Jet Propulsion Laboratory
California Institute of Technology

Instrument Level Tuning and Calibration of ExCam and LoCam

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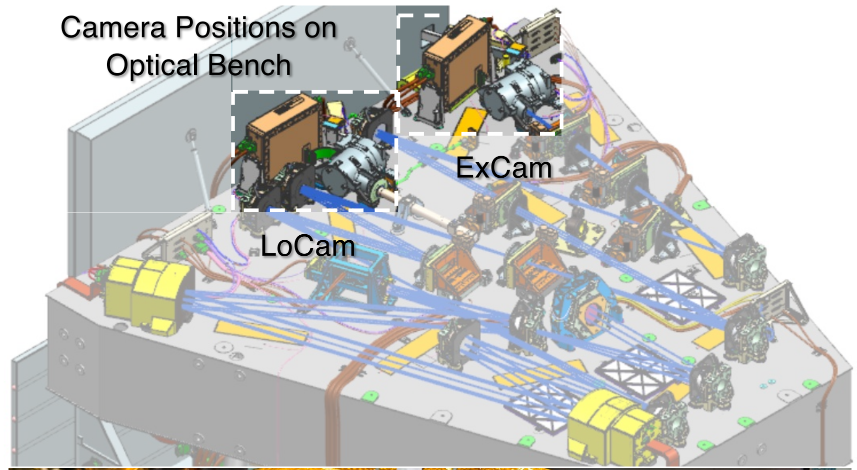
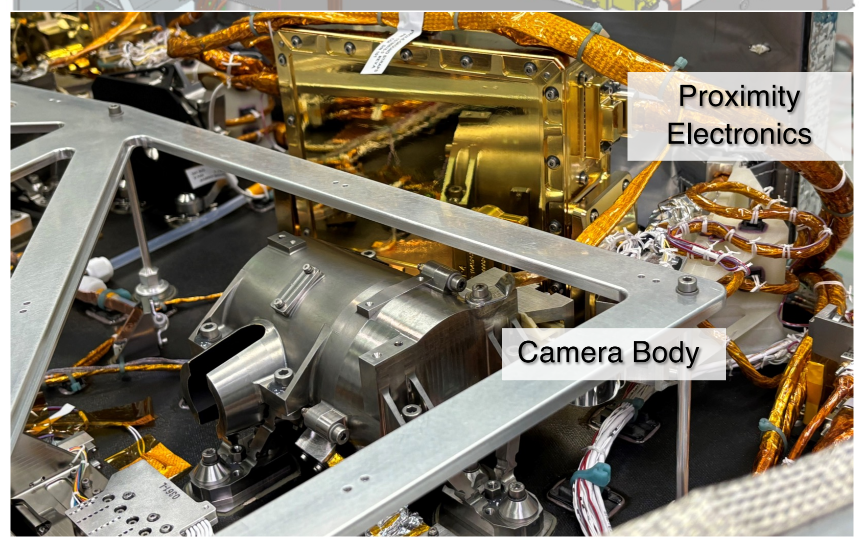
The Roman CGI Cameras

- Roman CGI has two camera systems - ExCam and LoCam:
  - LoCam: The Low Order Wavefront Sensing Camera. Operates at 1000 FPS in a 50x50 pixel window. Operates continuously in LOWFS loop with flux as high as 10^7 counts/pix/s – the starlight reflected off the Focal Plane Mask.
  - ExCam: The Exoplanetary Systems Camera. Operates with flux ranging from 10^4 down to 10^{-2} counts/pix/s. Images the “dark hole” created through the HOWFSC loop.
- The camera subsystems are comprised of three major components:
  1. A radiation hardened EMCCD detector, provided by the European Space Agency.
  2. A Proximity Electronics module, manufactured by ABB in partnership with Nuvu.
  3. A tungsten-copper camera body, designed and manufactured at JPL, which significantly reduces the radiation exposure of the EMCCD. Designed for a 5 year lifetime.

  Each camera is mechanically and electrically identical, but customized through internal camera software.





The EMCCD

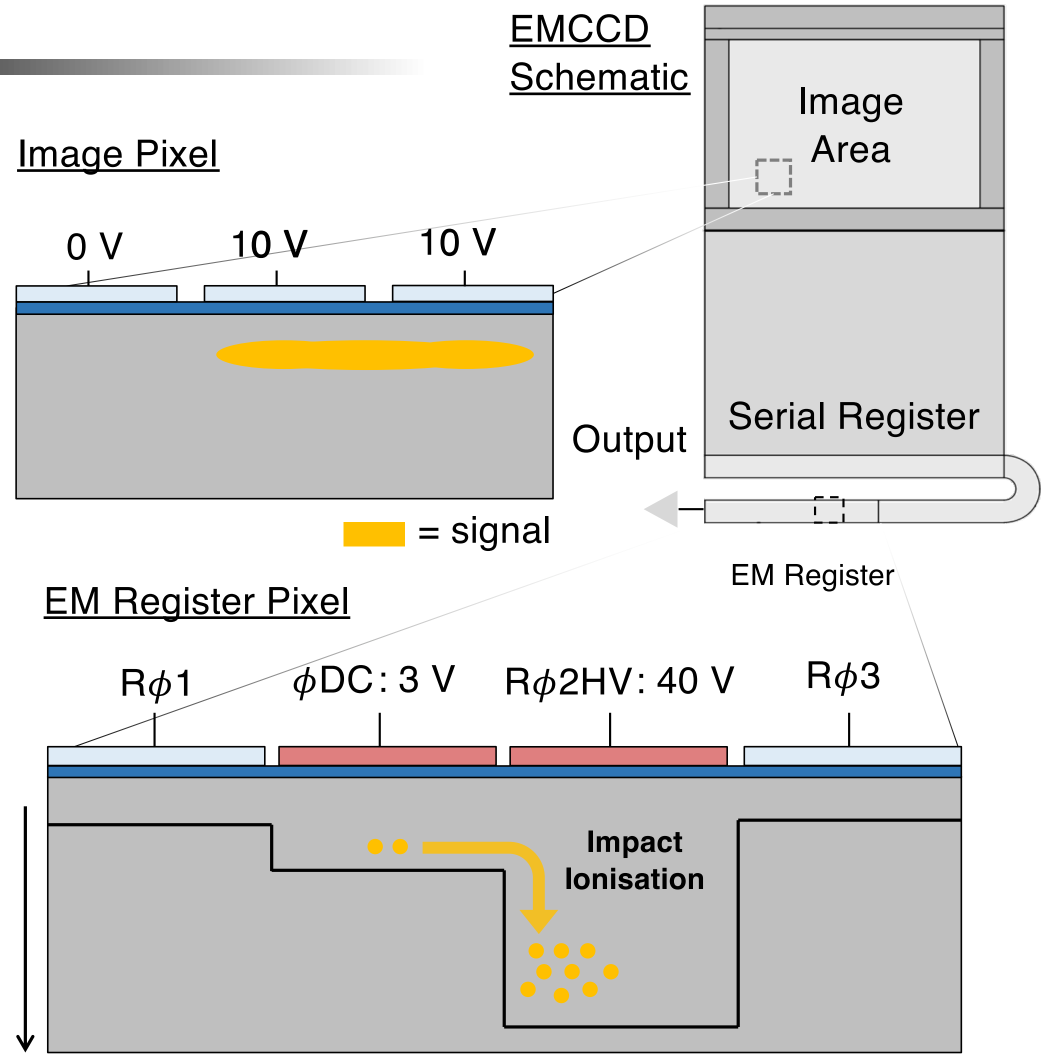
- **E**lectron **M**ultiplying **C**harge **C**oupled **D**evice (EMCCD). Similar to a standard CCD, but with an additional Electron Multiplication (EM) register.

