Signal-Dependent Interpixel Capacitance in HgCdTe Detector Arrays for NEOCam

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Abstract

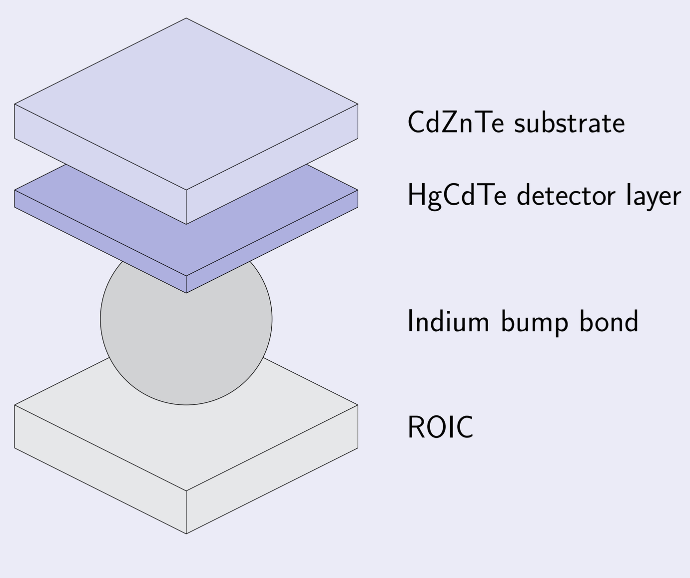
A first-order correction for signal-dependent interpixel capacitance (IPC) was developed for long-wave HgCdTe infrared detector arrays like those that will fly on NASA's Near Earth Object Camera (NEOCam) mission. IPC was not previously known to have a dependence on signal strength, but a recent paper provided evidence of this effect in mid-wave HgCdTe arrays for the James Webb Space Telescope (JWST). To characterize this dependence for NEOCam arrays, we used dark exposures of one test array to measure the spread of signal from hot pixels of various signal strengths to their four nearest neighbors. We fit an exponential functional form to this distribution and applied it to proton irradiation data taken with two different test arrays in order to measure the magnitude of the correction. Preliminary examinations of these data show a 10–20% decrease in the average number of pixels affected by a single proton hit after the correction. Further exploration of the dependence of IPC on background strength will improve the accuracy of the correction. An IPC correction algorithm will be present in the data reduction pipeline for NEOCam, which is designed to identify and characterize most potentially hazardous near-Earth objects (NEOs) that are larger than 140 meters in diameter.

Introduction

Mercury cadmium telluride (HgCdTe) is a semiconductor that is used to detect infrared photons. Like all photodetectors, HgCdTe detector arrays are subject to physical effects that serve to blur images. One such effect is interpixel capacitance, or IPC. To explain how IPC works, we can model an array of photodetectors as an array of capacitors upon which some charge is deposited (via the photoelectric effect) and across which some voltage is read out. Ideally, the voltage V measured across a pixel $[i, j]$ is directly related to the charge Q collected in the pixel via the familiar equation below for a parallel-plate capacitor.

$$V[i,j] = \frac{Q[i,j]}{C[i,j]}$$

Here, $C[i,j]$ is the nodal capacitance of the pixel which can be fabricated with high precision. However, fringing field effects from the edges of the individual pixels cause the voltage measured in one pixel to be dependent on the charge collected in neighboring pixels. Thus, IPC helps to couple pixels with their neighbors. IPC was known to be detector-dependent because it is sensitive to the geometry of the pixels in the detector as well as the readout circuitry. Recent developments in performance analysis of IR detector arrays for JWST's NIRCam have noted that IPC is also **signal-dependent**. For these arrays, the more signal that is deposited onto a pixel, the less the signal is spread to nearby neighbors. The opposite is true for pixels with less signal deposited onto them. This suggests that developing a functional form for how signal strength affects coupling between pixels is important for salvaging angular resolution in faint sources, which is crucial for a mission like NEOCam.



