Residual bulk image characterization and management in CCD image sensors

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ABSTRACT

The phenomenon called Residual Bulk Image ("RBI") was studied in a large format scientific CCD (KAF09000) image sensor. Operating at –20 C, ghost images were observed in dark images taken hours after a photographic image exposure. This is an undesirable image sensor characteristic and can cause significant problems in some applications such as long exposure scientific imaging applications.

The image sensor's key RBI characteristics were measured: charge capacity of the traps, leak out rate and total trapped charge exhaustion time. For temperatures ranging from +10 C to -30 C, the CCD was first flooded with light and then flushed. Then using a sequence of dark exposures the trap decay was measured.

A Light-Flood/Flush/Integrate protocol was used to eliminate the RBI by pre-filling the traps prior to any exposure. Four important findings resulted: the ghost images were eliminated, the amplifier luminescence sometimes observed was eliminated, the dark shot noise was significantly increased and leakage from non-uniform trap distribution altered the appearance of the dark fixed patterns.

The additional dark noise component can be reduced by deeper cooling. The relationship of dark shot noise versus exposure time at various operating temperatures for this RBI-mitigation approach was examined using an Arrhenius plot. For half hour exposures with a target 5 e- dark shot noise limit, an operating temperature of –87.8 C was projected.

The fixed patterns caused by the non-uniform trap distribution can cause images to be uncalibratable if high signal level flat-field images are taken prior to taking long exposure images unless RBI-mitigation is used.

Keywords: CCD, RBI, substrate traps, luminescence, fixed patterns, flat-fielding

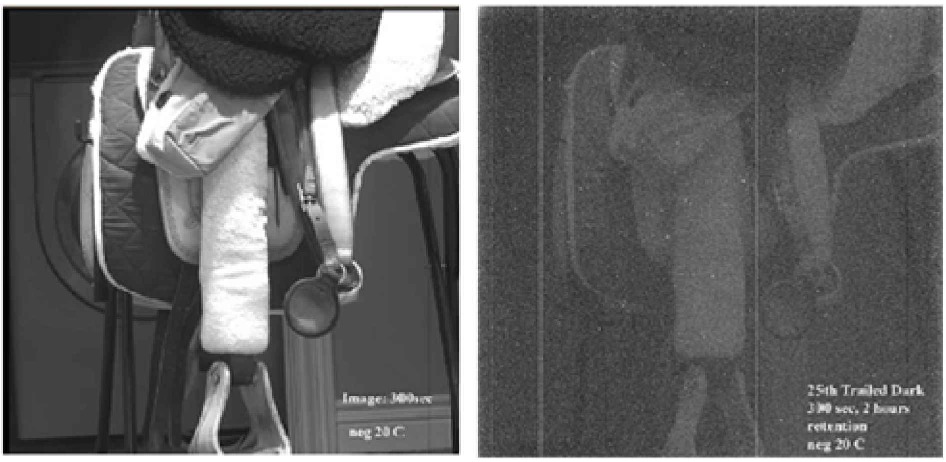
1. INTRODUCTION

RBI is a phenomenon that can affect full frame CCDs. The telltale signature of RBI is the existence of an image from prior illumination in a subsequent integration. For example a KAF09000 CCD had a partially saturated exposure at the Hydrogen Alpha wavelength (656.4 nm) that resulted in an observable residual image in a dark frame taken over 2 hours later (Figure 1).

The root cause of RBI is the presence of trapping sites in the CCD's active layer that cause image lag. These trapping sites can have different origins including impurities in the silicon lattice, residual mechanical stresses in the silicon lattice introduced during the crystal growth process and interface states at the substrate-epitaxy interface for CCDs fabricated on epitaxial wafers [1].

During exposures the traps can capture some charge which remains trapped or deferred upon image readout. During a subsequent exposure, the previously trapped charge can leak into the new image, corrupting its integrity.

Residual Bulk Image (RBI) Example
(656.4nm light)



Image

Dark Image:
two hours later
@-20C

Figure 1

Preloading the traps prior to exposing the sensor places all of the traps into a known state. This permits the sensor to be used to take a high integrity image since the unavoidable trap leakage only adds to the image a fixed pattern that can be removed via dark subtraction.

This paper has three parts. The first part characterized the physical parameters of the sensor traps: trap charge capacity, leakage rate vs temperature and time to total trap exhaustion time. The second part determined the operating temperature required for a given exposure time to limit dark shot noise to specific target values. The third part shows examples of fixed patterns caused by trap leakage from prefilled traps that are removed by proper dark subtraction.

2. SENSOR CHARACTERIZATION (PART 1)

The KAF09000 CCD from Kodak (Now Truesense Imaging Inc.) is a frontside illuminated 9.6 Megapixel CCD that has an active imaging area of 36.8 mm x 36.8 mm with 12 x 12 micron pixels.

