Is it true that cooled cameras are more sensitive than non-cooled cameras?

The temperature has a significant impact on certain noise sources prevalent in cameras, which contribute to the total readout noise of an image sensor. When electronic devices are operated continuously, they dissipate heat due to losses in the signal processing. Reduction of temperature via “cooling” of image sensor components or electronic circuits in devices can indeed improve image quality and performance.

Upon further inspection, the advantages and disadvantages of cooling reveal that cooled cameras may not necessarily be more sensitive than non-cooled cameras. For this we need a closer look at the underlying effects of cooling.

Temperature Control

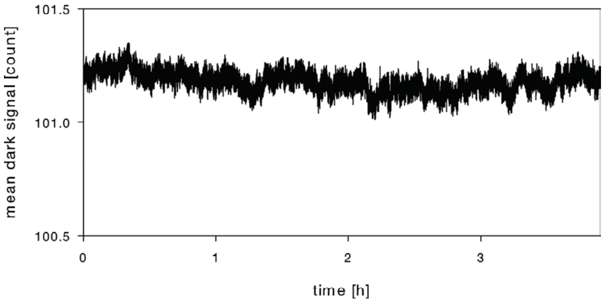

Figure 1: A four hour measurement of the mean dark signal of an sCMOS camera, which was continuously read out at full speed (100 fps) and whose image sensor was temperature controlled at + 5 °C (pco.edge 5.5).

The major reason for cooling is the temperature control of a camera system and especially the image sensor. Figure 1 shows an image sensor that is thermally stabilized with a thermo-electric Peltier-cooler; the camera can be operated, but the offset, the dark value, stays constant.

Subsequently, this camera can be used for light intensity quantification, because any change of the signal will be due to incoming light as opposed to fluctuations in temperature. However, there is no direct link between the quality of this stabilization and the absolute temperature. Therefore, it is less important to stabilize the image sensor at a deep or low temperature, but rather more critical to stabilize or control it. The drift or signal change in figure 1 per hour is about 0.5 [count], which means it is extremely stable.

Reduction of Dark Current

Another reason for cooling is the reduction of noise. In a light sensitive pixel there are temperature related noise sources which can be minimized by cooling. There also remains the possibility of temperature generated charge carriers called dark current. One of the remaining advantages of CCD image sensors compared to CMOS and sCMOS image sensors is the lower dark current, as the latter always have significantly higher dark current values. The contribution of the dark current to the signal is dependent on the exposure time and the operating temperature. If we have a look at the dark signal μ_d of an image sensor or camera, there is a temperature independent part $\mu_{d.0}$ and the temperature related part μ_{therm}. This goes linearly with the exposure time and equals the dark current μ_I (unit = [e-/(pixel *s)]) times the exposure time t_{exp}:

$$\sigma_d^2 = \sigma_{d.0}^2 + \sigma_{therm}^2 = \sigma_{d.0}^2 + \mu_I \cdot t_{exp}$$

According to the laws of error propagation, the variance of the dark signal is then given as:

$$\mu_d = \mu_{d.0} + \mu_{therm} = \mu_{d.0} + \mu_I \cdot t_{exp}{}^1$$

The thermally induced electrons are Poisson-distributed, as are the light induced ones with

$$\sigma_{th\,erm}^2 = \mu_{th\,erm}$$

Therefore, the dark current has different consequences.

Firstly, it always adds a light independent constant part to the signal, which depends on the exposure time and the temperature. Secondly, it has a readout noise contribution, which as well depends on the exposure time and the temperature. This means that at high frame rates and short exposure times the dark current can be negligible, while at low frame rates and long exposure times (> a few seconds) the dark current can accumulate and has a more significant contribution.

In relation to temperature it means the lower the temperature, the lower the dark current. In the case of a very low light application where long exposure times of seconds up to minutes can be expected, the image sensor should be cooled as much as possible (as long as the desired signal is not a longer wavelength than red) and if it is possible, a CCD camera might be used instead of a CMOS or sCMOS camera. But for applications with short exposure times (for example in the range of milliseconds), the cooling to reduce the dark current might not be required. It is not possible to give fixed numbers here as it depends on the application requirements in combination with the camera performance parameters.

Temperature Compensation as an Alternative for Non-Cooled Systems

Applications with frame rates of approximately higher than 2 fps (exposure times of < 500 ms) might benefit from a dark current compensation by proper camera calibration and pre-processing of the raw images. The red curve in figure 2 shows the image sensor temperature of an uncooled sCMOS camera, when images are recorded continuously and the image sensor was additionally heated up externally. Over the 80 minutes of the experiment, the temperature of the image sensor rises and it looks like it would reach a steady state. According to the temperature with a slight delay, the non-compensated dark signal (offset) follows the temperature and rises as well.

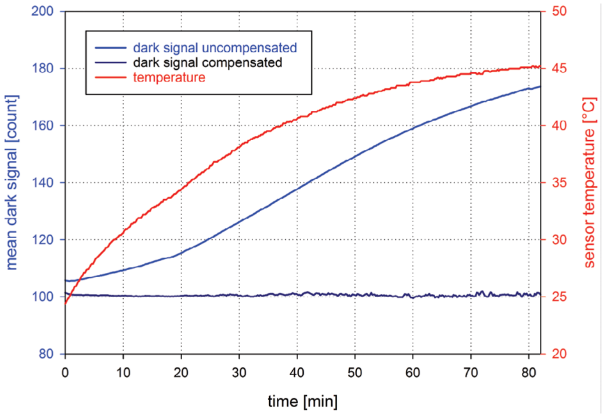

Figure 2: The switch-ON behavior of a non-cooled sCMOS camera if continuous images are recorded. The red curve depicts the temperature of the image sensor, the bright blue curve is the uncompensated mean dark-signal of the camera and the dark blue curve represents the compensated mean dark-signal of the same camera.