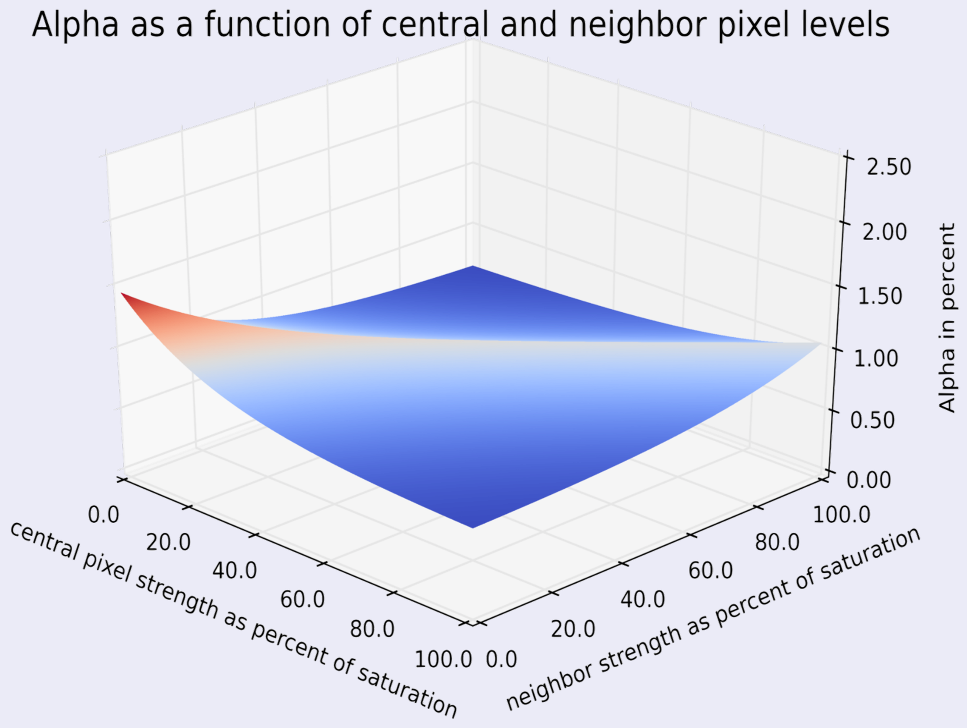
Above: A simplified deconstruction of a pixel in an infrared HgCdTe detector array for NEOCam. The layers are not to scale.

Interpixel Capacitance

We determine the relationship between the amount of coupling to neighbor pixels and signal strength using **hot pixels** in dark exposures. To achieve IR "darkness" when testing in the laboratory, HgCdTe arrays must be cooled using liquid nitrogen and helium. Hot pixels have high **dark current**, which is the amount of current measured in a pixel when the array is not being illuminated. The charge that integrates in a hot pixel will spread to neighbor pixels via IPC. We can define a **coupling coefficient**, α, for each hot pixel to quantify the fractional spread of signal from that pixel. The expression below, from Donlon et al. (2016), assumes zero background illumination.

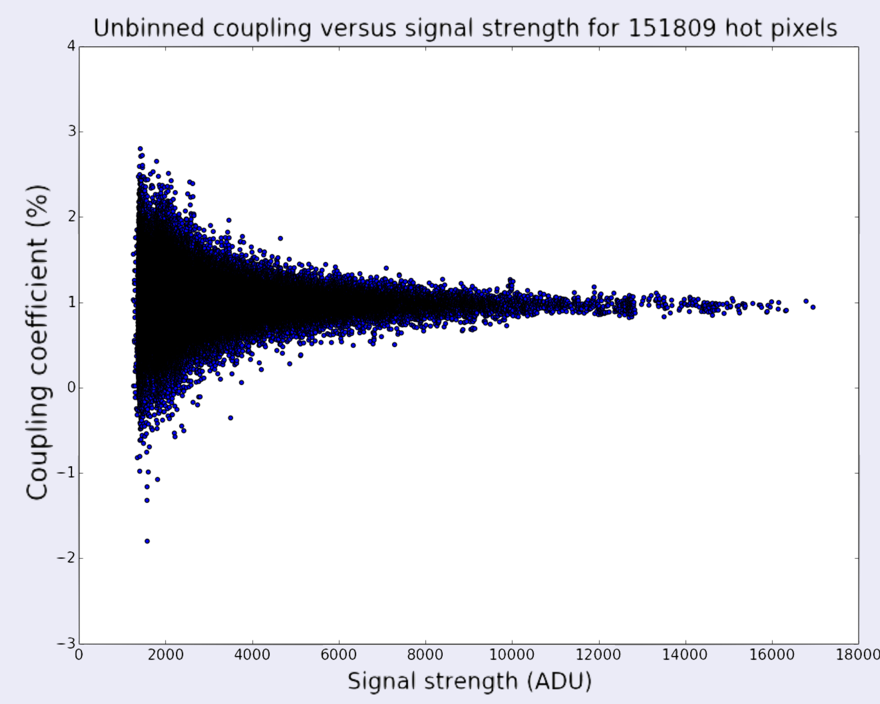
$$\alpha = \frac{\langle Neighbor \rangle - \; LocalMedian}{4 \cdot (\langle Neighbor \rangle - \; LocalMedian) + (Center - LocalMedian)} \quad (1)$$

