

Synthetic Correction of Dark Signal Data in a Space Situational Awareness Sensor

Thomas Chrien

Millennium Space Systems, a Boeing Company

Richard Pepe

Millennium Space Systems, a Boeing Company

ABSTRACT

Optical Cameras used for space situational awareness missions must consider the performance limiting impacts of dark current. If not removed, dark signal will increase spatial noise in the image, and impede the ability to reduce noise by the averaging together multiple frames. There are several strategies for eliminating the negative impact of dark current, but each approach comes with regrets. We have developed a new technique that estimates the dark signal from a detector array over a range of temperatures from routine SSA image data. We form a synthetic dark correction from this data that does not require an additional measurement. The technique is significant in that it enables the use of lower cost SSA cameras, without impacting the sensor availability to perform dark calibrations. In this presentation, we will describe the method for creating the synthetic dark frame and how the synthetic corrections are applied. We also evaluate the performance of these corrections.

1. INTRODUCTION

Space situational awareness (SSA) sensors search the sky looking for star-like objects that are in motion relative to the celestial background [1]. To detect a dim object, a sensor must collect enough signal photons to discriminate it from the noise background at some threshold. Processing proceeds by (1) Detector response calibration and associated corrections, (2) Elimination of radiation hits, which do not appear to have point spread functions like the stars, (3) Star object detections above threshold, (4) Subpixel location of the star detections, and (5) Computing the angle between detections and comparing these angles to a star catalog. Detections that are left over are either dim stars, not in the catalog, or resident space objects (RSO) such as space vehicles and asteroids. RSOs will move with respect to the star background, while dim stars will stay fixed. SSA searches are desired over wide field of view, much wider than a single frame SSA sensor can provide. The SSA sensors scan over a sky field by imaging in a piecemeal fashion, and then this cycle is repeated continuously. Down time for calibration collection takes away from time to perform the SSA mission. One important calibration measures the dark current signal content of each data frame and subtracts this signal. This paper describes a method to compute a dark signal correction term synthetically, from routine star field images, without the need to perform a shuttered dark signal calibration. We have also applied similar techniques to correct for stray light backgrounds. The bulk of this work was done using archived images from a prototype SSA sensor.

2. DARK CURRENT IMPACT TO MISSION PERFORMANCE

Dark current is the electric current generated in photodetectors even when there is no light incident on the detector. The dark signal collected in an element is a function of the detector area, temperature, material purity, and integration time. Material defects are spatially distributed throughout a large format detector array, and as a result some pixels will have higher dark signal than others. These defects are fixed in position. Dark signal is also a function of temperature [3]. As a result, image data frames will have signal levels that include dark signal, as well as signal and stray light. Detector systems will also include a fat-zero constant offset.

The level of dark signal that can be tolerated depends on the detection threshold. First, one considers the average dark level (average local signal level around a star). The threshold is set at some number of noise standard deviations above that level. Lowering the detection threshold increases the sensitivity, which allows detection of dimmer objects, at the cost of increased false alarms. Raising the detection threshold reduces false alarms at the cost of sensitivity. Another issue to be aware of is the limited well capacity of most detectors. If the wells fill up with dark signal and stray light, then there is limited well left to capture real signals.

The dark signal will increase the average dark level and add to the background noise. Spatial variations in dark signal are an additional noise source when setting the threshold. Since dark signal is temperature dependent, the average dark and the noise level are also temperature dependent. Finally, uncorrected dark signal becomes an additive term when trying to average together multiple frames. Therefore, in a sensor with uncorrected dark signal, only limited improvement by frame averaging is expected. This is shown in the simulation pictured in Figure 1.

