CMOS Image sensor characterization experimental setup

Thierry Avignon, Baptiste Perrin, Jean Augereau, Julien Moreau, Lionel Jacubowiez

Institut d'Optique Graduate School

Laboratoire d'Enseignement Expérimental (LEnsE)

2 Avenue Augustin Fresnel, 91127 Palaiseau (France)

Abstract

We demonstrate a very simple experimental setup that allows our students to study and fully characterize an industrial CMOS Image Sensor. In 2014, 95% of produced cameras are CMOS image sensors (Complementary Metal Oxyd Semiconductor) and only 5% are still CCD sensors (Charge-Coupled Device).

The main difference between CMOS and CCD is that each CMOS sensor pixel has its own readout circuit (voltage-photoelectron conversion and amplification) directly adjacent to the photosensitive area. CMOS image sensors are not only cheaper, because simpler to manufacture, they have a lower power consumption than CCD sensors. They also allow image processing at the pixel level (zones of interest (ROI), Binning, filtering, etc ...). However, compare to CCD sensor, CMOS sensors often demonstrate a lower dynamic, a larger read-out noise and a larger non uniformity of the spatial response. In overall, it is very important to understand every characteristic of an image sensor and be able to measure it in a simple way.

Our system consist in a small integrating sphere illuminated by a white LED, a standard calibrated photodiode (or a light power meter) and a small monochromator (or several colored LED). Control of the camera parameters, Image acquisition and data processing are achieved with a single Matlab homemade software.

Keywords: CCD and CMOS image sensors characterization, dark signal, readout noise, photon noise, pattern response non-uniformity, quantization, binning, ROI

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1. CMOS sensor datasheet :

The purpose of the lab is to measure the characteristics of an industrial camera with a CMOS sensor manufactured by the E2V company (1.3 Mpix 5.3 µm pixels square). A part of the datasheet is given below.

Capteur EV76C560 Typical electro-optical performance @ 25°C and 65°C, nominal pixel clock

Parameter		**Unit**	**Typical value**	
Sensor characteristics	Resolution	pixels	1280 (H) × 1024 (V)	
	Image size	mm inches	6.9 (H) × 5.5 (V) - 8.7 (diagonal) ≈ 1/1.8	
	Pixel size (square)	µm	5.3 × 5.3	
	Aspect ratio		5 / 4	
	Max frame rate	fps	60 @ full format	
	Pixel rate	Mpixels / s	90 -> 120	
	Bit depth	bits	10	
Pixel performance			**@ 25°C**	**@ 65°C**
	Dynamic range	dB	>62	>57
	Qsat	ke-	12	
	SNR Max	dB	41	39
	MTF at Nyquist, λ=550 nm	%	50	
	Dark signal [1]	LSB_{10}/s	24	420
	DSNU[1]	LSB_{10}/s	6	116
	PRNU [2] (RMS)	%	<1	
	Responsivity [3]	LSB_{10}/(Lux.s)	6600	
Electrical interface	Power supplies	V	3.3 & 1.8	
	Power consumption: Functional [4] Standby	mW µW	< 200 mW 180	

1. Min gain, 10 bits.
2. Measured @ Vsat/2, min gain.
3. 3200K, window with AR coating, IR cutoff filter BG38 2 mm.
4. @ 60 fps, full format, with 10 pF on each output.

Figure 1 : Datasheet of the CMOS sensor

We first ask to the student to understand the definitions of each characteristic of the datasheet.

For example Q_{sat} is the Full Well capacity. It defines the amount of photoelectrons an individual pixel can hold before saturating.

If the sensor is photon noise limited, the SNR max depends only of the full quantum well capacity:

$$SNR = \frac{Q_{sat}}{\sqrt{Q_{sat}}} = 110 \text{ and } 20\log(110) = 41dB$$

From the full well capacity of one pixel, the students can also deduce an approximate value of the conversion factor between numbers of photo-electrons and level of the digital signal.

