IEE3873/ASP5406 Astronomical Instrumentation Experiment 2 - Characterization of a CCD Detector

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***Abstract*—This document presents the characterization of a CCD detector of a STF-402M camera of 16 bits from SBIG, measuring it's bias level, hot, dead and noisy pixels, read-out-noise, conversion factor and dark current. A brief explanation of fundamental concepts are first introduced, followed by details of the methodology and setup used for each measurement, using calibration frames. The bias level obtained was 1018 ADU. Also, it was measured that 0.69% of the pixels that the detector has are hot pixels, 0.58% are dead pixels and 1.6% are noisy. The read out noise experimentally calculated was $17\mathrm{e}^-$, which only has 2 electrons of difference with the RON that the datasheet presents[1] while the dark current experimentally calculated was $1.78\frac{\mathrm{pA}}{\mathrm{cm}^2}$ which is not really near to the sensor datasheet[1]. This is probably because the main problem with dark current is that it accumulates at a different rate in every pixel. Some pixels are "hot" and others are "cold". Fortunately, the effect of hot and cold pixels can be easily removed[2]. Knowing all this characteristics, it is possible to characterise correctly the detector and it's internal noise. This is great help to process images and improve their quality.**

I. Introduction

A detector is any device that converts an amount of radiation into some other measurable phenomenon. Ultimately, most of these other measurable phenomena will be tied to an electrical signal [3]. One type of detectors are optical detectors, which convert the visible range of the electromagnetic spectrum into an electrical signal and therefore can be used along with a telescope to get images of space. There are two types of optical detectors used in astronomy: CCD (Charge Coupled Device) and CMOS (Complementary Metal Oxide Semiconductor). Both are made essentially by metal oxide semiconductors and are arranged on a matrix form.

In particular, a CCD detector is an integrated circuit containing an array of linked, or coupled, capacitors. Under the control of an external circuit, each capacitor can transfer its electric charge to a neighbouring capacitor [4]. It's function is to save electrons on each of the positions of the array (called pixels). The electrons in a pixel are converted into counts, or ADUs (Analogue-to-Digital conversion Units). The number of ADUs corresponding to one electron is called the *gain* [5]. These electrons can be generated by incoming photons or heat. The electrons of interest are the ones generated by the photons, but it is impossible to get rid of the electrons produced by heat because the CCD will always have a temperature greater than 0 K. Therefore, a way to increasing the signal to noise ratio is to take calibration frames and use them in an image pre-processing technique.

A. Calibration Frames

Calibration allows us to mathematically calibrate each pixel to react the same way to each photon it sees. The calibrations frames include [6]:

- **Bias Frames:** Bias frames are images taken in the dark (camera can be inside a box with the lens cap on) and with the shortest exposure time possible. The more Bias frames taken, the merrier. Then all these frames can be averaged to generate the Master Bias Frame that will be used for the light image pre-processing.
- **Dark Frames:** Dark frames are also taken in the dark but their exposure time must match the exposure time of the Light frames. ISO and temperature must also match the Light frames. To match the temperature, it is recommended to take the darks after finishing imaging for the night or on another night the temperature is the same. Afterwards, the averaging of all the Dark frames taken is needed to create the Master Dark Frame.
- **Flat Frames:** To take a Flat frame, every part of the aperture must be evenly lit by a plain light source (one way to do this can be to put a white t-shirt over the end of the aperture and point it at a laptop screen). The exposure time can vary from setup to setup but no part of the camera sensor should be lit more than 80% of the full range (on a DSLR the exposure time should be such that the histogram is between 1/2 and 2/3 on the back of the camera). The ISO must be the same as in Light frames. Flat frames are useful to capture how were the conditions when imaging (dust, etc) so they should be done right after finishing the imaging for the night. It is important that the focus, rotation, etc. does not change before you capturing the flats since doing so will change the optical path to each pixel. A Master Flat Frame must be obtained as well.
- **Dark Flat Frames:** Dark Flat frames are taken in the dark and have same ISO and exposure time as Flat frames. Averaging several of these frames produces the Master Dark Flat Frame.

With the above information in mind, the intensity ADU_i in each pixel i of a Light frame is:

$$ADU_i = \alpha \left(BIAS_i + DARK_i \cdot \Delta t + \eta \cdot I_i \cdot \Delta t \right) \quad (1)$$

where $BIAS_i$ are the electrons accumulated in pixel i of the Master Bias Frame, $DARK_i$ are the $e-$ per second accumulated in pixel i of the Master Dark Frame, α is the gain (it has units $ADU/e-$), Δt is the exposure time of the Light frame, η is the efficiency and I_i is the incident intensity in $e-/s$.