Featuring a full well capacity of 110,000 electrons (“e-“), along with low read noise (7 e-) and low dark current, it is well suited for many scientific applications, including cooled long-exposure use in astronomy [2]. An engineering grade KAF09000 was evaluated in a Finger Lakes Instrumentation Proline PL9000 camera for this work.

The camera used for evaluating the sensor incorporates near-infrared (“NIR”) LEDs used for flooding the sensor prior to flushing and exposure. After flooding the sensor for 5 seconds followed by flushing it, a sequence of dark frames was taken. Each of these dark frames was reduced by subtracting a reference dark taken from the same sensor but with the traps in a non-filled state. The delta was the trapped charge that leaked during the exposure. The total trap capacity and time for total trap exhaustion was then calculated from the reduced dark frames.

Total exhaustion was defined as that time when the flooded sensor’s dark current matched its reference dark current, indicating no trapped charge remained. The reference dark current was measured at the same temperature in a non-flooded sensor from a cold start: no residual image trapped. After prefilling the sensor’s traps its dark current was measured using a sequence of half hour dark exposures for the trap exhaustion measurements. Plots showing the incremental charge leakage (frame to frame) and cumulative charge leakage are shown in Figures 2 and 3 respectively.

Figure 4 shows the trap capacity as a function of operating temperature. Since the camera always performs a flush prior to any integration, some charge is lost with the flush and is not recorded. Because the trap leakage is highest with completely filled traps at the warmest temperatures, the charge loss is greatest in those cases. In a 5 minute long integration taken at +10C immediately after flood/flushing of the sensor, approximately 900 electrons are leaked. It takes approximately 45 seconds to cycle between exposures (readout, download, flush) so it is estimated that approximately 300 electrons are lost in the flush. For this reason the reported trap capacity is underreporting the true value at the warmer operating temperatures. This could explain the apparent reduction of trap capacity at the warmer operating temperatures. Figure 5 shows the time for total exhaustion as a function of operating temperature.

In Figure 6 amplifier luminescence is observed in the upper left corner of the left side image. That image was a half hour dark exposure from cold-start camera without flooding and flushing the sensor prior to the exposure. The right side image shows a dark exposure taken under the same conditions but using light-flood. Using the light-flood, the amplifier luminescence is suppressed.

Additional investigation revealed the luminescence to decay in the non-flooded case in a manner identical with RBI. This suggests there is a transient luminescence occurring between initial application of power and the first integration. The transient amplifier luminescence is believed to load the substrate traps with photoelectrons created by the transient luminescence that subsequently leak into the following integrations. Because the luminescence monotonically decays with time, this argues that the luminescence is triggered by a single event, such as could occur with a fully-saturated sensor being flushed after the initial application of power. Upon initial power-up, the source follower transistor in the output amplifier’s first stage can be placed in a bias regime conducive to creating impact ionization, generating NIR light, ideal for aggravating RBI [3].