The quantity *Center* refers to the signal strength of the hot pixel, $\langle Neighbor \rangle$ the average strength of the pixel's four nearest neighbors, and *LocalMedian* the median value of a five by five square centered on the hot pixel. Ideally, we would be able to incorporate a dependence on signal strength as well as neighbor pixel strength into our IPC correction. We could do this by measuring some coupling coefficient that accounts for a nonzero background level for hot pixels with various backgrounds to get a distribution of coupling parameters for a variety of signal and neighbor strengths, like in the figure at right (Donlon et al. 2018). However, we did not have sufficient data to do this with any of the detectors we had available, so we instead decided to make a first-order correction for IPC in which we assume that there is zero background illumination anywhere in the image we are correcting. We developed a functional form for the correction by calculating the coupling coefficient using Equation (1) above for hot pixels in dark exposures of a test array for NEOCam, H2RG-18481. We ensured that the hot pixels were viable for analysis by only choosing hot pixels which were isolated, were not saturated, and had nearest neighbors that were sufficiently symmetric (Donlon et al. 2016).

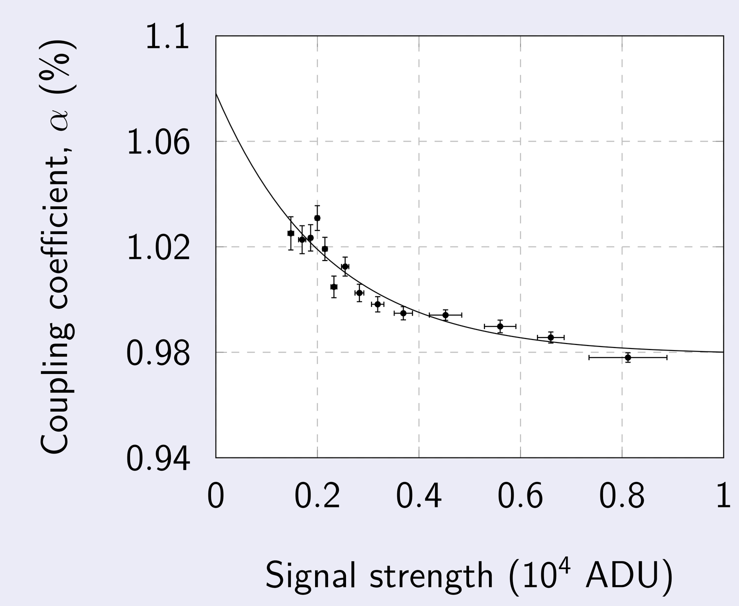


Above: A three-dimensional relationship between coupling coefficient (α), signal strength, and neighbor strength. This figure is presented in Donlon et al. (2018).

IPC Correction



Above: The distribution of coupling coefficient versus signal strength for hot pixels in the array H2RG-18481 at 35 K with 150 mV applied bias. **Below:** The binned averages of the distribution above. The exponential fit used in the correction algorithm is overlaid.



The distribution at left shows the coupling coefficient in percent for viable hot pixels. The vertical spread in coupling coefficient is greater at lower signal strengths because the noise in the read-out of the detector affects the coupling to a higher degree at these lower signal strengths. When we bin this distribution, however, we see an exponential trend. The plot below shows average binned values for the distribution above, using two smaller bin sizes at higher signal strengths. The vertical error bars are 95% confidence intervals on the bin means, and the horizontal error bars are the standard deviation of the signal strengths in the bins. We fit an exponential function to this binned distribution and used the resulting parameters to apply our correction. The exponential fit is described by Equation (2) below.

