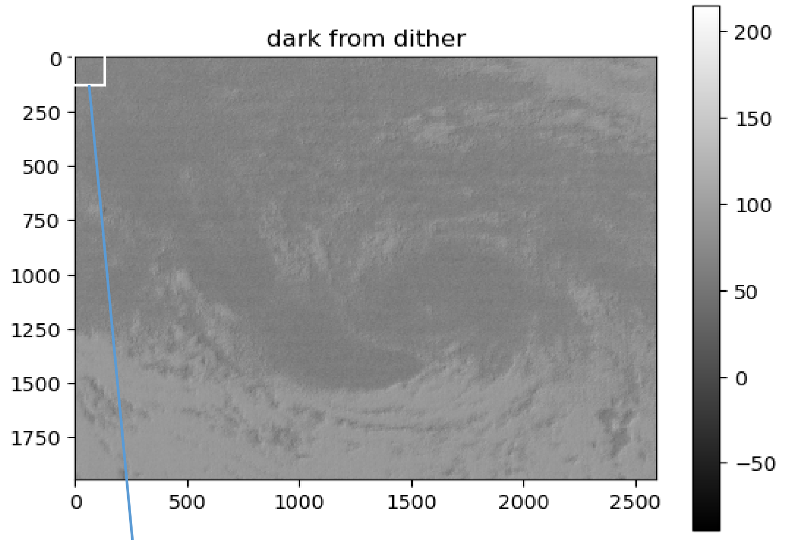


- **CMOS Camera image of printed MODIS cloud image**
- **Image taken at 4 ms and at 6 ms**

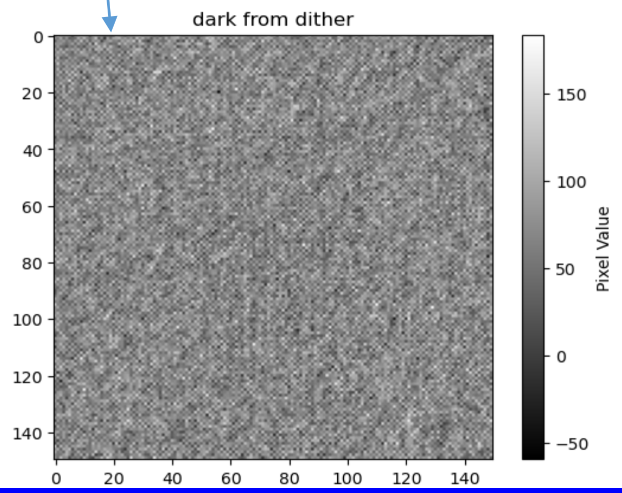
Dither Dark Compared To Measured Dark

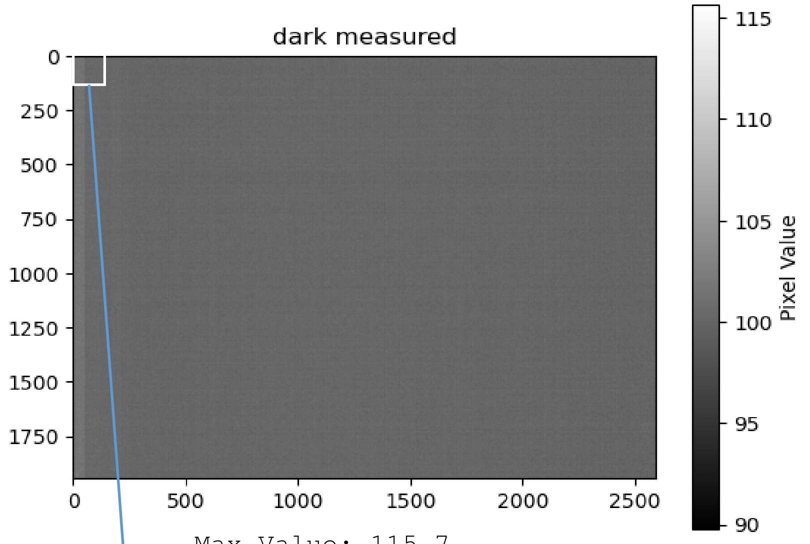







```
Max Value: 214.8
Min Value: -89.2
Mean Value: 73.2
stdev value 32.5
```



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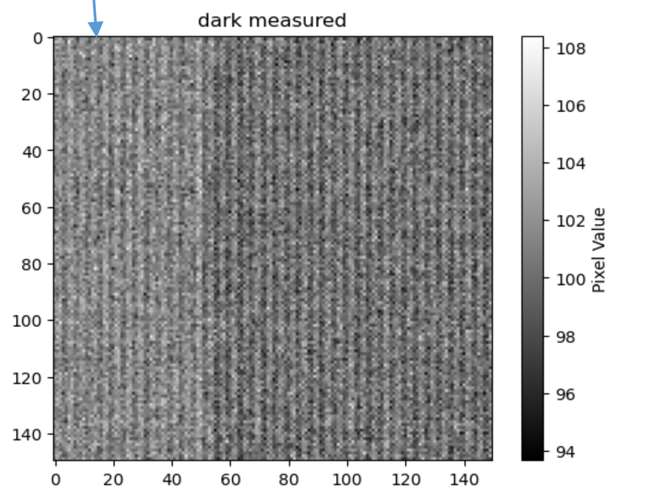
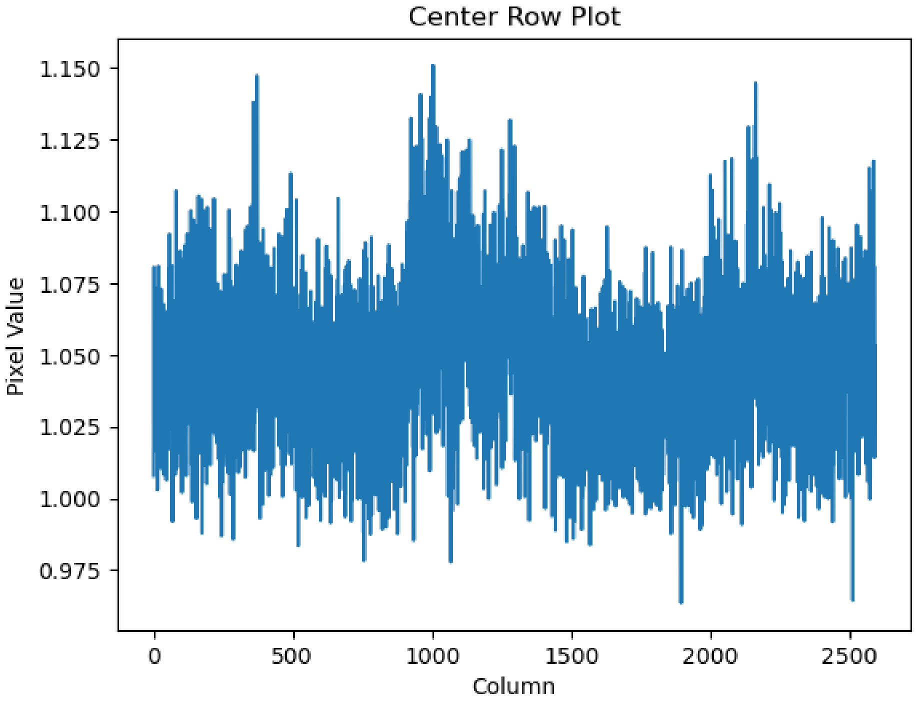
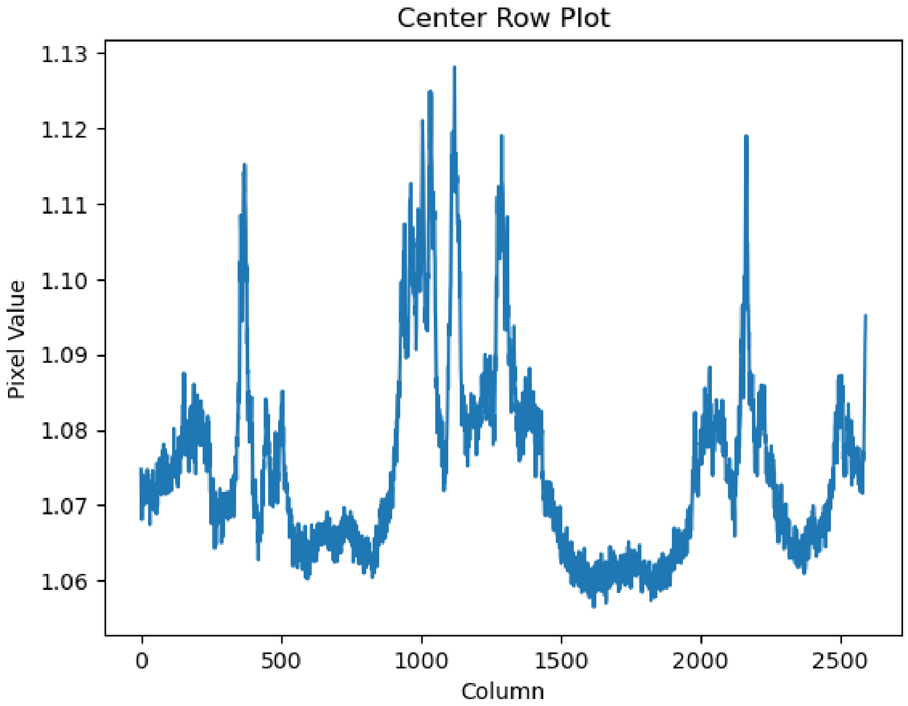
Max Value: 115.7
Min Value: 89.7
Mean Value: 100.2
stdev value 2.11
```



Dark offset patterns are recoverable, but are noisier, due to added signal noise

How does dither dark correction compare?

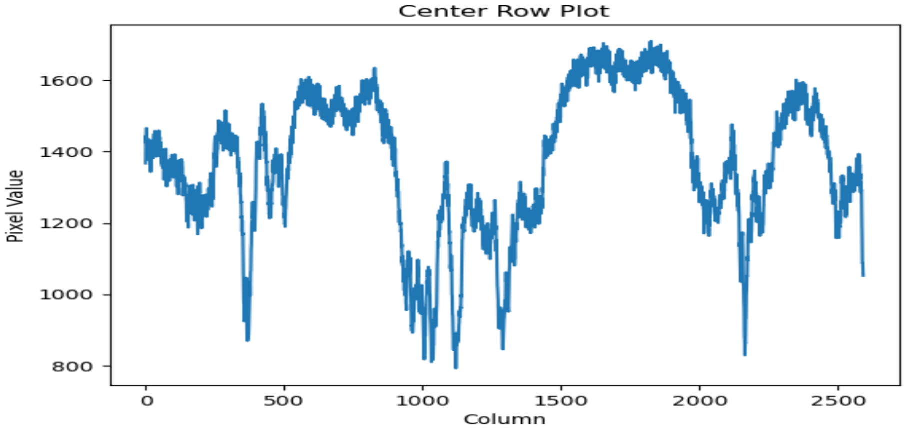




