DARK CURRENT AND INFLUENCE OF TARGET EMISSIVITY

Low-noise InGaAs camera Cougar-640

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Abstract: *We will report on the dark current and the influence of target emissivity and temperature on the measured "dark" current. This is of special interest for advanced scientific applications with extremely low light levels in the short-wave infrared (SWIR).*

Low dark current allows the user to (a) use very long exposures – for increased sensitivity and high signal-to-noise ratio, and (b) limit the dark current generated shot noise contribution, resulting in a very low noise performance. When performing a dark current measurement, it is of utmost importance to take the target temperature and emissivity into account.

1. Introduction

For very advanced scientific applications with extremely low light levels, Xenics has developed the Cougar camera to meet the required performance level. The Cougar camera is based on Xenics' well-established 640 x 512 pixel InGaAs detector array (with 20 µm pixel pitch), combined with a completely new in-house developed Read Out Integrated Circuit, based on a low noise SFD topology rather than a standard CTIA pixel interface.

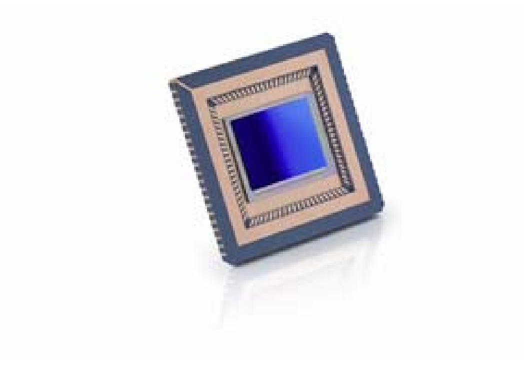

Figure 1-1 : Xenics' XFPA-1.7-640-LN2 sensor, the central part of the Cougar camera.

To limit the dark current to an absolute minimum, the sensor is placed in a vacuum dewar and is cooled using liquid nitrogen. This ensures sensor temperatures around 80K without having any moving parts (avoiding vibrations) or electrical coolers (causing interference and noise), yielding typical dark current levels down to 10 electrons per second or even below. This allows for an extremely long maximum integration time (~ hours), virtually without losing significant charge handling capacity, and consequently maintaining an excellent signal-to-noise ratio.

In general, this camera is the ideal candidate to monitor static scenes with extremely low light levels. Example applications are (Raman) spectroscopy, semiconductor failure inspection or photon emission microscopy (electro-luminescence) or astronomy.

In this technical note, we will focus more on the dark current and the influence of target emissivity and temperature on the measured “dark” current.

2. The camera

The camera consists of two parts: the vacuum dewar with the sensor device (the ROIC and the hybridized photodiode array) together with the proximity electronics and on the outside the electronics box with Analog to Digital converters, the CameraLink output interface, and sensor controller. Figure 2-1 shows a side view picture of the Cougar camera, with both parts clearly visible.

2.1. Cooled electronics

To ensure signal integrity and quality, one buffer-amplifier for each of the 4 output channels is integrated, and drives the signal towards the ADCs further in the signal chain. The buffer amplifier and ADCs were not integrated onto the sensor readout circuit (ROIC) to avoid self-illumination (also known as the Narcissus effect, i.e., photon emission by ROIC captured in the InGaAs SWIR photodiode array).

Figure 2-1 : Side view of cougar camera with grey electronics box (left) and vacuum dewar (right)

For similar reasons, the pixel rate is relatively low, and equal to 125 kHz, which results in a maximum frame rate of approximately 1.38 Hz. Note that the true image frame is a 648 x 520 pixel image with 4 dummy pixels (not connected to a detector device) on either side of the active array (which results in a 640 x 512 pixel captured image).

Two temperature sensors are integrated for temperature monitoring, they are located on the ROIC, and on the “cold finger” in the vacuum dewar.

2.2. Sensor and ROIC

Xenics in-house developed InGaAs detector array (640 x 512 pixels with 20 µm pitch) is the core of the system. This material has a cut-off wavelength of 1.7 µm at room temperature, which is reduced to approximately 1.55 µm when cooled to 80 K. When lowering detector operating temperature, the detector dark current reduces with a factor of 2 with every reduction of approximately 8 °C (rule of thumb). The InGaAs detector photodiode array or focal plane array is hybridized to the ROIC chip using the Xenics proprietary flip-chip technology.

Figure 2-2 : InGaAs Spectral Response curves at 80 K

The big differentiator for this camera is in fact the ROIC, which makes use of a SFD topology in the pixel (a simplified schematic of an SFD topology based on 3 transistors can be found in Figure 2-3). The integrating capacitor is basically the parasitic gate capacitor, and the junction capacitor of the detector diode. One can show the main noise contribution in this topology is the reset noise on the integration capacitor (which is in this case approximately 77 fF). The topology allows for signal integration without virtually any power dissipation, resulting in very low glow or self-illumination from the ROIC. Therefore it has a significant advantage in achieving low dark current levels over the CTIA or any other amplifier-based readout cell.