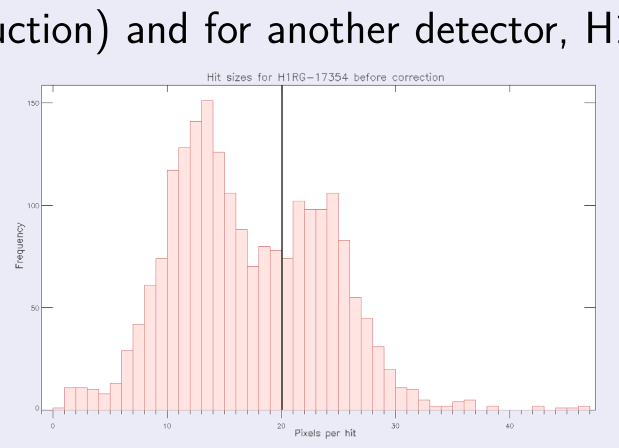
$$\alpha(S) = A \cdot \exp\left(-\frac{S}{B}\right) + \alpha_\infty \quad (2)$$

$$A = 0.0992 \pm 0.0543$$
$$B = 2202.9 \pm 2105.4$$
$$\alpha_\infty = 0.979 \pm 0.0184$$

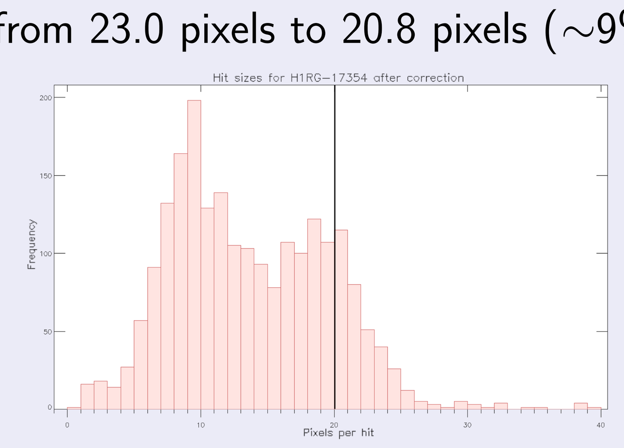
The 3σ uncertainties on the parameters for this fit are relatively high, so much so that the full range of fits suggested by the uncertainties would not fit the data well. These uncertainties could be reduced greatly by refitting the data as follows. One could fix one of the parameters (namely A or B) and allow the other parameters to vary while the curve fit is performed. The above coupling coefficient at infinite signal strength, $\alpha_\infty = 0.979$, closely matches the value found by the Rochester IR group previously.

Results

IR detectors for space missions are subject to tests involving high-energy protons in order to determine the effect of cosmic ray hits on detector health and parameters. When these protons interact with the detector, they leave behind small circles during an integration. Because of IPC, these circles appear larger than they should. Thus, one way to measure the magnitude of an IPC correction is to compare the size of the proton hits in an image before and after the correction is applied. The histograms below show the number of hits affected by a single proton hit in a ramp for the detector H1RG-17354 before and after the IPC correction is applied. A vertical line is drawn at 20 pixels per hit on both histograms. For H1RG-17354, the average hit size went from 16.7 pixels to 13.2 pixels (about a 20% reduction) and for another detector, H1RG-17346, the average hit size went from 23.0 pixels to 20.8 pixels ($\sim$9%).



Left: A histogram showing the number of pixels affected by a single proton hit in one ramp for the detector H1RG-17354 before the correction was applied. **Right:** A histogram created in the same fashion after the correction was applied. The bimodal nature of the distributions is due to the presence of two main populations of proton hits which are incident on the detector: those which are normally incident (smaller on average), and those which hit at some angle (larger on average).



In order to characterize IPC as a function of background level, the next step will be to collect data using the **single pixel reset (SPR) method**. Before an integration, any given pixel in an array can be reset to a desired voltage. This allows us to measure the coupling due to IPC for any pixel in the array by setting the background level in a region and measuring the amount of coupling from a pixel of any signal strength. In the SPR method, the signal generated is not subject to cross-pixel diffusion. Such a process is described in further detail by Dudik et al. (2012).

Conclusions and Further Work

- An algorithm to correct for signal-dependent interpixel capacitance, given the assumption that there is zero background illumination in an image, has been successfully developed.
- More data taken using the single pixel reset method are needed to characterize the dependence of IPC on neighbor pixel strength and improve our IPC correction.
- Exploration of the functional forms produced by several different test arrays that the University possesses will provide insight on how the coupling differs in similarly-fabricated arrays.

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