$$G = \frac{Q_{sat}}{\text{Bit depth}} = 1200/1024 = 11.7 \;\; e^{-} / ADU$$

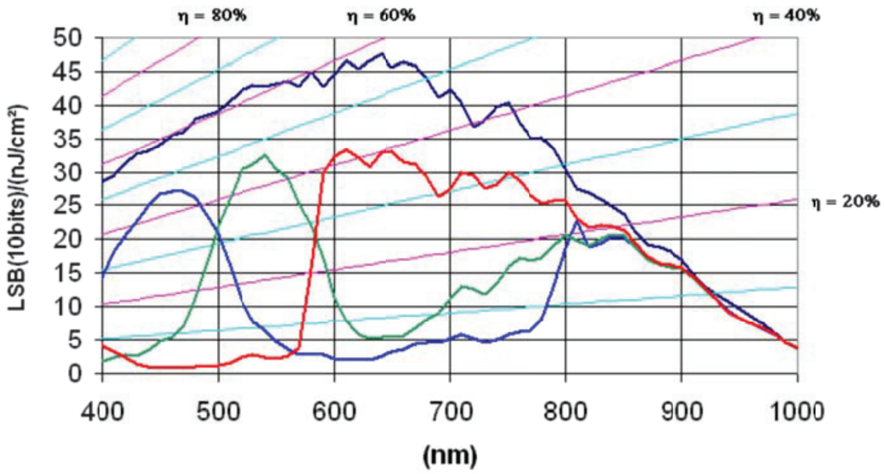

Figure 2 : Spectral response of the sensor (from the datasheet of the sensor)

From this curve, the students can check the consistency between quantum efficiency and the spectral response of the sensor.

For example, at 600 nm, according to this datasheet, the sensor will measure a level of 45 for a radiant exposure of 1 nJ/cm^2. This radiant exposure of 1 nJ correponds to 849 photons. For a quantum efficiency equal to one and conversion factor of 11.7, the sensor would measure a level of 72 (849 / 11.7). A level of 45 given in the datasheet leads to a quantum efficiency: $\eta = {}^{45}\!/_{72} = 0.62$

2. Experimental set-up:

The measurements are done with 2 simple experimental setups:

1. For linearity and noise measurement: a small integrating sphere. The source is a white LED driven by an adjustable power supply.
2. For spectral response measurement: a monochromator with a collimator to shine the CMOS sensor with an adjustable wavelength. For each wavelength, a photodiode measure the irradiance of the sensor.

Figure 3 : experimental set-up

2. Matlab software:

Matlab homemade software was developed to easily change the parameters of image acquisition and quickly perform measurements of characteristics. An example of measurement is given in figure 4.