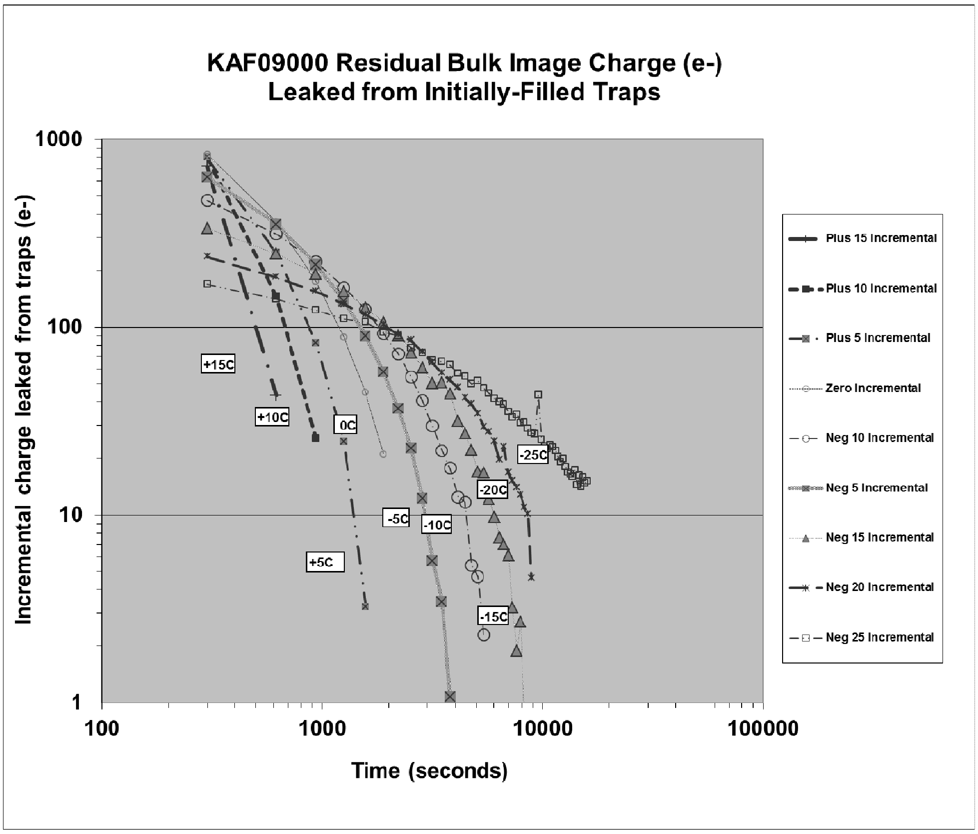


Figure 2: Incremental Charge Leakage (frame to frame)

3. MANAGING RBI (PART 2)

An accepted method for managing RBI is flooding the sensor with NIR light followed by flushing it prior to any integration [4]. However since filled traps leak charge, such leakage increases the shot noise of the overall dark signal, adding noise to the image. Minimizing the overall dark signal including the additional leakage from the pre-filled RBI traps can be accomplished by deep cooling of the sensor but some criterion must be set to determine how much cooling is adequate. A commonly used metric for establishing the maximum operating temperature of a sensor is constraining the noise contribution from the dark shot noise to be less than or equal to the read noise contribution for the maximum planned exposure time.

Plotting the leakage data as an Arrhenius plot provided a convenient way to determine the projected operating temperature that satisfied the camera noise constraint for any given read noise scenario. It should be noted that for the camera noise calculation, the read noise term is squared in the quadrature summation with the dark shot noise term as shown in equation (1). The target trap leakage limits are therefore squares of the numerical value of the read noise and are plotted as intersecting lines on the Arrhenius plot of the trap leakage data in Figure 7.

$$dark\_camera\_noise = \sqrt{dark\_shot\_noise^2 + read\_noise^2} = \sqrt{dark\_signal + read\_noise^2} \quad (1)$$