- Read Noise reduced by applied EM gain. Three use cases:

  - Unity gain “CCD mode”. High signals, shot noise limited.
  - Analog Mode; operation whereby EM gain is used to reduce detector read noise. (LoCam + HOWFS).
  - photon counting mode - Gains of a few thousand combined with thresholding. ExCam has this capability for post processing.

- Noise considerations differ compared to standard CCDs:

  - In analogue mode, generally the EM gain is increased until read noise < shot noise.
  - In photon counting mode, dominant noise sources become thermal dark signal and Clock Induced Charge (CIC).



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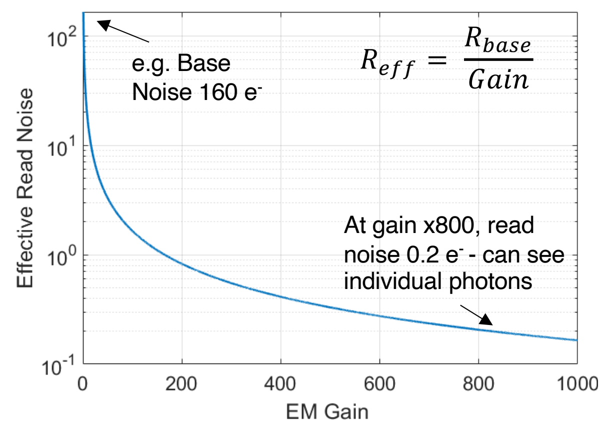
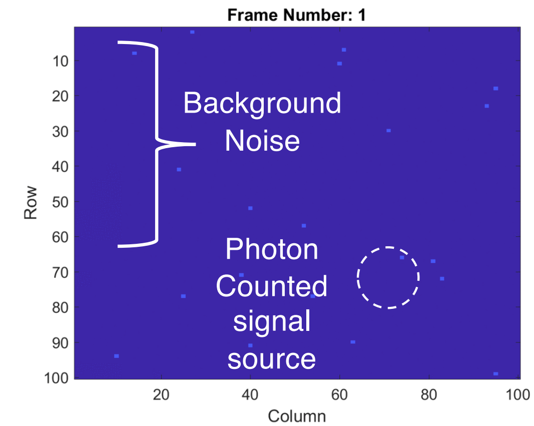
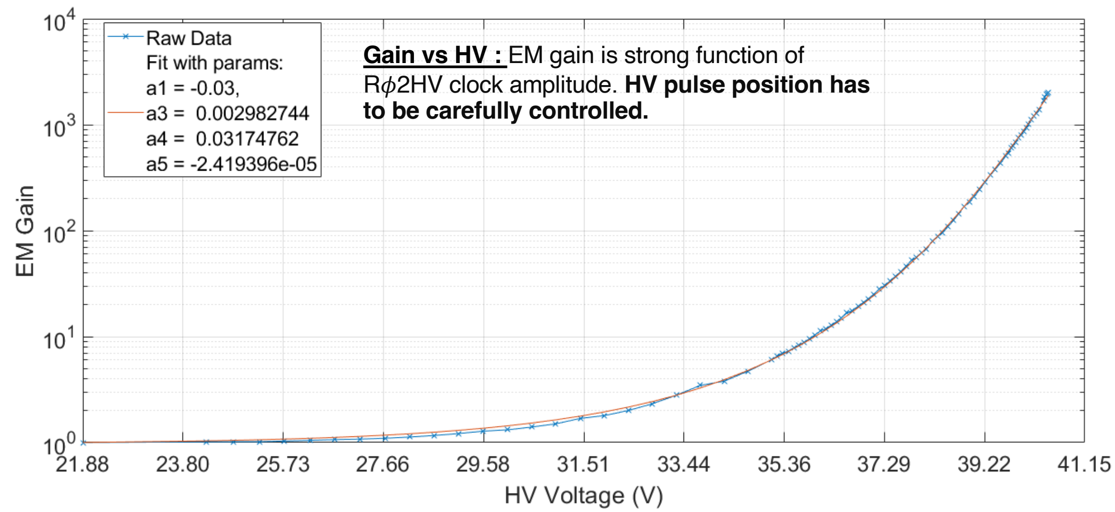






Proximity Electronics

- The CGI Camera Proximity Electronics (CPEs, “Prox-E”) were procured through a partnership between JPL, Nuvu and ABB. Adaption of a commercial controller for space applications.

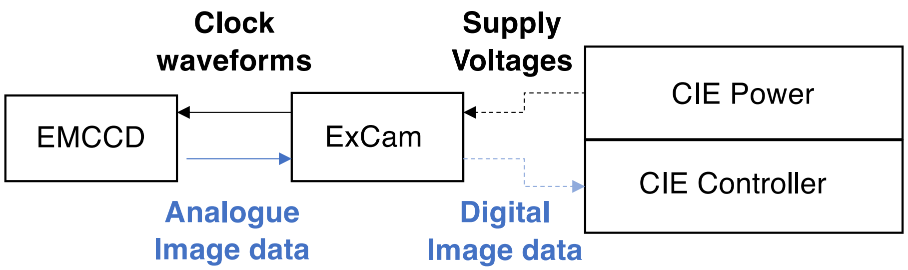
- Modifications to waveform control reduced power consumption from 50 W to ≈ 15 W.

- The Prox-E generates all clock pulses to drive the EMCCD. It also takes the EMCCD output, digitizes it and passes the data to the CIE controller/LOWFS slice.

- 10 MHz serial clock rate, timing resolution of 3.125 ns. Triangular pulses for vertical clocks and “RC” shaped horizontal clocks. EMCCD HV clock is generated via a sinusoidal resonant circuit.

- Timing, position and amplitude of pulses is fully programmable. The collection used to generate an image is termed the “Readout Sequence”.