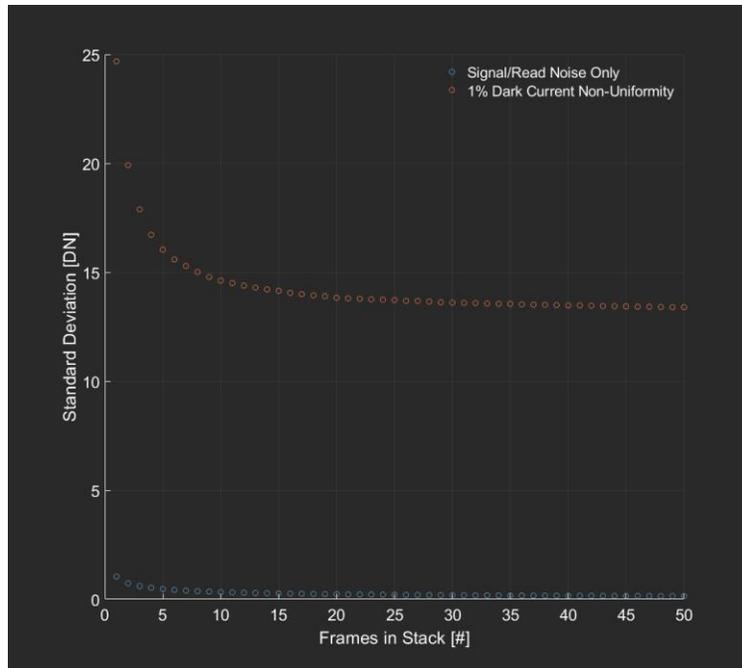


Figure 1: Shows that Frame averaging noise reduction is limited when dark signal is not corrected, and greatly improved when the data is dark signal corrected.

Best results are achieved when the dark signal spatial noise is much smaller than other noise sources. The first defense is to use detector array materials that have a low and uniformly distributed dark current and to cool this detector as much as possible. This adds to system cost by either the price of the detector or the price of the cooling and temperature control system. Variations in dark signal due to an uncontrolled detector temperature is especially problematic since this makes it necessary to calibrate more often. This results in the need for dynamic adjustment of the detection threshold or false alarm rate performance.

Another approach is to perform a dark signal subtraction using dark calibration data. A sensor system may include a shutter, so that dark signal can be collected, averaged, and then subtracted from light gathering images. The frequency of dark signal calibrations depends on the dark signal stability, which in turn depends on the detector temperature stability. If the detector is stable in temperature, a dark correction frame may be measured once and used throughout the life of the sensor system. If the detector temperature and integration time vary, the dark signal must be collected for each unique temperature and integration time condition. The dark calibration shutter represents additional system cost and risk of the shutter failing in the closed position. The time required for dark signal calibration is also time when the SSA sensor is not executing the primary mission.

3. MOTIVATION

We were given over 600,000 archived digital images from a prototype SSA sensor that was operated on orbit. A defect in the design of this sensor system resulted in detector temperature that varied daily by 5 to 15K and seasonally by over 50K. The sensor included a dark shutter calibration device, but the device was found to leak light and so its use was not used. Finally, the sensor data was found to have high levels of stray light, which varied with time of day and SSA sensor pointing. When the detector was cold and stray light level was low, the sensor exhibited

excellent sensitivity that met the specified performance goals of the system. However, the bulk of the data was found to be unusable due to the high dark signal and high levels of stray light.

Inspired by a paper by Porter Et. Al. [2], we speculated that it would be possible to synthetically generate this dark signal data after the fact through data mining the star field images. Our approach was to use the dark sky between star detections as a training set to estimate both dark signal and stray light. We envision this as an ongoing process for future SSA sensors, eliminating the need for dark current calibration down-time. This allows for less expensive detectors and cooling control systems, as well as robustness against variations in stray light.

Conceptually, the components of a star field image are divided into star light, stray light, dark signal, fat zero and noise components, as shown in Figure 2. The star field is assumed to consist of a range of star intensities with instrumental point spread function responses. Radiation hits do not exhibit a point spread function and are eliminated onboard. The stray light is modeled as a smooth, slowly varying function, using a Gaussian smoothing kernel.