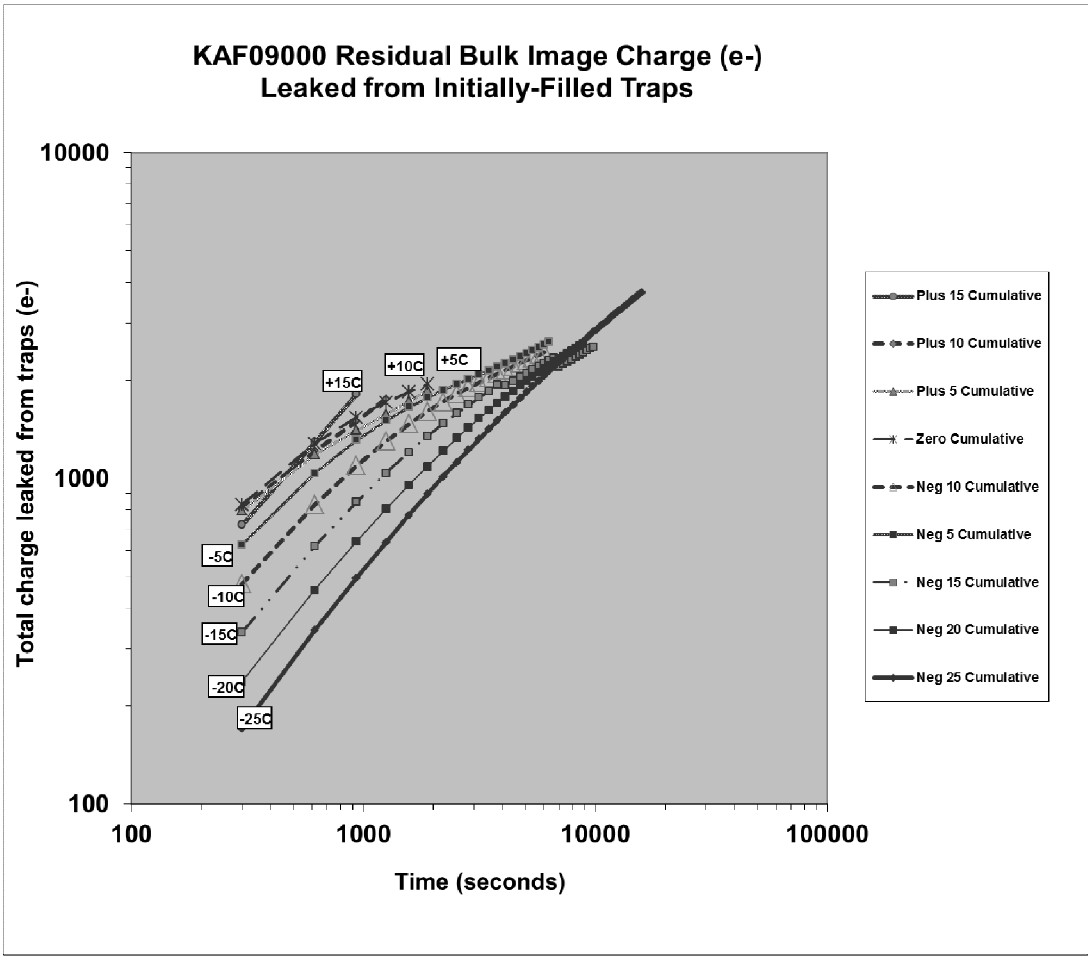


Figure 3: Cumulative Charge Leakage

Using the criterion of maximum exposure time being limited by dark shot noise equaling the read noise, Figure 12 shows the projected maximum operating temperature as a function of exposure time for three different read noise values. The graph shows that the projected maximum operating temperature for a half hour exposure with a 5 electron dark shot noise target is –87.8 C.

From a noise perspective it should be noted that if the deep operating temperatures are not met the result is a reduction of dynamic range in the same way as if the read noise was increased. That may or may not affect the final image quality depending on image signal level and the associated shot noise but is another noise factor that should be considered when planning exposures or analyzing data.

4. DARK FIXED PATTERNS RESULTING FROM RBI MITIGATION (PART 3)

The dark frames created after RBI mitigation for this KAF09000 show a distinctly different dark fixed pattern than for the darks from the same sensor that hasn't been preflooded as shown in Figure 9. In this case a KAF3200 standard grade sensor was measured. The image on the left in Figure 9 shows a 500 second dark exposure taken at -25 C operating temperature with no RBI mitigation. The image on the right in Figure 9 shows a dark taken under the same conditions after RBI flood mitigation. There are arc-like features prominently visible in the mitigated case.

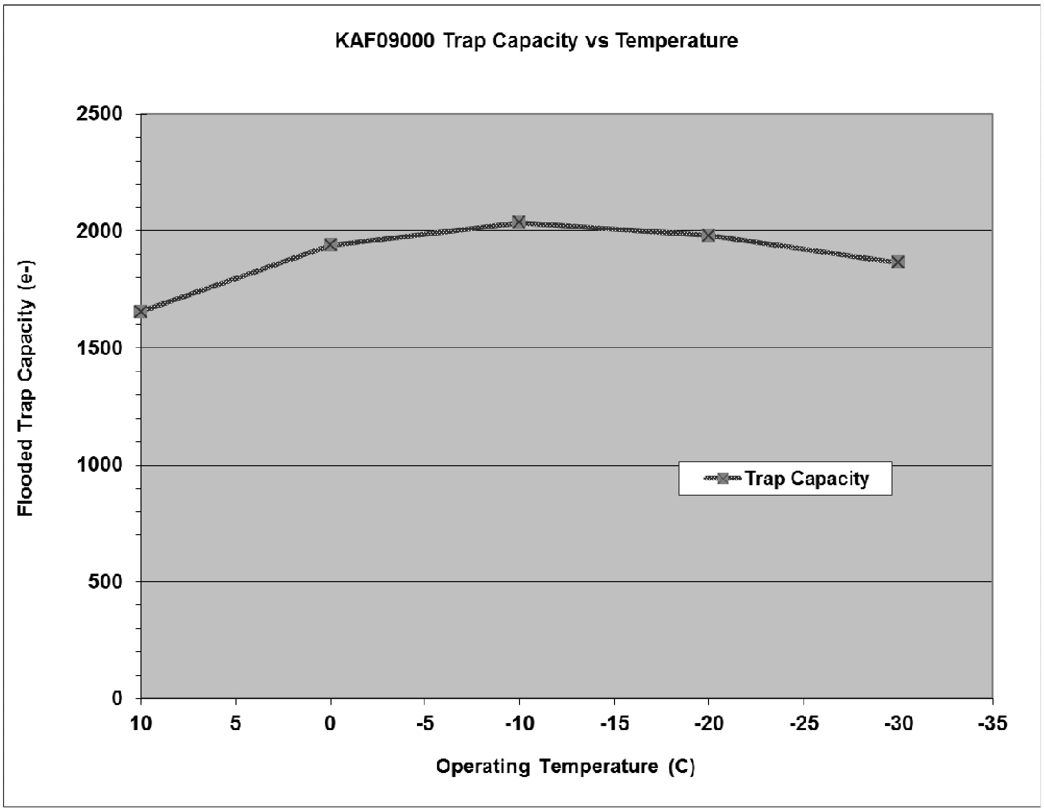


Figure 4: Trap capacity vs operating temperature

Proper dark subtraction will remove these artifacts. In Figure 10 a fifteen minute astronomical exposure is shown. The left hand image shows the image before dark subtraction and flat-fielding. The right side image shows the same image after dark subtraction and flat-fielding. As can be seen by inspection, the dark fixed pattern is removed in the calibrated image on the right.