Ratio of Raw Signal to Dark corrected signal

- **Left: Dither dark from the ave of 30 sets of dithers**
- **Right: Traditional measured dark, ave of 30 frames**

Bottom: cross-track of corrected scene (measured dark)



Dither dark would require 1000's of sets to suppress noise level to measured dark levels

Target Detection Algorithms already Provide Some Calibration Correction

If the task at hand is to detect and missile against a cluttered Earth background, there are a number of existing algorithms

Frame differences suppress background and fixed pattern noise as the same time, while increasing contrast on a moving target

- Tends to remove fixed pattern noise by frame differencing

Principal Components Background Suppression

- Also helps to remove jitter-enhanced clutter
- J.A. Kirk, “Principal Component Background Suppression,” 1996 IEEE Aerospace Applications Conference Proceedings

Integration Time Dither Assessment

- **Can be used to estimate offset correction, However**
  - Offset Noise is higher due to higher scene photon noise
  - Dark current signal is a function of integration time
    - Must be known or small
  - Near field signal is a function of integration
    - Must be known or small
  - Previous works shows that these maybe modeled separately, but that requires time to characterize dark and near field signal
- **It does appear to be possible to use time dither to recover the gain term**
- **It is difficult to assess improvement due to offset correction**
  - Noise assessment is easier on a flat field