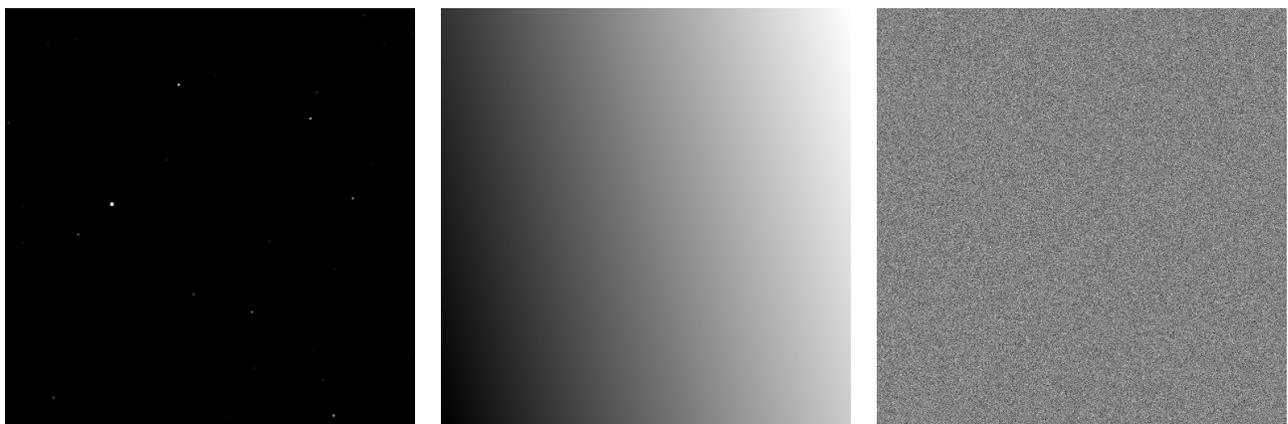


Figure 2: Image data can be thought of as the addition of a star field image, a straylight gradient image, and a dark signal pattern as shown in the figure above.

Over the large data sets we were able to obtain images with low stray light to use in the calibration of the synthetic dark signal. We were able to discover these frames in a plot of average frame signal vs detector temperature, as shown in Figure 3. We developed a routine that found the data sets near the lower boundary, making sure to have data uniformly distributed over the range of detector temperatures.

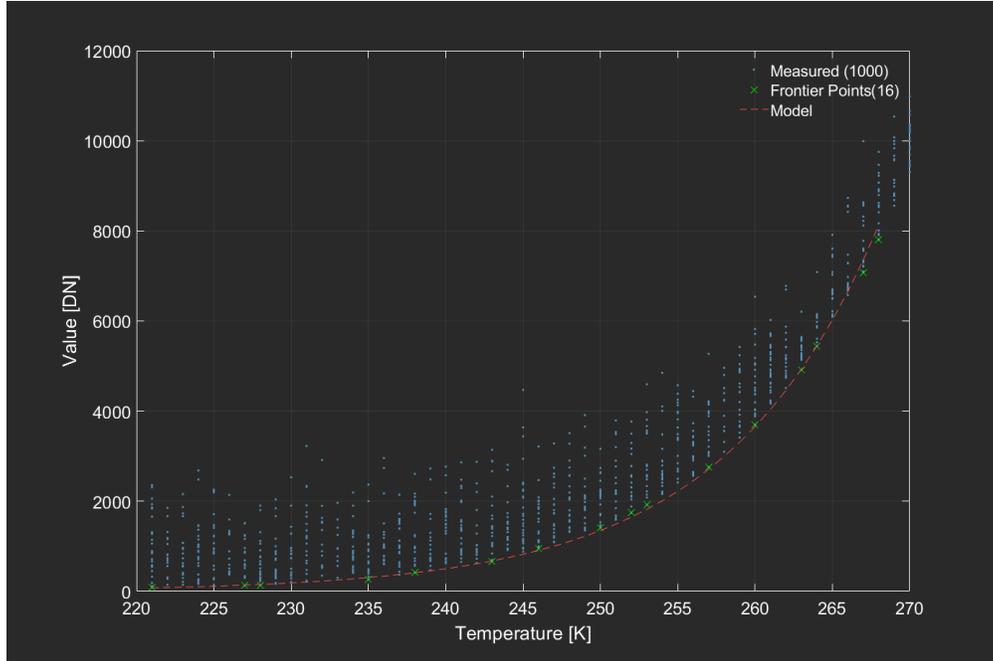


Figure 3: Average Image signal level versus detector temperature for a simulated data set. Notice the lower boundary (red plot). We selected calibration frames from images close to or on this boundary.

We include checks to make sure that all the calibration data had the same integration time, and that none of the images contained values that exceeded a saturation threshold. This saturation level ultimately limited the highest detector temperature that we can correct to, which was a temperature of about 275K.