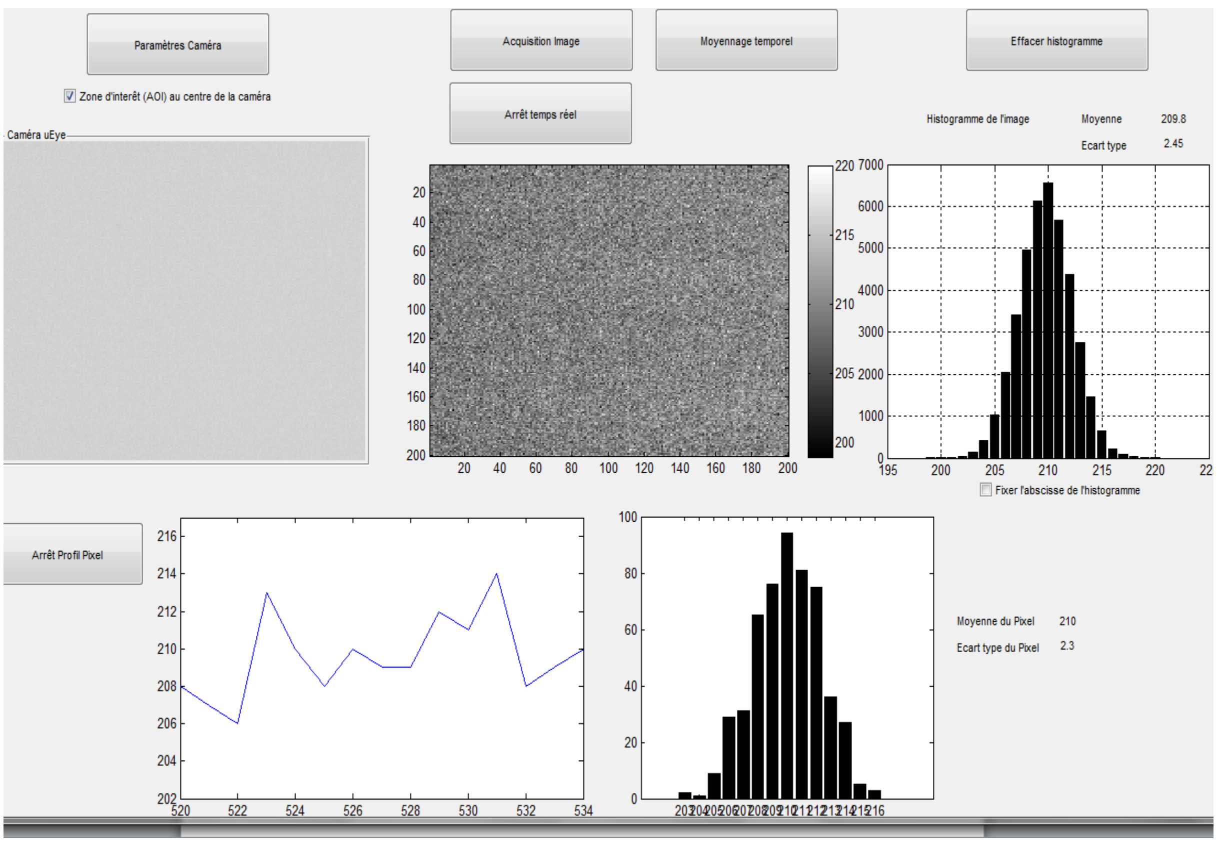

Figure 4 : Home made Matlab GUI

This software allows to choose all the parameters of the sensor and adjust the integration time. Here, we study a region of interest (ROI) of 200 x 200 pixels in the middle of the sensor. The software dispay the image of the ROI and the corresponding hitogram. We can also follow the value of one pixel and dispay the histogram.

3. Measurements of the image sensor characteristics:

1. Readout noise and dark signal:

In the dark with a very small integration time (less than 1 ms) , we measure a bias of 28 ADU and a the standard type deviation of 1.04 ADU.

Then we increase the integration time from 0 to 2 seconds and measure the mean value on the image. We can see the presence of hot spots on the sensor. For 1 second integration time we find a black level of around 20 ADU/s to compare with 6 ADU/s of the datasheet at 25°C. This value depends dramatically on the temperature of the camera. This explain why, for very low illumination, sensors must be cooled down.

2. Linearity and photon noise:

With the integrating sphere with have an almost uniform irradiance of the sensor. To check the perfect linearity of the sensor with meaure the mean value in the ROI when we increase integration time.

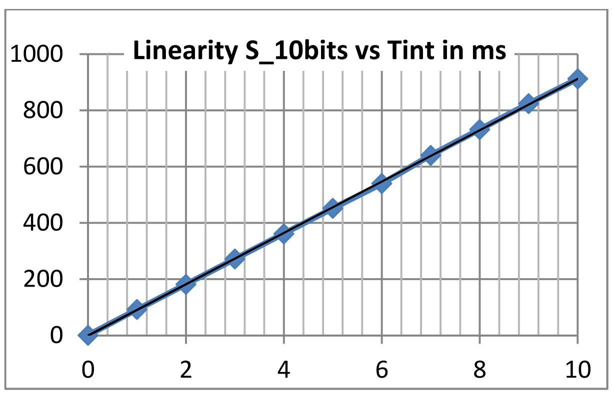

Figure 5 : Sensor linearity

To measure photon noise with measure the fluctuation of the level of one pixel.

Photon noise distribution is a Poisson distribution. The variance of the number of counted photo-electrons in one pixel is equal to the mean value of the number of photo-electrons:

$$\sigma_{Ne}^2 = < N_e >$$

The number of photoelectrons is converted into a digital signal: $S_{10bits} = Ne/G$ where G is the conversion factor or gain.

So the variance of the digital signal should be proportional to the mean value of the digital signal and the slope is the conversion factor of the sensor. Figure 6 is a typical plot that the students will find.