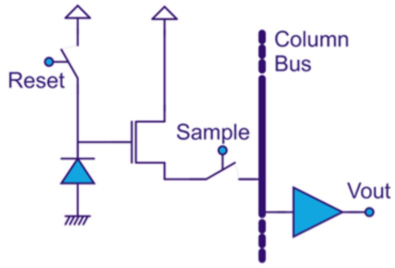

Figure 2-3 : SFD 3T Active Pixel

2.3. Camera electronics

The camera electronics basically consists of buffer amplifiers and ADCs combined with an FPGA generating the required digital signals to drive the sensor chip and the converters. Due to the very low noise and dark signal, a regular 16-bit ADC is not accurate enough to digitize the signals coming from the detector device. To avoid dominating quantization noise, a 24-bit ADC (6 V input dynamic range) was integrated.

3. Dark Current Measurements at low temperatures

Since the InGaAs detector device is cooled down to near liquid nitrogen temperature (~80 K), the detector dark current will be extremely low, and we will have to consider the radiation of the object the detector is staring at (target). This target radiation can be readily calculated from Planck's law, which gives the emitted radiance of an object at a specific temperature (see Figure 3-1). Planck's law enables us to calculate the number of emitted photons in a specific wavelength band, on to a detector pixel given a solid angle defined by the F-number or aperture of camera and optics.

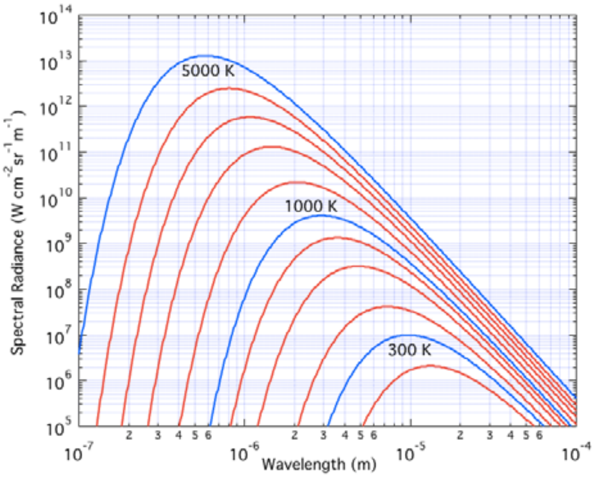

Figure 3-1 : Spectral Radiance as a function of wavelength for a blackbody radiating at a specific temperature as predicted by Planck's radiation law

We will now consider an object emissivity ε of 5 %, and temperature of 300 K (an aluminum plate), a detector pixel area A_{Pxl} of 20 µm x 20 µm, an F number of 0.7, and a wavelength range of λ_{min} = 900 nm to λ_{max} = 1550 nm. The number of photons per unit time depicted in Figure 3-2 is based on the following expression:

$$n_{\Phi} = \varepsilon \frac{\pi}{1 + 4F_{\#}^{2}} A_{Pxl} \int_{\lambda_{min}}^{\lambda_{max}} \frac{2c}{\lambda^{4}} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} d\lambda$$

Where h and k are Planck's and Boltzmann's constant, and c is the speed of light in vacuum.

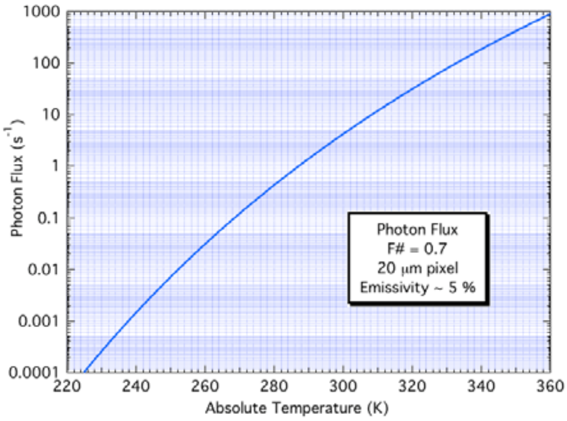

Figure 3-2 : Photon flux as a function of object temperature for Cougar detector pixel size and solid angle defined by F number.

With the information in Figure 3-2 as a guideline, we can conclude that if we want to measure actual dark current (which is the charge generated by the detector device, without any light present) accurately, we need to do this measurement with a *cooled* target, and preferably a material with low emissivity. This, in order to make sure that the charge, generated by the incoming photon illumination, is negligible compared to the detector current.

If we do the measurement looking at an object at room temperature (approximately 300K), and even with low emissivity of only 5%, we would collect almost 10 electrons per second due to scene or target radiation, and on top of this the actual dark current. For an accurate measurement of the dark current generated in the detector we need a target cooled down to at least 200 K (taken into account the fact that the emissivity of a controlled source, i.e., a black body reference source, is close to 100 %).

4. Dark current measurement results

Dark current consists of the charges generated in the detector when no radiation occurs. However, as there is always some type of radiation present, a true measurement of detector dark charge generation has to be performed using a cold target - a target at a very low temperature, such that induced charges are negligible compared to the true dark charge generated by the device.