This temperature dependent behavior is well-known and characterized, thus each camera can be calibrated. There is also the possibility to read out the values of the shielded "dark" columns and rows additionally to the image and use this information as an indicator for a temperature related drift. This has to be done carefully, since the shields don't prevent light from scattering below. In case of a camera calibration with an integrated compensation (sometimes called "offset control"), the dark signal will look like the dark blue curve (figure 2). Obviously the noise increases with increasing temperature (see fig. 2, dark blue curve towards the end of the recording), because the dark current noise contribution is increasing, but the offset drift is compensated and the camera can be used for quantification.

Dark Current Influence in Total Readout Noise

Readout Noise [e-] (median)	Exposure time [ms]	Dark current [e-/pixel s]	Image Sensor Temperature [°C]	Total readout noise [e-]
2.1	1 ms	30 @ 28 °C	28	2.11
2.1	100 ms	30 @ 28 °C	28	2.72
2.1	10000 ms	30 @ 28 °C	28	17.45
2.1	1 ms	3.25 @ 7 °C	7	2.10
2.1	100 ms	3.25 @ 7 °C	7	2.18
2.1	10000 ms	3.25 @ 7 °C	7	6.08
2.1	1 ms	0.41 @ -14 °C	-14	2.10
2.1	100 ms	0.41 @ -14 °C	-14	2.11
2.1	10000 ms	0.41 @ -14 °C	-14	2.92

For the above table, a doubling temperature of the dark current of 7 °C was assumed. The table uses some exemplary values of an sCMOS image sensor, which has 30 [e-/pixels] dark current at 21 °C temperature. A reduction of the temperature by 7 °C means half of the dark current. The total readout noise, which determines the achievable signal-to-noise-ratio, changes then according to exposure time and temperature of the image sensor. There are three different exposure times assumed: 1 ms – 100 ms – 10,000 ms to show the contribution of the dark current to the total readout noise, and all this is given at different image sensor temperatures from 28 °C via 7 °C down to -14 °C. Clearly, for the long exposure time of 10 s and the high sensor temperature, the additional noise contribution is much too high. At 100 ms exposure time, the dark current related increase of 0.6 [e-] of the total readout noise is reasonable and at 1 ms exposure time, the dark current has no impact. If the image sensor is cooled down to -14 °C, even the 10 s exposure time can be used, because the readout noise increase of 0.82 [e-] is acceptable.

As the table shows for this performance data, the image sensor can be used at 28 °C for exposure times of 100 ms and shorter. If, for the given example, the image sensor should be used at exposure times of 10 s, a cooling of the image sensor for example down to -14 °C would be required.

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Disadvantage of Cooling

An intriguing relationship of temperature and image sensor behavior exists, likely attributable to the pure semi-conductor physics of silicon. Measuring light within an integrating sphere and with homogenous illumination at different image sensor temperatures and different wavelengths produces unexpected and somewhat surprising results. The results in figure 3 show the temperature dependence of the relative quantum efficiency for various wavelengths. The signals are all related to the values of the camera when the image sensor has a temperature of +5 °C. Similar results have been obtained with CCD image sensors. From UV to green radiation, the sensitivity of the image sensor increases a little with cooling, but only 1-2 %. Red to NIR produces the opposite effect, where the more the image sensor is cooled, the less sensitive it becomes for this spectral range of radiation. For example, for a wavelength of 950 nm, the loss of relative quantum efficiency with a cooling from +5 °C down to -25 °C is 18 %. In turn this means using a deep cooled camera (-50 °C sensor temperature) to measure long wavelength radiation (> 700 nm) is not optimal.

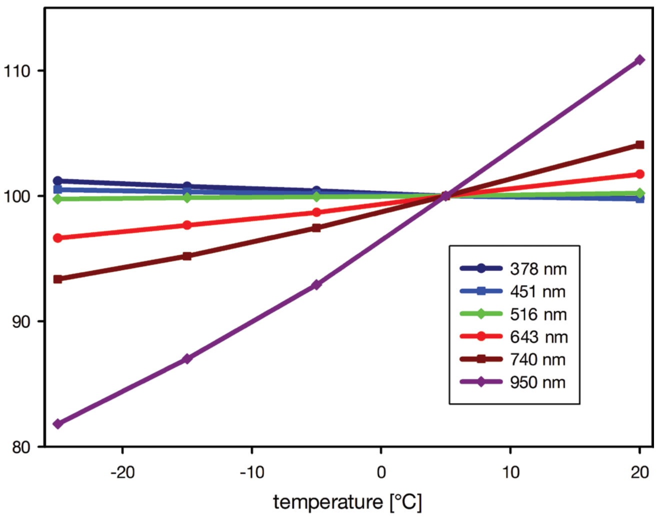

Figure 3: Measurement of the relative quantum efficiency of an sCMOS image sensor taken at different image sensor temperatures for various wavelengths (378 nm – 451 nm – 516 nm – 643 nm – 740 nm – 950 nm).

Cooling reduces the mobility of the charge carriers and for long wavelength detection, the radiation penetrates deep into the silicon to be able to generate a charge carrier (electron-hole pair). Now the charge carrier has to drift a large distance, and it does it slower, which increases the probability that it either recombines or gets lost by other mechanisms, but it doesn't contribute to the signal. For sure this effect has to be balanced with the temperature induced dark current noise contribution.

So Are Cooled Cameras more Sensitive?

No, not in general! As described, the cooling reduces the readout noise in some situations, and is recommended for longer exposure times (many seconds to minutes), but it also might have a negative effect on the quantum efficiency. Thermal stabilization is a good thing in general, but in case proper calibration and compensation is conducted, it is not always required.

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