Astronomical images taken using CCD image sensors are generally flat-fielded and dark subtracted in the image calibration process. Many times the flat-field calibration frames are taken prior to an imaging session. Typically a good flat-field image set will be taken at high signal level. A common signal target for flat-field images is 60 to 75% of full well capacity. Exposing the sensor to enough light to reach those signal levels can cause partial trap loading.

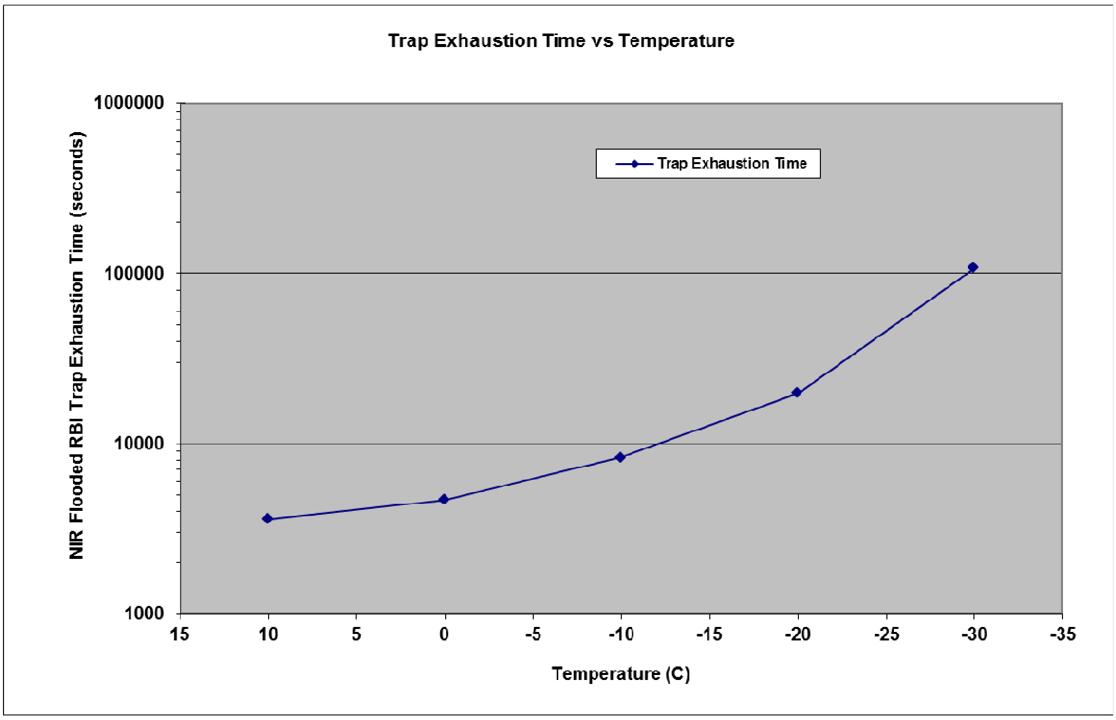


Figure 5: Time to trap exhaustion

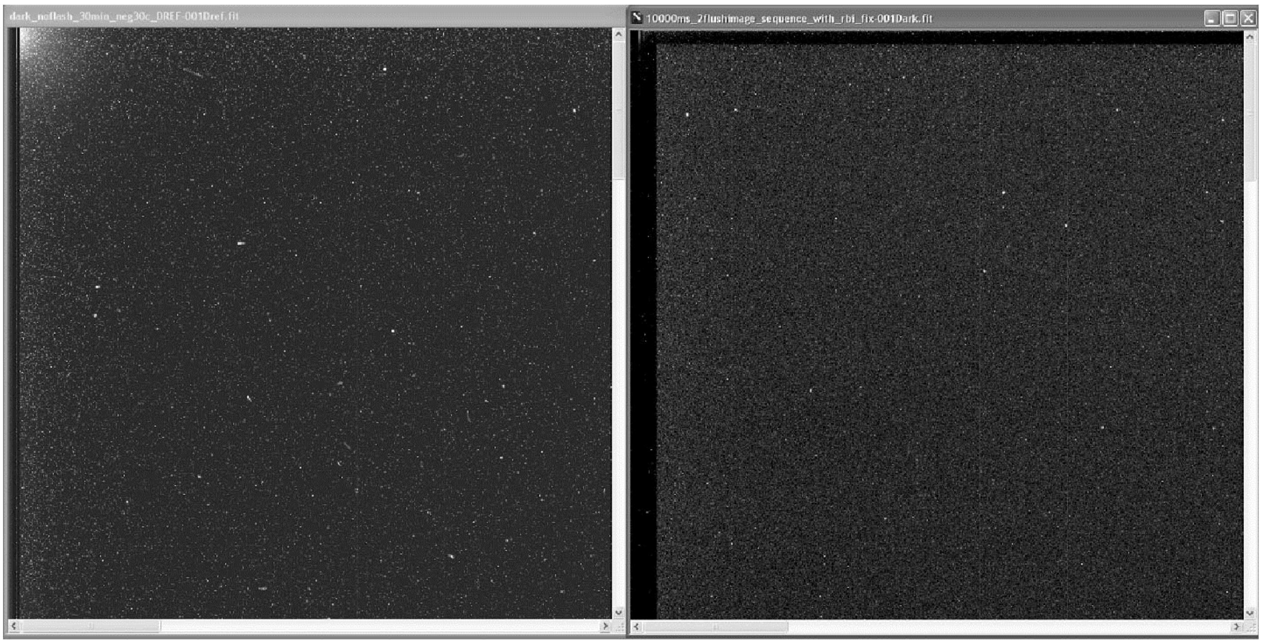

No Light Flood: Shows Amplifier Luminescence With Light Flood: No Luminescence

Figure 6: Amplifier Luminescence suppressed by light flood

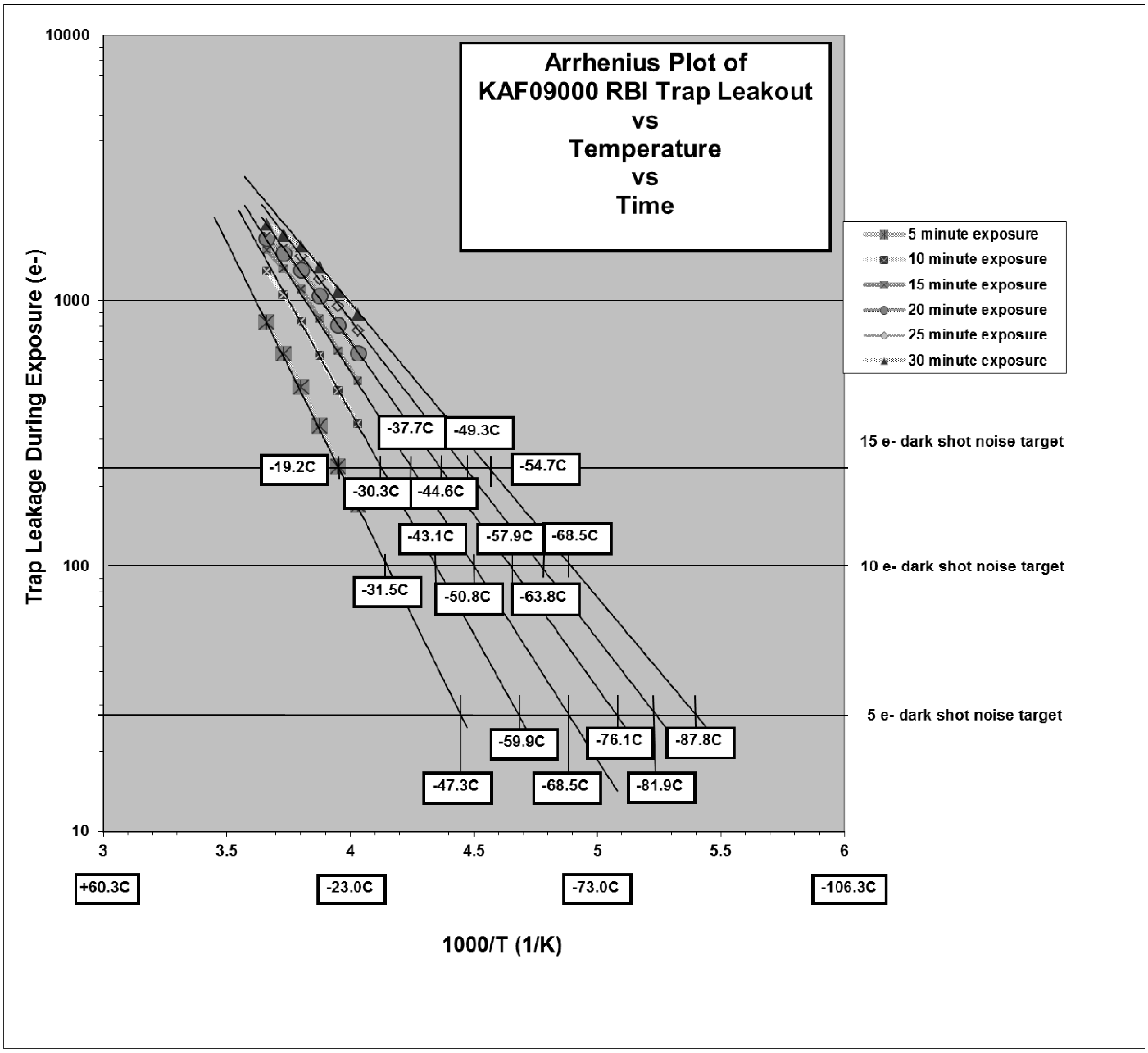


Figure 7: Arrhenius Plot showing trap leakage versus temperature for various exposure times

If RBI mitigation is not used for the subsequent images taken after these flat-field exposures, there is risk that leakage from the traps will introduce fixed patterns into the images similar to those shown in Figures 9 and 10. Unlike the case where RBI mitigation is used to put the sensor's traps into a known state of fill prior to exposure, this scenario leaves the sensor's traps in a partially-filled state of unknown level. It is very difficult to guarantee proper calibration in that scenario, leading to potentially uncalibratable image data. For that reason an image sensor used for long exposure images that will be fully calibrated should consider using RBI mitigation if the sensor exhibits any significant Dark Fixed Pattern Noise resulting from RBI.