We selected calibration data sets from those images that were closest to the dark current fit line over the full range of temperature variations. We process these images by identifying and removing stars and subtracting the “stray light” signal and the fat zero offset. We applied a base-10 logarithm to the remaining data to fit a temperature-dependent polynomial fit to each image pixel. In Equation 1, DN represents the signal counts, and gcf is the gain conversion factor used to relate DN to signal electrons.

$$\text{Equation 1} \quad \text{coeff}_{x,y} = \text{polyfit}(T, \log_{10}\left(\frac{DN}{gcf}\right), \text{order})$$

The algorithm is flexible for use of any order of polynomial, but satisfactory results were obtained with first-order fits. The fit coefficients, a, and b have unique values for each detector pixel. Once these coefficients are determined, they can be used to predict a synthetic dark signal for any detector temperature using Equation 2.

$$\text{Equation 2} \quad \text{correction}_{x,y} = (gcf)(10^{aT+b})$$

4. DATA CORRECTION RESULTS

We applied our dark signal correction to over 12,000 SSA images, none of which were used to create the calibration fit coefficients. First, we computed the synthetic dark signal frame based on raw image temperature. We removed the stray light gradient, using the method described earlier, and the fat zero offset. Then we subtract the synthetically generated dark frame. In order to evaluate quality of the correction, we compare the raw and the corrected images and their respective histograms, as shown in Figure 4.

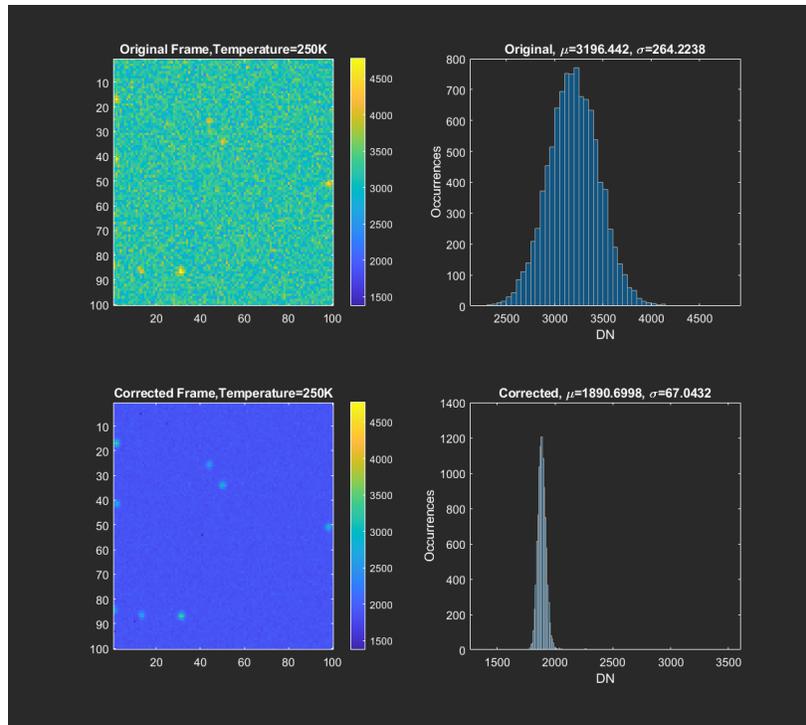


Figure 4: Raw Image compared to dark signal corrected image example. Notice that the raw image has a median value of 3196 and a standard deviation of 264. The corrected image has a much lower median value of 1890, and a much tighter noise distribution of 67 counts. The stars are easy to see in the corrected image.

The quality of the correction was evaluated by comparing the background level and noise and comparing it to the post correction image. Most of the corrected images show the improvement that was to be expected upon removal of dark signal. In other words, the spatial noise from the non-uniform dark signal was removed, but the Poisson noise from the excess dark signal was not. When we inspected images that did not show improved performance, they were found to contain data dropouts (due to failed data transfer) or excessive stray light conditions that did not conform to the assumption that stray light signal could be described as a gradient and an offset. Figure 5 shows the magnitude of the correction as a function of temperature. As stated earlier, the low temperature data already shows good performance, and the improvement in performance is greatest at the higher temperatures.

