

Signal-to-Noise impact of CCD Operating Temperature

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Introduction

Previous papers have dealt with the impact of Sub-exposure times and the number of dark frames used for calibration. This paper will investigate the impact of certain sensor parameters and how they impact the sensor operating temperature to determine noise contribution. Running a sensor colder than necessary can lead to an increase in Residual Bulk Image (RBI), which has the appearance of a “ghost” of the original bright star or object. One approach to minimizing RBI is to run the sensor as *warm* as possible, consistent with SNR goals. Of course there are other techniques to reduce RBI as well, but by minimizing the occurrence in the first place, they can be more effective.

Analysis

All CCD sensors generate a dark signal to a greater or lesser degree. This is the charge that accumulates on every pixel during integration mode when the shutter is closed and is called the dark signal flux, N_e . It is given by:

$$(1) \quad N_e = \frac{D_e}{2^{\frac{T_s - T_c}{X_e}}}$$

Where

- D_e = the average dark signal at T_s
- T_s = the temperature at which D_e is specified
- T_c = the CCD operating temperature when cooled
- X_e = the dark signal doubling temperature

D_e , T_s and X_e are unique to and specified for a given CCD sensor.

D_e is normally measured by the sensor vendor by averaging the pixel levels over the entire sensor area. In many cases, this may actually *overstate* the actual dark current level, since hot pixels may skew the average higher.

What this equation tells us is that for every X_e reduction in the sensor temperature, the dark signal reduces by a factor of 2. For example, if we have a Dark signal of 50e/sec at a sensor temperature of -10°C and X_e is 6.5, the dark signal will be 25e/sec. at -16.5°C.

From a previous paper, we saw the Signal-to-Noise equation was given by:

$$(2) \quad SNR = \sqrt{N} \frac{E_{obj} t}{\sqrt{E_{obj} t + E_{sky} t + N_e t + R_{on}^2}}$$

Where

N = number of sub-exposures and assumes a mean combine.

E_{obj} = Object flux in electrons per sec.

E_{sky} = Sky background flux in electrons per sec.

N_e = Dark current signal in electrons per sec.

t = Exposure time in sec

R_{on} = Readout noise in electrons

The denominator of (2) is the noise term that accompanies a single exposure. We can consider two conditions: sky noise limited and read noise limited. The former is most appropriate for narrow band imaging and the latter for broad band imaging.

Sky noise limited

Assuming we choose our sub-exposure duration sufficiently long so that sky noise overwhelms read noise, and ignoring object noise for the moment, the noise term is given by:

$$(4) \quad \text{Noise} = \sqrt{E_{sky}t + N_e t}$$

Now, assume we don't want the dark signal noise to add more than a factor of r to the sky noise. Stated mathematically,

$$(5) \quad (1+r)\sqrt{E_{sky}t} = \sqrt{N_e t + E_{sky}t}$$

Solving for the dark signal level:

$$(6) \quad N_e = [(1+r)^2 - 1]E_{sky}$$

We can combine this result with (1) to determine the camera operating temperature that meets this requirement:

$$(7) \quad T_c = T_s - X_e \frac{\ln(D_e) - \ln([(1+r)^2 - 1]E_{sky})}{\ln(2)}$$

Thus, given a specific sensor and local sky flux, we can define the lowest sensor operation needed to achieve the desired contribution, r , to the overall sky noise. Remember the effect of hot pixels skewing the D_e value so this is actually a worst case. Also note the exposure duration is not an explicit part of the desired operating temperature, since both the Sky signal and the dark signal increase linearly with increasing exposure duration, when in the sensor's linear range.

Read noise limited case

When narrow band filters are used for imaging, the sky flux is usually too low to overwhelm read noise so operation is in fact read noise limited. Examining the denominator of (2) above, and assuming we are read noise, the noise term is given by:

$$(8) \quad \text{Noise} = \sqrt{N_e t + R_{on}^2}$$

Now let us allow the dark signal noise to add no more than a factor of r to the read noise. Stated mathematically,

$$(9) \quad (1+r)R_{on} = \sqrt{N_e t + R_{on}^2}$$

We can now solve for the Dark Signal level needed for a given dark signal noise contribution factor, Readout noise and exposure time to be:

$$(10) \quad N_e = \frac{[(1+r)^2 - 1]R_{on}^2}{t}$$

Substituting (6) into (1), we can then determine the camera operating temperature to meet our noise contribution requirement, r, from the following equation:

$$(11) \quad T_c = T_s - X_e \frac{\ln(D_e) - \ln([(1+r)^2 - 1]R_{on}^2) + \ln(t)}{\ln(2)}$$

Here the exposure time is a factor as expected since the dark signal, and therefore its noise increases with increasing exposure time.

Discussion

Equations (7) and (11) give us separate criteria for the sky noise and read noise (wide band and narrow band filter) cases. It is instructive to calculate some numerical examples. Consider three Kodak sensors, the KAF3200ME, representing an older sensor design the KAF16803, representing a recent design, and the popular KAI11002. Here are the salient typical sensor data on dark signal:

	KAF 3200ME	KAF 16803	KAI 11002
De, Dark Signal (e/sec)	15	3	880
Ts, Dark Signal measurement temperature (°C)	25	25	40
Xe, Dark Signal doubling Temperature (°C)	6	6.3	6.3
Ron, Read Noise (e)	10	10	15

A moderately dark, suburban sky might have a sky flux with a sensitive camera of 3 e/sec. Assume we will allow a dark signal noise contribution to be 1% of the relevant total noise. Here are some calculation results for a 10 minute sub-exposure:

	KAF 3200ME	KAF 16803	KAI 11002
Sky noise limited	-18.3	-5.9	-42.5
Read noise limited	-47.8	-36.8	-66.0

This table illustrates the predicted sensor temperature to achieve a dark signal noise contribution of 1%. We can see that extra cooling is required in the narrow band case if the dark noise is to be kept to a small percentage of the total noise. However, for the broad band case, the camera can be run considerably warmer to achieve the desired noise performance, mitigating RBI effects. Also, don't forget the overstated dark signal due to the manufacturer's specification methodology. In all probability, at least for Kodak sensors, one could run the camera an additional 5°C warmer and still achieve the desired noise contribution.

Note that throughout this discussion, we are talking about the dark noise, not the magnitude of the dark signal itself. When we subtract a dark frame from the data, we are subtracting a dark signal but the dark noise remains. So it would be nice if we could eliminate adding this noise by not subtracting a dark. This is in fact the subject of another paper.

Conclusions

In addition to the numeric example, we can now understand some underlying trends. First, a lower dark signal sensor specification is always better. The lower it is, the less we have to cool a given sensor, assuming we are working in a sky glow limited environment, to minimize the dark signal's noise contribution.

As we might expect, there is a point beyond which cooling will have little further noise reduction, when compared to read noise. Calculating some test cases can give some insight into where the returns diminish.

When we compare imagers, we need to consider not only cooling capacity, how far below ambient a chip can be cooled, but also the read noise and the magnitude of the dark signal.

Steve Cannistra has done an interesting view of this issue that compliments this analysis with some great graphics, demonstrating these concepts. See his write-up at <http://www.starrywonders.com/coolinghidden.html>