- **Different readout sequences allow the customization of each camera as e.g. ExCam or LoCam.**



Animations edited for conceptual illustration only and do not represent up-to-date simulations of the waveforms used on the device.

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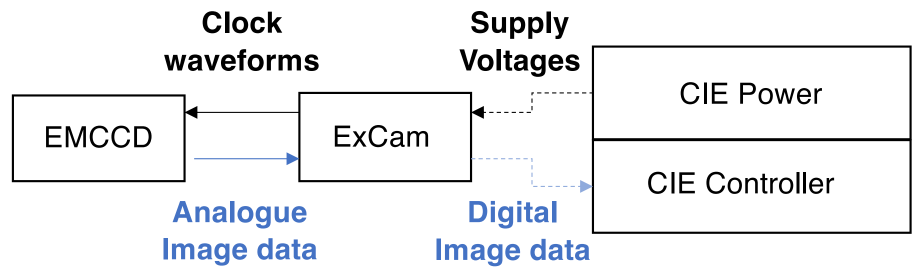

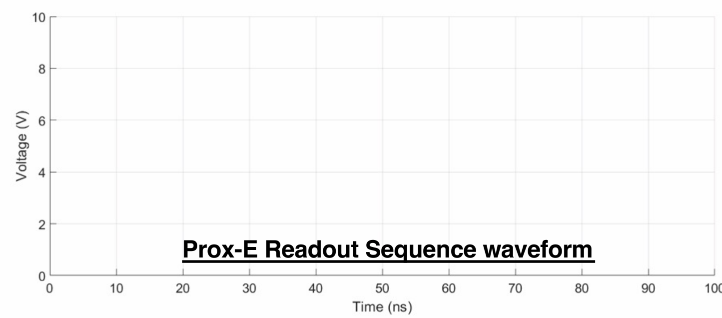

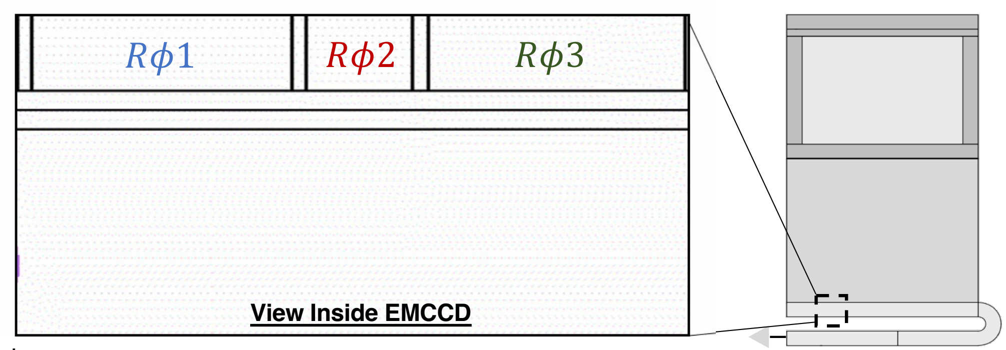

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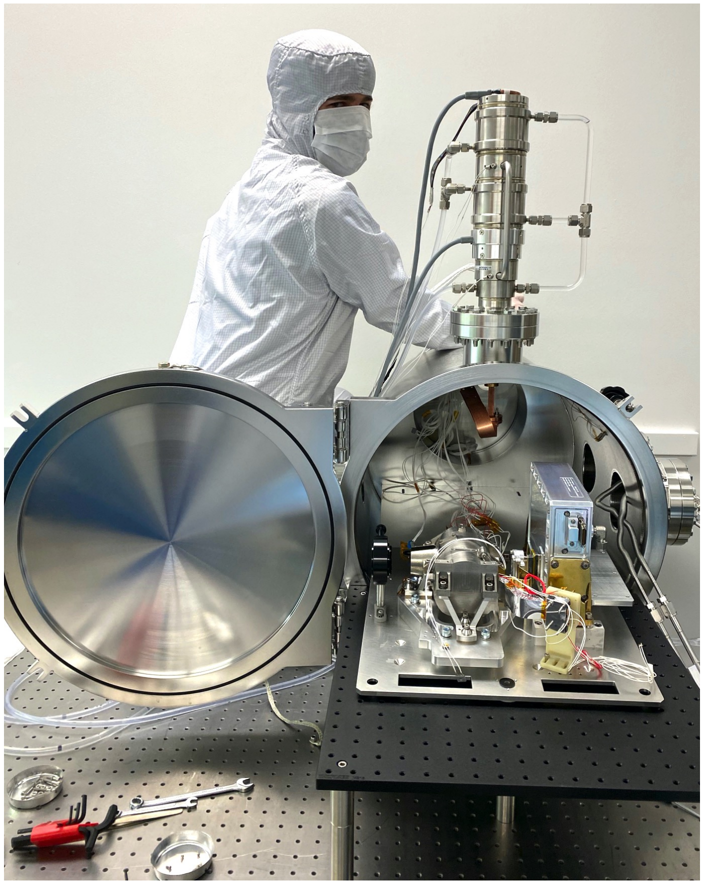
ExCam/LoCam Requirements + Pre Delivery Validation

- Table 1 summarizes key requirements for each camera, some more applicable to ExCam than LoCam.
- Pre delivery testing was performed with camera subsystem, CIE power supply + ABB EGSE. Testing was as flight-like as possible (grounding, cables etc.) but still not fully representative of the integrated subsystem.
- Requirements met with large margin in most cases.
- Delivery to II&T in fall of 2022, ready for alignment and integration.

Table 1: Summary of key ExCam and LoCam Camera Subsystem Requirements and results

Measurement	Requirement	ExCam	LoCam
Read Noise (e^-)	200	108	106
Image Area Full Well Capacity (ke^-)	50	78	98
Serial Register Full Well Capacity (ke^-)	90	105	119
Parallel Charge Transfer Inefficiency	$< 5x10^{-5}$	1.29×10^{-6}	1.04×10^{-6}
Serial Charge Transfer Inefficiency	$< 5x10^{-5}$	1.45×10^{-5}	1.40×10^{-5}
Thermal Dark Current 188 K (e^-/pix/hr) (req. applies to 95 % of pixels at BOL)	< 1.65	1.65	Not Applicable. Estimated at $\approx$15
Average Thermal Dark current (188 K) e^- /pix/hr	--	1.11	10.08
Unity Gain Non-linearity (%)	< 4	< 0.5	< 0.5
Clock Induced Charge e^-/pix/frame	0.01	0.0129	Less Applicable – 0.020