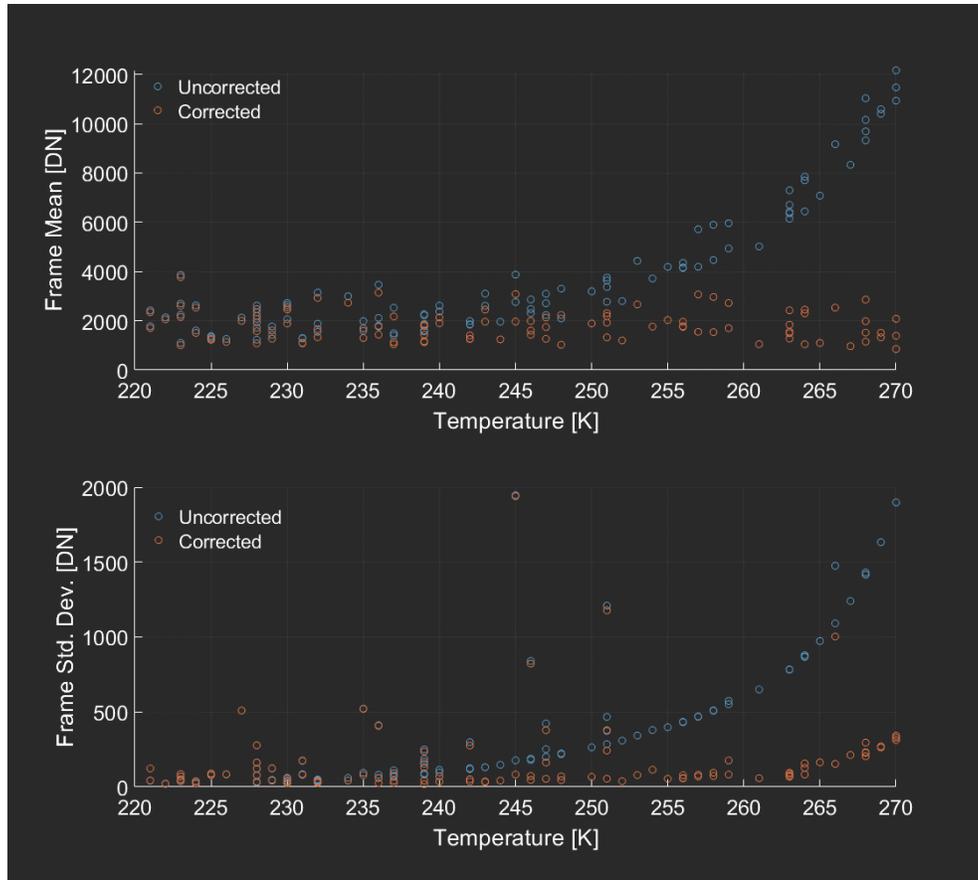


Figure 5: Degree of dark signal correction and improvement in noise standard deviation for a range of images collected at different temperatures.

5. RESULTS SHOWN USE SURROGATE DATA

Classification restrictions do not allow us to show actual image data or correction results from the SSA system described above. However, it was straightforward to reproduce this effect using an unclassified laboratory camera. We collected data from a temperature-controlled CMOS camera (ZVO model ASI1600MM Pro). We added simulated star images and stray light gradients to the measured dark signal data sets.

6. CONCLUDING COMMENTS

We have demonstrated significant improvements to image data using a synthetically computed dark signal correction on a real SSA sensor system. In this paper we reproduce these results using dark signal data from a surrogate camera. The synthetic fit parameters are computed on a pixel-by-pixel basis and work over a range of different temperatures. This enables developers of SSA sensors to use less expensive detectors and detector cooling and temperature control systems. Developers of digital cameras may be able to encode similar calibration data into camera electrons to correct for dark signal over a wide range of integration times and temperatures. If used operationally, the method does not require down time for the collection of calibration data frames. Rather, the process can generate and update calibration coefficients using the normal data collected by the SSA sensor. We have also shown that the corrections work for stray light that is well fit by a gradient and offset model. We are working to apply these corrections to a current project tracking SSAs from the ground during daylight hours. We plan to apply these corrections to remove both sky background and camera dark signal.

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7. REFERENCES

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