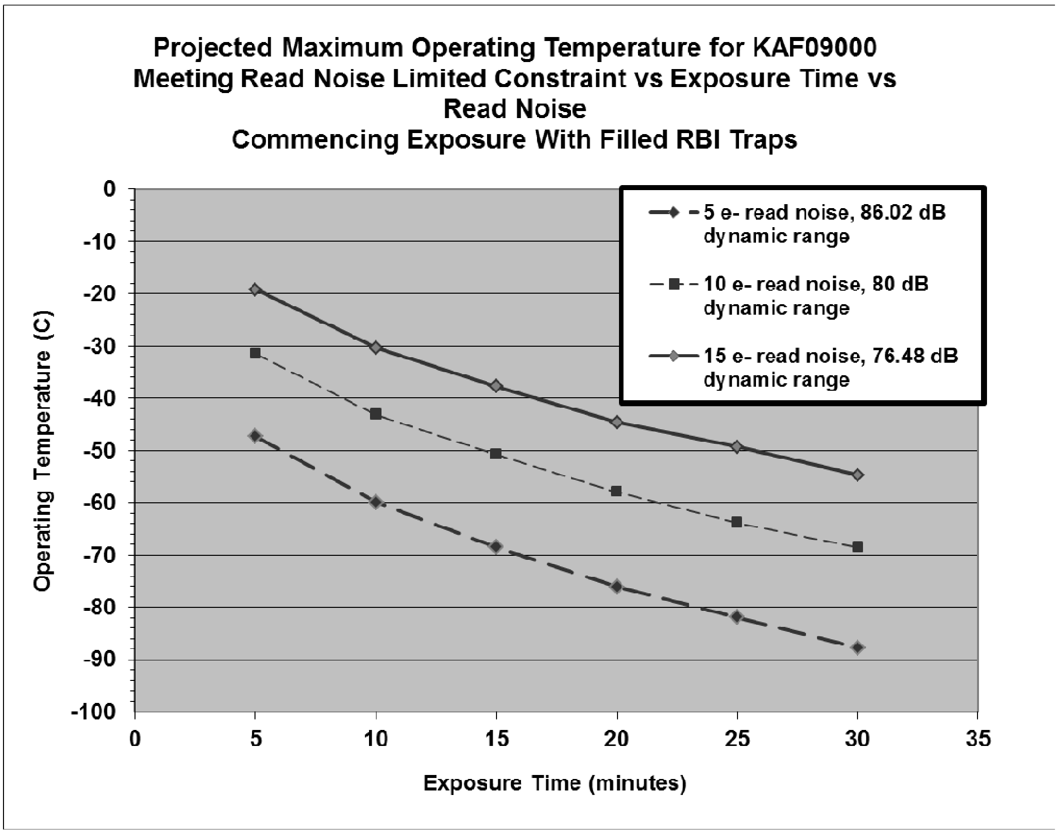


Figure 8: Projected maximum operating temperature versus time

5. CONCLUSION

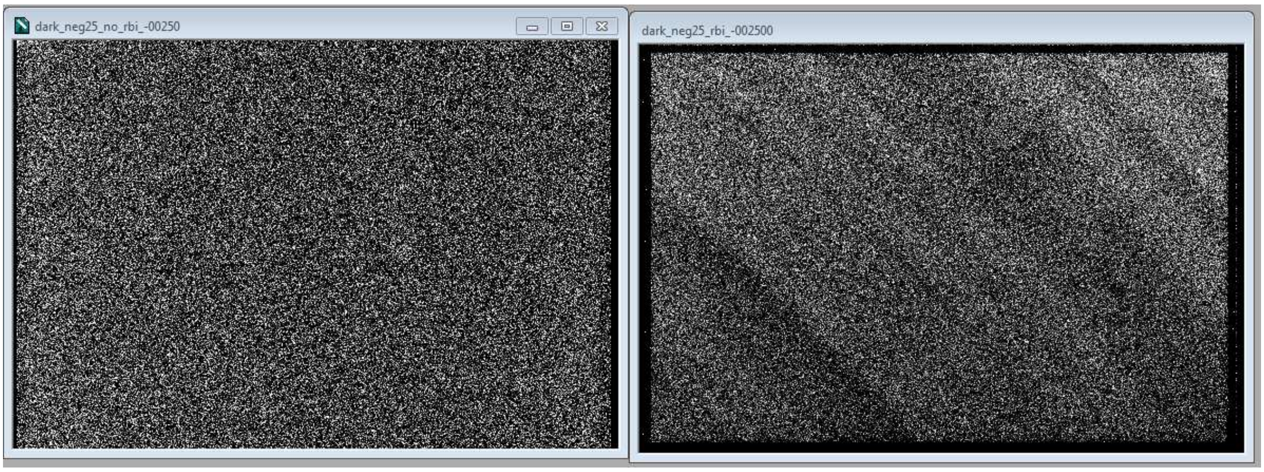
Any long-exposure image taken using a CCD that exhibits RBI is at risk of trapped charge corrupting the image's integrity unless RBI-mitigation is used. There are two components to the risk: trapped residual images caused by previous exposure to modulation and fixed patterns caused by charge leaking from non-uniformly distributed traps filled by previous exposure to high average signal levels. Placing all of the CCD's trapping sites into a fully-filled state by flooding and flushing the sensor immediately prior to any long exposure provides an effective method to mitigate RBI.

Leakage from the filled traps adds to the thermally-generated dark signal leading to an increase in dark shot noise. This can be managed by additional cooling, with the temperature set by the noise target for the longest planned exposure.

