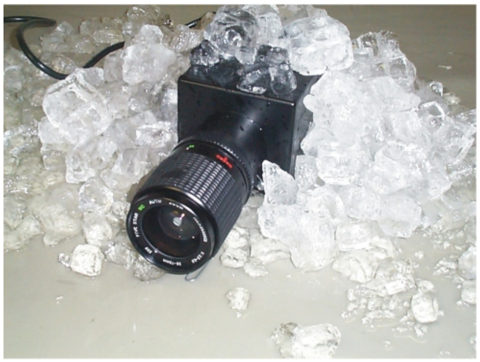
SALVADOR IMAGING *Precision Imaging Systems* **Advanced Camera Technology**



Does Your Camera Need Cooling?

Introduction:

Since the beginning of time, man has posed the question: Do I need to cool my CCD camera or not? Oh OK, maybe that's an exaggeration, but people do seem to get confused about it a lot. So, let's look at some of the reasons why people cool cameras and what performance improvements they hope to achieve. From this, you can determine whether your application would benefit from cooling and, if so, how much cooling is needed.

A Cool Sensor Produces Less Dark Current

One of the better known reasons for cooling an image sensor is to reduce dark current. Dark current refers to unwanted free electrons generated in the CCD due to thermal energy. The name dark current or dark charge comes from the fact that it has nothing to do with the incident light, and is generated equally well in complete darkness. Depending on where in the silicon these electrons are generated, some of the charge will get collected in the individual CCD pixels and contaminate signal electrons (generated from the image itself). At the CCD output, electrons generated from dark current look identical to signal generated electrons, so dark current appears as a noise source in the image.

At a given temperature, the average dark current in a given pixel is pretty much constant resulting in a fixed offset which is added to each pixel value. However, the dark current generation rate typically varies spatially across the array leading to a fixed background pattern which is superimposed on top of the desired image. By capturing an image in complete darkness, a pixel-by-pixel representation of the average dark current can be obtained for that temperature and exposure period. By subtracting this "dark reference image" from all subsequent real images, the effects of the spatially varying dark current offset can be partially eliminated. This process of subtracting off the dark reference image to eliminate dark current offset is known as dark-field correction. Unfortunately, dark current generation is a random process and is actually composed of two components. A fixed average value (the offset above) which can be removed through dark-field correction, plus a randomly varying part due to shot noise. The random portion of the dark current is given by the square root of the dark current collected in a given pixel and <u>cannot</u> be corrected. For example, a CCD which generates 4,000 electrons in a pixel during a one second exposure will have an offset of 4,000 electrons which can be subtracted plus a random noise of = 63 electrons rms which cannot be corrected.

Who cares, its only 63 electrons those things are really tiny little buggers aren't they?

Consider an example where you have purchased a 12-bit camera where each pixel can hold a maximum of 40,000 electrons (the “full well capacity”). If properly calibrated, each A/D count of the camera output would represent 40,000 electrons/2^{12}= 10 electrons. In other words, an increase of 10 photoelectrons captured by a given pixel would increment the camera's digital output by one count.

If this camera had a dark current of 4,000 electrons per second, and a one second exposure is taken, the average pixel would have an offset of 4,000 electrons which could be subtracted and for the most part eliminated. Keep in mind, however, that the dark current has consumed 4000 of the 40,000 maximum capacity, so your signal full well has been reduced to 36,000 electrons. Furthermore, the process of subtracting images takes time and computational power. Added to this 4000 electron offset, you also have a random noise from the dark current of 63 electrons rms. With the camera biased so that one A/D count represents 10 electrons, this means that your camera has about 6.3 counts of rms noise, and any signal which is less than this will never be seen. As a result, your 12 bit camera is only providing you a real dynamic range of

(40,000-4,000)/63 = 571:1 or about 9 bits.

How Does Cooling Reduce Dark Current?