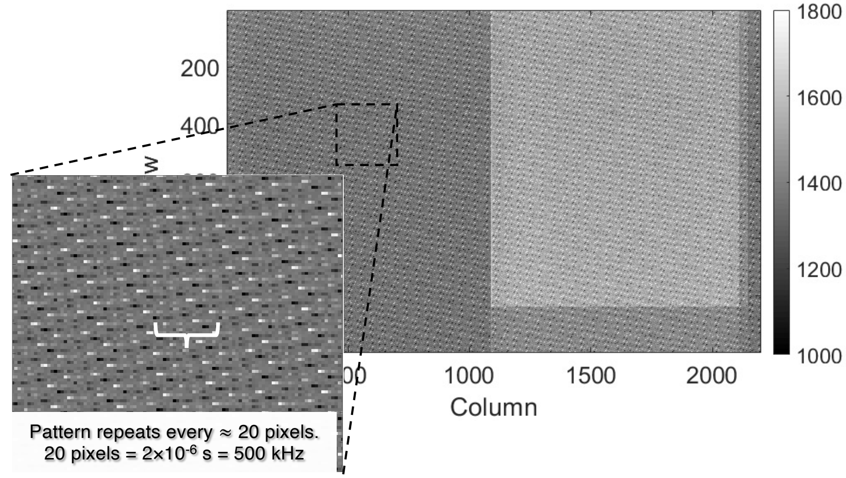
L5 Test Setup for camera performance evaluation



Instrument Effect #1: Excess Noise

- Cameras were first powered on as part of “Aliveness” testing and showed estimated read noise of 750 e^-, compared to room temperature pre-delivery value of 140 e^-.
- Investigations performed at Functional Test Bed revealed grounding loop due power supply cable. Noise performance improved when internal cable shields were disconnected from the connector backshell for the power cable.
- This change was implemented for each camera, as well as additional changes to both improve noise performance and reduce susceptibility to EMI/EMC:
    - Thicker ground straps + reduced path length where possible.
    - Installation of “bleed resistors” to remove direct path of chassis ground to internal CCD headboard traces.
- Best room temperature result was 140 e^-. Consistent with pre-delivery and functional test bed results for room temperature operation. Note this was prior to complete instrument assembly.
- Change to grounding configuration impacted the waveforms used to drive the device – **became clear that both ExCam and LoCam would require “re-tuning” when cooled to nominal operating temperature.**

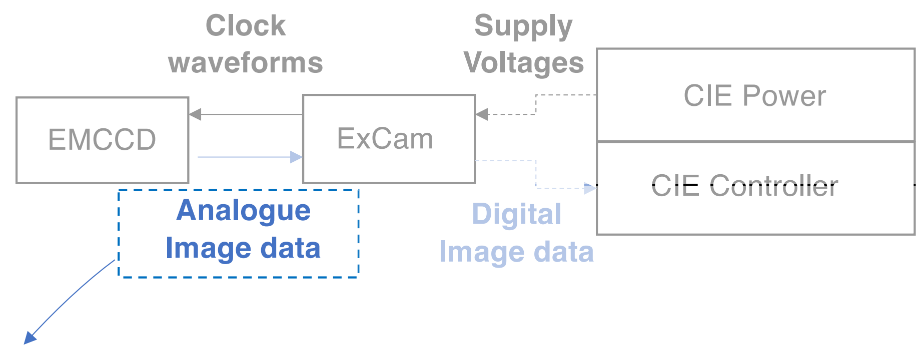
ExCam Aliveness Test Image

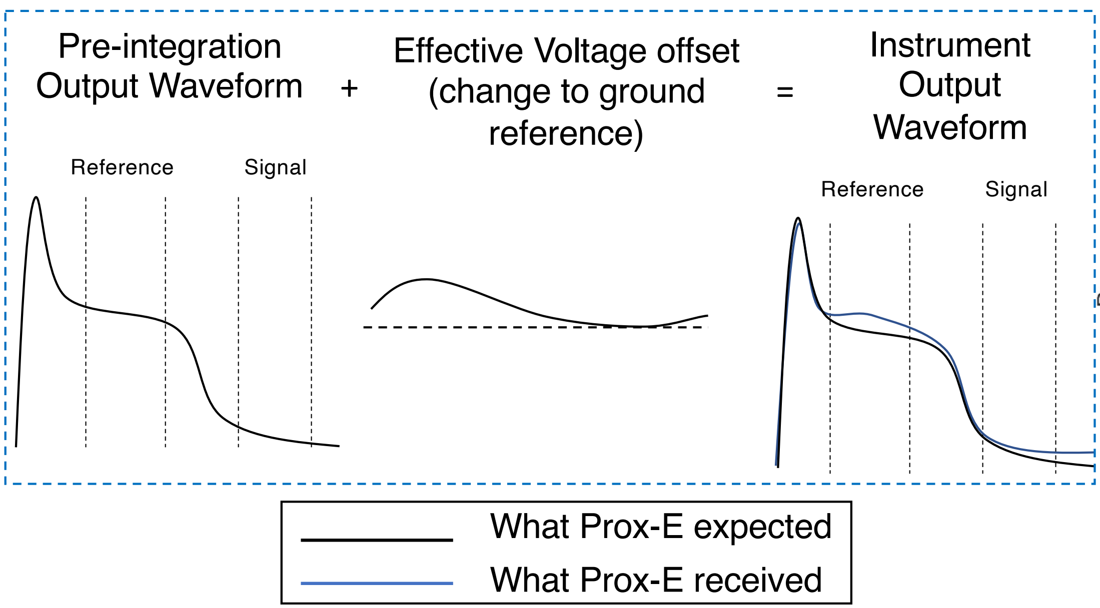


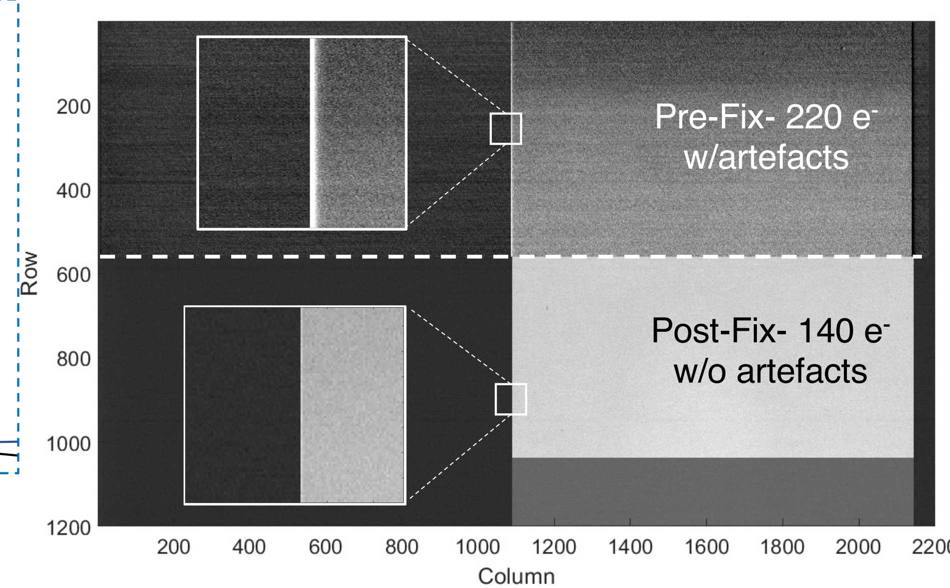
Instrument Effect #2: Overshoot/Undershoot