Amplifier luminescence related to a power-on event was suppressed by RBI mitigation.

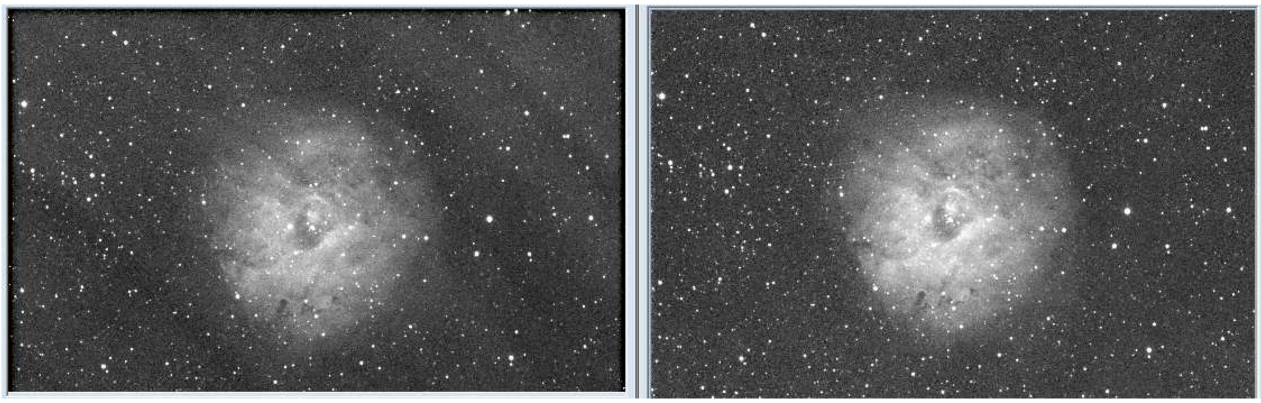
Fixed patterns observable in darks arise from the non-uniform distribution of trapping sites. These fixed patterns can be completely removed through proper dark-subtraction. The simplest way to guarantee complete removal is by always completely filling the traps prior to any exposure.

Because flat-field calibration images are usually taken at high signal level and often just prior to an imaging session, significant risk of non-calibratable images arises unless RBI mitigation is used for the long exposure images if the sensor exhibits RBI characteristics.



No RBI-Mitigation With RBI-Mitigation

Figure 9: Dark frames with and without RBI Mitigation



Uncalibrated RBI-mitigated image Fully calibrated RBI-mitigated image

Figure 10: Dark Fixed Pattern visible in RBI-mitigated image before calibration

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