Just as dark current increases with increasing temperature, dark current decreases if the sensor is cooled. This fact is used by some camera manufacturers to lower dark current to extremely low levels. A common example where ultra-cooled cameras are needed is in astronomy where, because of low light levels, researchers may wish to cool to as low as -100C, and take an exposure which is 30 minutes to an hour long. Cooling a camera to this level involves significantly more than simply pouring liquid nitrogen over the sensor while the camera is running. Cameras of this type can be quite complex- utilizing liquid nitrogen or multistage thermoelectric coolers combined with vacuum enclosures and closed-loop feedback to lower sensor temperatures to extreme levels. Extensive knowledge of heat transfer, materials science and semiconductor physics are all crucial to successfully cooling a camera in applications where dark current must virtually be eliminated. As such, only a few highly skilled companies such as Spectral Instruments and Roper Scientific offer products which are geared towards the ultra-cooled market.

I run at high frame rates, so dark current generation is insignificant, right?

Since the amount of dark charge captured is directly proportional to the exposure time, a shorter exposure (higher frame rate) will reduce the effects of dark current at a given temperature. However, the user should be careful not to assume that running at high frame rates alone makes them immune to dark current and other thermal issues. CCD and camera manufacturers typically specify dark current at a specific temperature (typically 25C). Higher frame rate cameras have significant self-heating within the sensor itself due to higher amplifier bias currents and higher speed clocking of the gate capacitance. It is not unusual to find a commercially available camera running at 30 frames with a sensor temperature of 45C. A rough approximation is that dark current doubles for every 6C increase. Using this rule of thumb, the sensor at 45C would produce dark current which is roughly 10 times greater than the specification shows. Not only is the dark current significant on this high frame rate camera, but the dark current changes by an order of magnitude between the time it is turned on (cool) and the time that the sensor reaches thermal equilibrium (perhaps 30 minutes later).

To further complicate things, the dark current will also change in an uncooled camera when operating modes are changed such as binning, TDI shift rate, frame rate, region of interest etc. Each time the dark current changes, the noise level and “black level” of the camera also change. As a result, any efforts to calibrate out these variations would require storing dark-field calibration frames for every possible operating mode, and even these are only valid once the camera has reached thermal equilibrium.

Is Dark Current the Only Parameter Affected by Temperature Variations?

With today's push for ever increasing speeds, many camera manufacturers have moved towards multiple output sensors. This is particularly true for TDI and area scan sensors used in high-speed inspection where composite data rates may exceed 1 billion pixels per second. For these multichannel cameras, varying sensor temperatures add a whole new set of challenges. In sensors which have multiple outputs, the gain and offset for each individual video channel must be precisely matched to all other channels. Moreover, these gains and offsets must not change over time and temperature. If they do, the resultant image will show “tiling” effects where the image section from a given output will vary in contrast and brightness with respect to adjacent image areas.

Both the gain and offset for these taps is affected by the operating temperature, and the operating temperature in an uncooled camera is affected by operating mode, ambient temperature, frame rate etc. As a result, cameras which are not thermally cooled typically have significant problems maintaining a good gain and offset balance. Attempts to correct this mismatch can be both time consuming and expensive for the customer; and in the end, a futile effort since the next change in operating mode or temperature will once again create imbalance.

I like the benefits of cooling, but isn't all that complexity going to cost me?

Clearly, low dark current and extreme thermal stability offer significant advantages in light-starved applications such as spectroscopy, crystallography and astronomy. Lowering the dark current to essentially zero with cryogenically cooled cameras allows the user to capture truly amazing images in situations where only a few photons are available. Camera manufacturers such as Roper Scientific and Spectral Instruments have built businesses upon their expertise in these ultra-cooled camera products.

In higher frame rate applications, the performance enhancement from a cooled camera would also be substantial. Reduced dark current noise coupled with a dramatic increase in stability and repeatability directly benefits applications ranging from semiconductor and web inspection to laser profiling and medical imaging. The problem is that most inspection applications are incompatible with the cost and complexity of cryogenically cooled sensors.

Fortunately, in the majority of these applications, most of the performance improvement can be accomplished simply by lowering the sensor temperature to a few degrees below ambient (e.g. 20C) and precisely stabilizing the temperature. Lowering the temperature to 20C reduces dark current in most inspection applications to an insignificant level and thermal stabilization insures that performance characteristics remain constant regardless of frame rate or operating mode. For higher speed cameras, this low-level cooling and thermal stabilization provides significant gains in imaging performance with little or no impact on camera cost.