1. Matching the “Analogue Front End” (AFE) settings of the camera with the modified EMCCD output waveform:

   - Change in grounding configuration resulted in a suspected change in form of EMCCD output waveform.
   - Prox-E waveform settings were modified to accommodate the new configuration. **Reset pulse narrowed by 3.125 ns.**







Retuning EM gain

When the cameras were cooled, Changes to grounding and electronics interface temperature meant EM gain response was less than expected compared to pre-delivery results:

ExCam (pre-tuning)		LoCam (pre-tuning)	
Commanded	Measured	Commanded	Measured
50	33	50	20
200	96	200	68
400	163	1000	250

The “tuning” involves aligning the Rϕ2HV waveform correctly for optimum EM gain and linearity performance:

- The CGI cameras utilize a sinusoid resonant circuit for the Rϕ2HV clock that provides EM gain.

- Rϕ2HV must peak when charge is released from Rϕ1 for optimum EM gain. If not aligned:

    - May not achieve high EM gains (for severe cases)
    - Non-linearity is increased.

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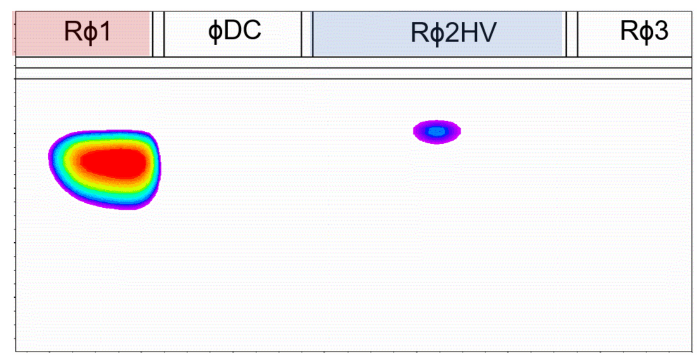
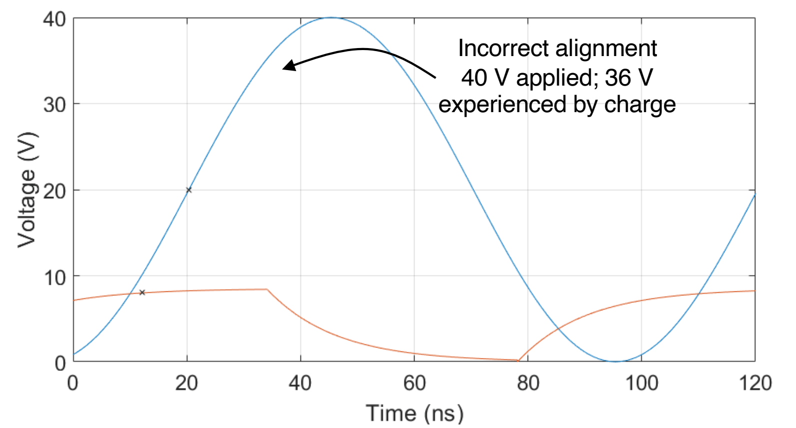
Example: Misaligned Rϕ2HV





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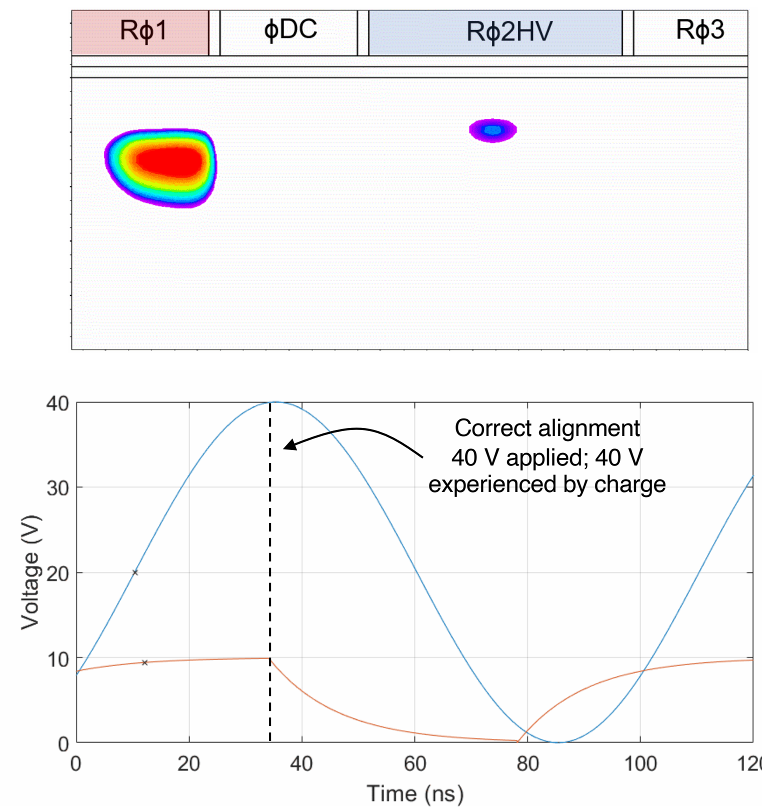
Example: Aligned Rϕ2HV



EM gain Tuning

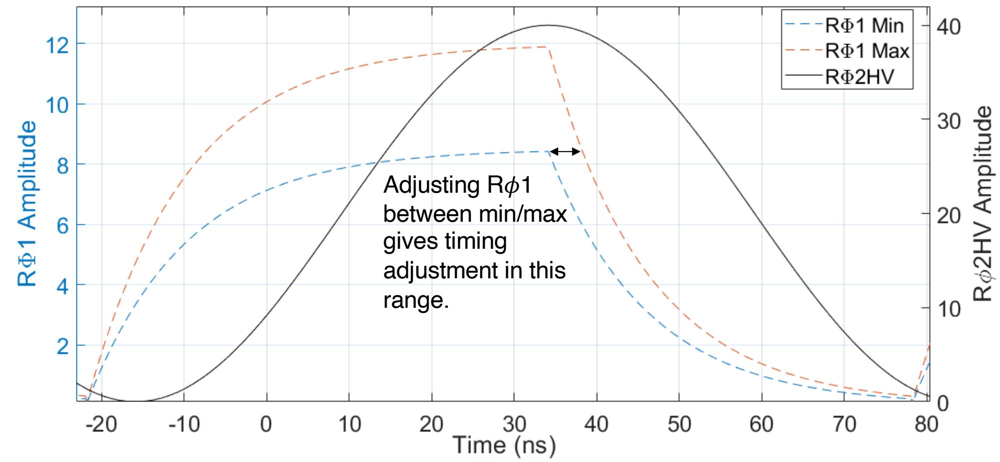
Complications:

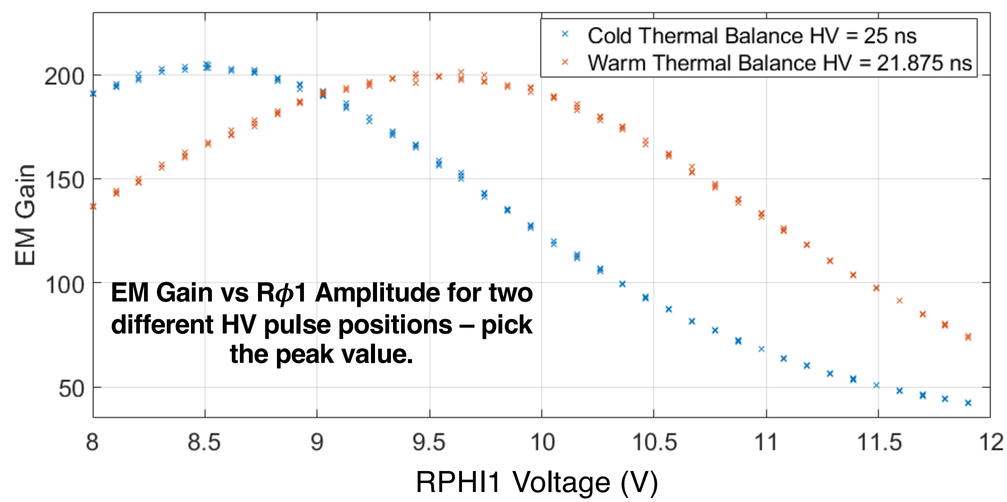
1. 3.125 ns resolution on HV. Not enough for perfect alignment. We improve alignment by adjusting Rϕ1 amplitude – provides *effective* >0.125 ns resolution. Novel technique developed for CGI.

2. HV pulse moves location with a change in Prox-E interface temperature. Estimated motion of approximately 3.5 ns per 10 ℃ based on TVAC measurements.

- Process:
    1. Stabilize Prox-E interface temperature.
    2. Change position of HV pulse (+/- 3.125 ns).
    3. Sweep through Rϕ1 amplitudes and chose value for maximum gain. This corresponds to charge being released at the peak of Rϕ2HV.

- Tuning was completed for both warm and cold thermal balance flight cases. Readout sequences updated, with backup files available for debugging should they ever be needed.

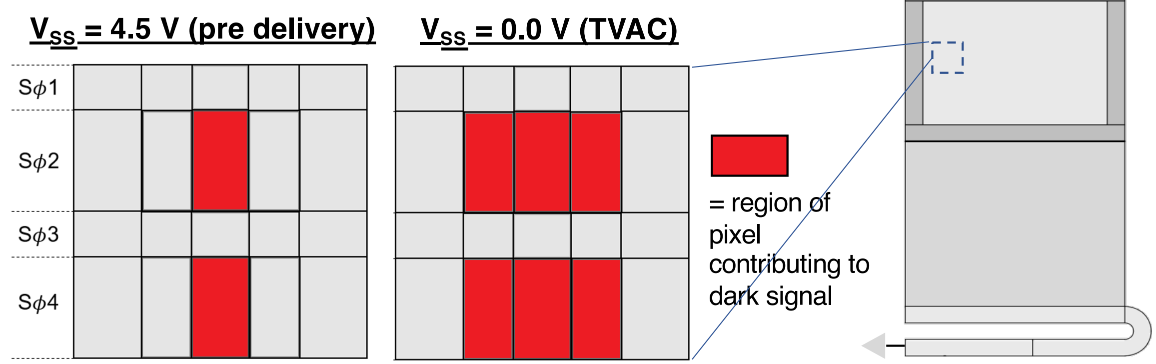


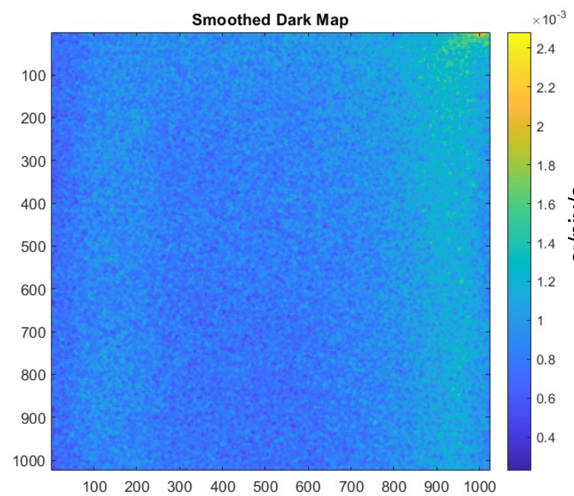


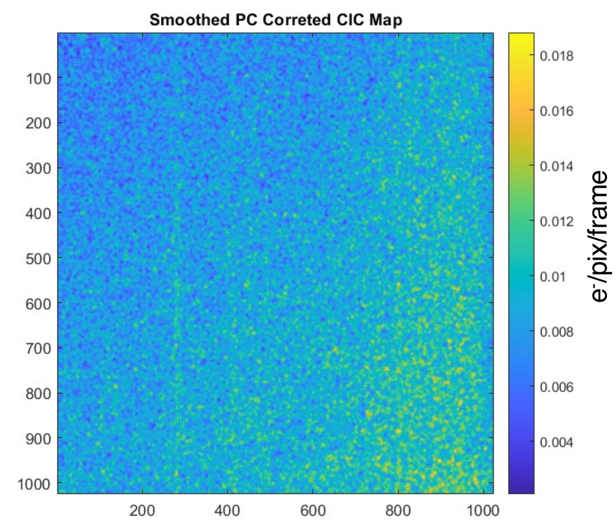
TVAC Calibration #1: Dark and CIC

- As part of tuning, the Substrate Voltage (V_{SS}) was changed from the default 4.5 V to 0 V. The result was an increase in baseline average dark signal to 3.6 e-/pix/hr.
- ExCam nominal operating temperature is -88℃. This temperature was chosen to reduce effects of Charge Transfer Inefficiency (CTI). As the sensor is cooled further, serial charge transfer degrades in high gain mode.
- Sensor can be cooled further as mission progresses to mitigate the effect of thermal dark current and charge trapping sites.
- Clock Induced Charge measured as 0.0088 e-/pix/frame when operating at DQE = 90 % (Requirement specification). This is a decrease from the L5 result, and correlated with the change in V_{SS}.