To allow users to verify generated dark current in a simplified way, without having to use cold target, the camera performance is also verified with an external shield at room temperature. Although this leads to additional thermal photons contributing to the dark signal and therefore noise, and therefore, it is not the actual dark current only of the camera, these conditions can easily be reproduced by a user. Figure 4-1 shows a dark current image calculated based on measurements taken with a target at 300 K, and emissivity of 5%. The edge effect is induced by the mechanical mounting of the device.

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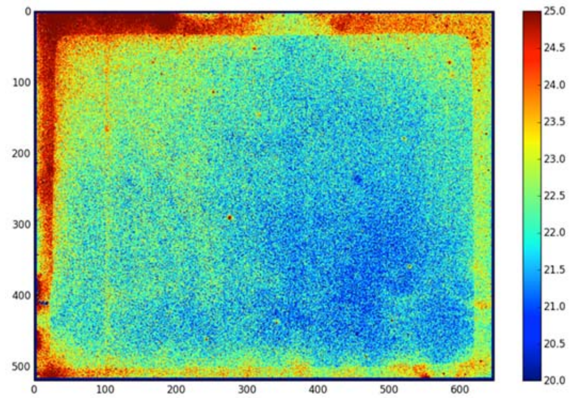

Figure 4-1: Calculated FPA dark current generation (e/s) using a target at 300 K (aluminium plate with emissivity of approximately 5%.

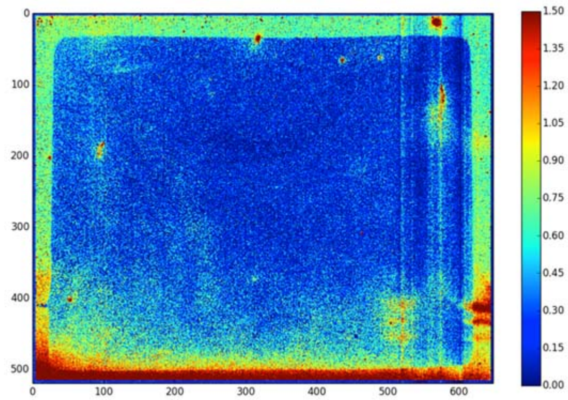

Figure 4-2: Calculated FPA dark current generation (e/s) using a target at 80 K (cold shield metal plate attached inside the vacuum dewar).

Figure 4-2 shows the same image, taken with a cold target at 80 K. One can observe that the generated charge is extremely low (in this case smaller than 1 e/s).

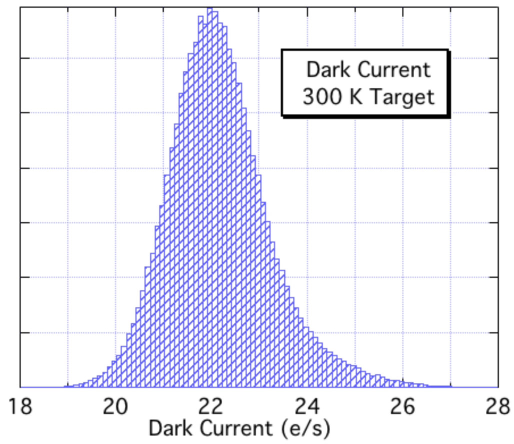

Figure 4-3: Dark current histogram (collected with target @ 300 K and emissivity 5%)

Figure 4-3 shows the dark current histogram collected with a target at 300 K (aluminum plate with emissivity of approximately 5%). The maximum occurs at 22 e/s, and 95 % of the pixels have a dark current between 20 and 25 e/s.

In this case (based on the presented calculations in 3) the measured current is dominated by radiation induced charges, as the collected charge is comparable to the photon flux generated by the target. In addition to the measurements described above, we have also used other target materials such as a gold plated mirror at room temperature (very low emissivity) and a black anodized aluminum target (high emissivity).

In summary, we can describe the influence of the target temperature and emissivity as follows:

- Aluminum plate (300 K, approx. 5% emissivity): dark current of 22 e/s
- Aluminum plate (300 K, black anodized, high emissivity): dark current of more than 80 e/s
- Gold plated mirror (300 K, very low emissivity): dark current of less than 10 e/s
- Aluminum plate (80 K, inside vacuum dewar): dark current of less than 1 e/s

5. Conclusions

In this document we have introduced the Xenics Cougar camera based on a 640 x 512 pixel InGaAs detector array (with 20 µm pixel pitch), and in particularly, we have focused on the extremely low dark current capabilities. The extremely low dark current allows the user to:

- use very long exposure times – for increased sensitivity and high signal-to-noise ratio
- limit the dark current generated shot noise contribution, resulting in a very low noise performance

We have also highlighted the extreme significance of target temperature and emissivity when performing dark current measurements. Therefore, it is important that any dark current calibration is performed on-site with all optics, and all possible contributions from targets at room temperature in place. It is also important to understand that the real, intrinsic dark current of the sensor (~1 e/s) cannot be measured in a real application setup, when using a target or scene at approximately room temperature.

Cougar cameras are currently in use by customers for medical spectroscopy, astronomy observations and electro-luminescence applications for semiconductor failure inspection. This can be expanded to the imaging of any static scene with a very low light yield, requiring an extended integration time.

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