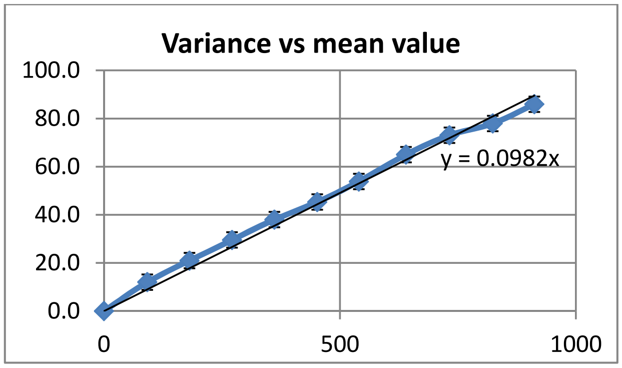

Figure 6 : Photon noise. The variance is proportionnal to the mean value

With this method we measure a gain : G = 10.2 +/- 0.5 e^-/ ADU. This value may be compared with G = 11.7

3. Spectral response of the detector :

For this last measurement, we use a monochomator and photodiode for which we know the spectral response. This photodiode allows measuring the irradianceof the sensor.

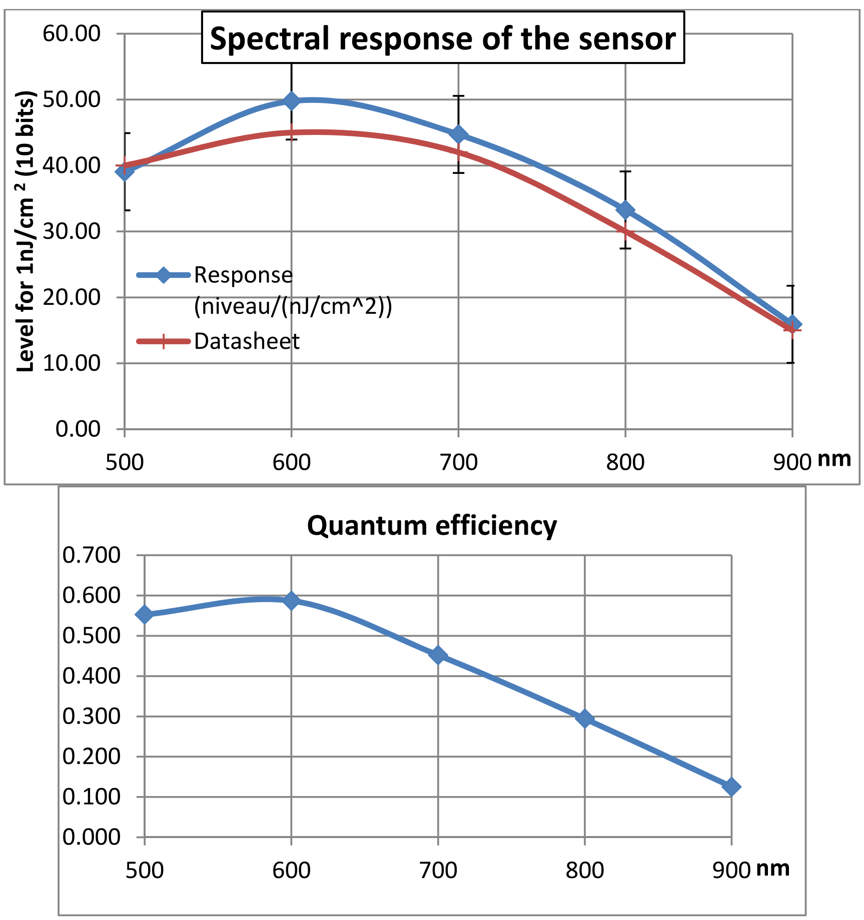

Figure 7 : Typical measurement of the spectral response and quantum efficiency

4. Conclusion

This simple setup allows our undergraduate students to measure and understand the difference between a bias and dark signal. They can measure the readout noise and the non-uniformity of the dark signal. They will see how the dark non-uniformity pattern increases with the integration time. They will check the linearity of the sensor. They will carried out accurate photon noise measurements at the pixel level, and that's seem very important for an future engineer specialized in optics. Finally, they will be able measure the spectral response of the sensor. This simple setup could be used with any image sensor (CMOS or CCD).