CCD311 Image/Store Pixel Cartoon







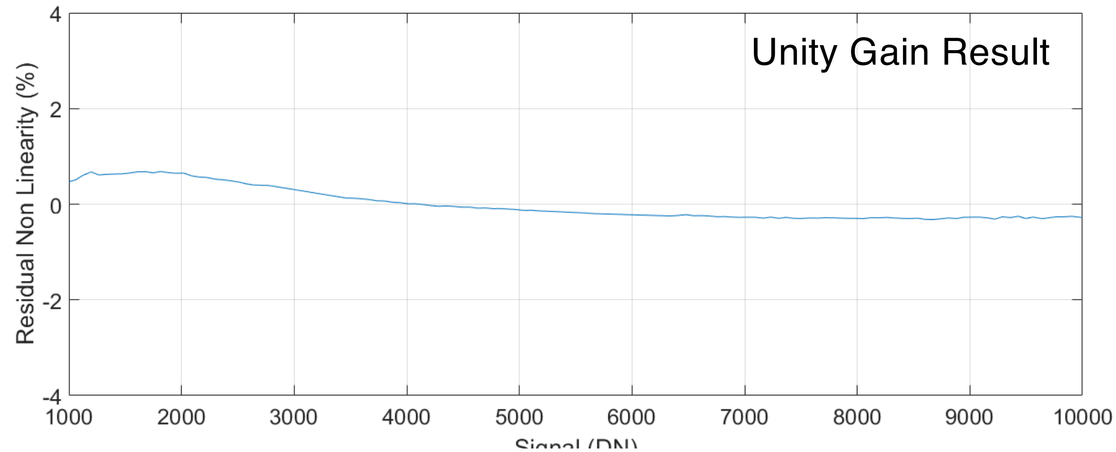
TVAC Calibration #2: Linearity

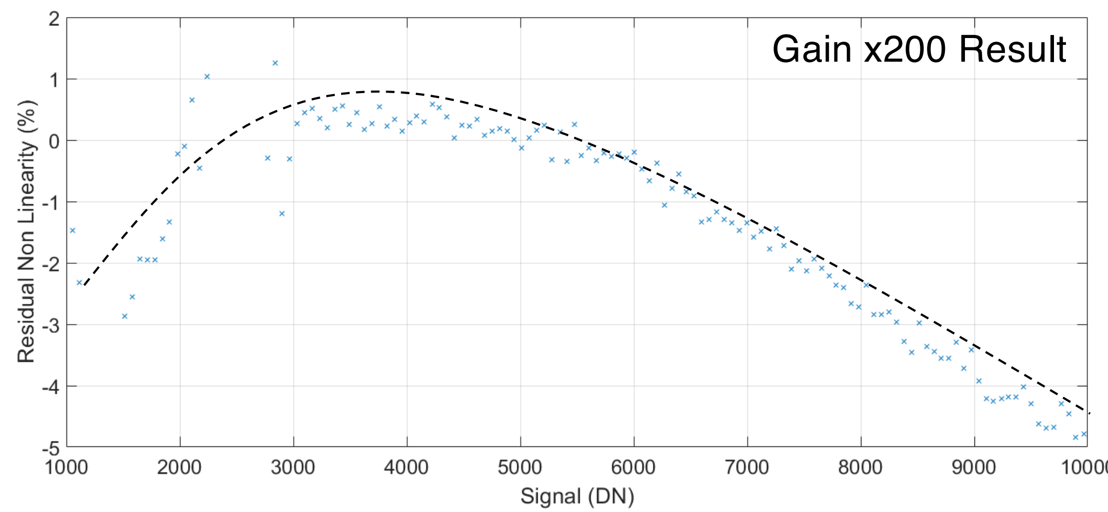
- Linearity; the deviation of calibration as a function of input signal. Reported as a % deviation from the normalization point, chosen as 50 % of Full Well Capacity.

$$NL = 100\left(1 - \frac{S_M/t_M}{S/t}\right)$$

NL = Non-linearity (%)
S_M = Midpoint signal
t_M = integration time corresponding to midpoint signal
S = Signal Levels across dynamic range
T = integration times across dynamic range

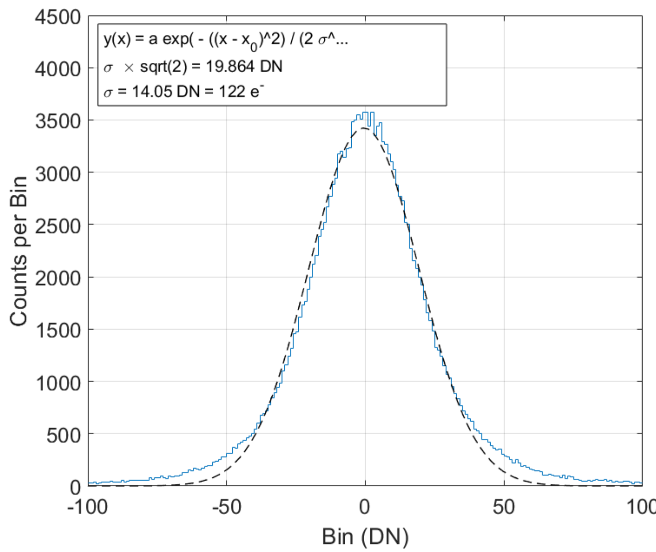
- Re-tuning impacts linearity in presence of EM gain. Was measured for multiple cases. Unity gain linearity met requirement level with margin. Linearity with EM gain applied was improved compared to pre-delivery values and deemed acceptable.

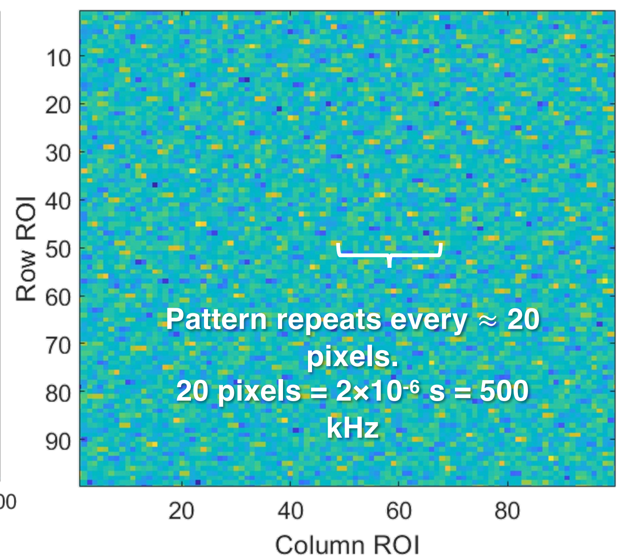




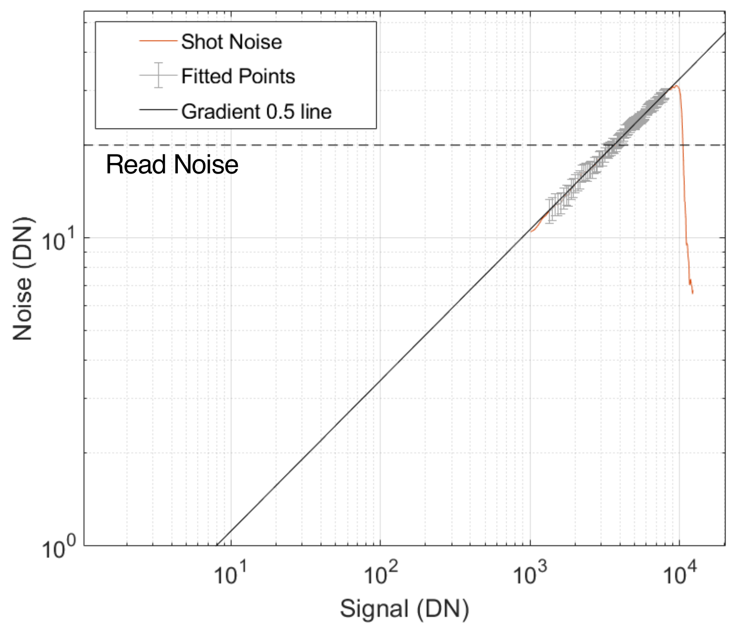
TVAC Calibration #3: Read Noise and Full Well Capacity

- Read Noise quoted as the standard deviation of a frame with fixed pattern noise removed, result of 165 e^- achieved at nominal flight operating temperature for Proximity Electronics and EMCCD.
- Standard deviation return by a Gaussian fit of data provides value of ≈125 e^-; A significant contribution is through noise "spikes"
- Image Area Full Well Capacity measured as 88 ke^-, close to pre-delivery value and beyond requirement level.



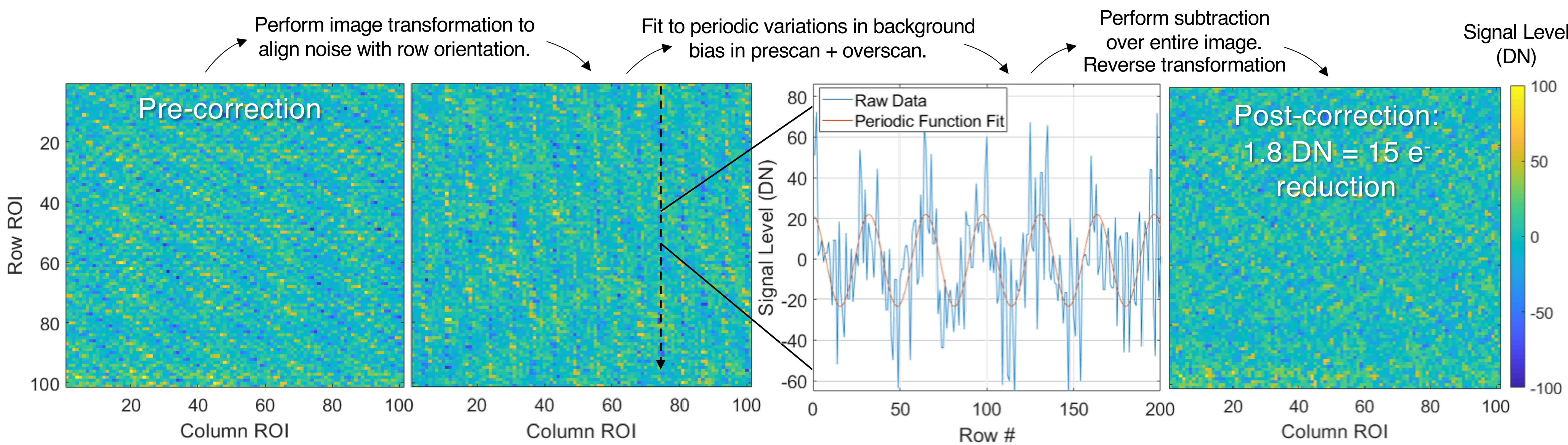


Photon Transfer, cold thermal balance



Noise Reduction Techniques

- Quoted values for read noise do not include post-processing techniques. While the excess noise is not fixed image-image, it follows a repeatable pattern on a per-image basis.
- The large portion of prescan and overscan allow the pattern to be determined, and applied to the active image area (with signal present) with reasonable success.
- Initial quick calculations have demonstrated that a reduction of 15 e^- (1.8 DN) is achievable on a single frame with basic processing.



Summary

- Both ExCam and LoCam have been re-tuned and recalibrated following integration with the instrument.
- Read Noise has increased for each camera compared to pre-delivery results, but remains below the requirement level with margin.
- For ExCam, a change in operating mode has resulted in an increase in thermal dark current compared to the pre-delivery result at the nominal operating temperature of -88 deg C. Incorporation of the revised number into combined noise models show the effect of this increase is low. The option to cool ExCam further as the sensor accumulates radiation damage remains.
- Following tuning, the cameras performed as expecting throughout the remainder of TVAC with no low-level performance issues. An important milestone in demonstrating low-noise photon counting technology for CGI.

Table 1: Summary of key ExCam and LoCam Camera Subsystem Requirements and results **(grey = not remeasured)**

Measurement	Requirement	LoCam	ExCam (BoL)	ExCam – estimated EOL (5 year)
Read Noise (e^-)	200	140	165	--
Image Area Full Well Capacity (ke^-)	50	90	88	--
Serial Register Full Well Capacity (ke^-)	90	100	100	--
Parallel CTI	$< 5x10^{-5}$	1.04×10^{-6}	1.29×10^{-6}	$< 5 \times 10^{-5}$
Serial CTI	$< 5x10^{-5}$	1.40×10^{-5}	1.45×10^{-5}	$< 5 \times 10^{-5}$
Mean Thermal Dark Current (e^-/pix/hr) (N.B Req. applies to 95 % of pixels at BOL)	-- (req. applies to distribution)	Not applicable - 10.08	3.6	6.6
Unity Gain Non-linearity (%)	< 4%	< 4	< 4	--
Clock Induced Charge (e^-/pix/frame)	0.01	Less Applicable – 0.020	0.008	0.0176