B. Detector Parameters

Furthermore, from the calibration frames explained above, multiple detector parameters can be obtained, such as:

1) **Bias Level:** The bias level of a CCD frame is an artificially induced electronic offset, that ensures that the analog-to-digital (A/D) converter always receives a positive signal in order to reduce digitization errors [7]. The bias level is consistent from image to image, so it can be subtracted to make image correction [1]. It is calculated as:

$$\text{Bias Level} = \frac{1}{N} \sum_{i=1}^{N} ADU_i \quad (2)$$

where N is the total number of pixels in the detector and ADU_i are the counts of pixel i in the *Master Bias Frame*.

2) **Hot Pixels:** Hot pixels are those saturated (or close to saturation) [8] so they always appear illuminated. A hot pixel is mathematically defined as the pixels whose counts satisfy the following expression:

$$ADU_i > \mu + 5 \left(\frac{\sigma}{\sqrt{2}} \right) \qquad \forall i = 1, ..., N \quad (3)$$

where N is the total number of pixels, ADU_i are the counts of pixel i in the *Master Dark Frame* and μ is the mean of those values. σ is the standard deviation of the ADUs of the pixels of the subtraction of two dark frames (therefore it must be divided by $\sqrt{2}$ to account for the error propagation of the subtraction).

3) **Dead Pixels:** These pixels are always dark. They can be blind or have very low quantum efficiency [8]. They are mathematically classified as those that satisfy the following expression:

$$ADU_i < \mu - 5 \left(\frac{\sigma}{\sqrt{2}} \right) \qquad \forall i = 1, ..., N \quad (4)$$

where N is the total number of pixels, ADU_i are the counts of pixel i in the *Master Flat Frame* and μ is the mean of those values. σ is the standard deviation of the ADUs of the pixels of the subtraction of two flat frames (therefore it must be divided by $\sqrt{2}$ to account for the error propagation of the subtraction).

4) **Noisy Pixels:** These pixels are significantly noisier than average, as, for instance, those with highly variable dark level or quantum efficiency [8]. Mathematically, these pixels are the ones with:

$$ADU_i > \mu + 5 \left(\frac{\sigma}{\sqrt{2}} \right) \qquad \forall i = 1, ..., N \quad (5)$$

or with:

$$ADU_i < \mu - 5 \left(\frac{\sigma}{\sqrt{2}} \right) \qquad \forall i = 1, ..., N \quad (6)$$

either in the *Master Flat Frame* or in the *Master Dark Flat Frame*. Therefore they include the hot and dead pixels.

5) **Read-Out-Noise:** The act of reading the voltage present at the output node has an associated noise level independent of the actual electron load present, including when there are no electrons present. This is called the read noise and is a fundamental limit on the dynamic range of the CCD. The read noise is the minimal noise level that a CCD camera can achieve, and the signal must be higher than the read noise for it to be detected [7]. It is measured in electrons. The RON can be calculated as the standard deviation of the values of the Master Bias Frame. However, this method does not eliminate "structural" errors of the detector, so instead, it is preferable calculate the RON as the standard deviation of an image obtained by *subtracting two bias* frames:

$$RON = \frac{\sigma}{\sqrt{2}} = \frac{1}{\sqrt{2}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (ADU_i - \mu)^2} \quad (7)$$

where σ and μ are computed from the values of the pixels of the image obtained by the subtraction of the bias frames, N is the total number of pixels and the $1/\sqrt{2}$ factor arises from the error propagation of the frame subtraction.

6) **Conversion Factor:** It has units of e-/ADU, therefore it is used to convert ADU counts into electrons or vice versa. It is represented as $1/\alpha$ in equation (1). To calculate it, 1) first at least three pairs of Flat frames must be captured. Each pair with a different exposure time Δt_j. 2) Second, with each pair, a Master Flat can be computed to which a Master Bias must be subtracted (so the values of the output represent purely the flats). From this output frame, a mean value μ_j can be obtained. 3) Third, for each Δt_j, one frame of the pair must be subtracted by the other one and then a variance σ_j^2 must be calculated from the output image. 4) In brief, for each Δt_j there there will be a set of values (μ_j, σ_j^2), which can be plotted in a $\sigma_j^2/2$ vs μ_j graph (the $1/2$ factor is added because of error propagation). 5) Finally, a linear fit must be added to the plot and the resulting slope corresponds to α. The conversion gain, α, given by this technique must be corrected for a factor that takes into account the coupling of adjacent pixels' capacitance [8].

7) **Dark Current:** A CCD cannot distinguish electrons generated by photons from those generated by heat. A CCD always generates electrons from heat at a constant

rate, called the dark current, and long exposure times allow more of these heat, or thermal, electrons to be captured in a pixel well. This adds an offset error—a systematic error—to the image, as well as some random noise to the signal itself. This dark noise can be minimized by cooling the CCD to very low temperatures [7]. To compute the dark current, equation (1) will be expanded:

$$ADU_i = \alpha \cdot BIAS_i + \alpha \cdot DARK_i \cdot \Delta t + \alpha \cdot \eta \cdot I_i \cdot \Delta t$$

Then, if a Master Dark Frame is being analysed, $I_i \to 0$:

$$ADU_i^{M.Dark} = \alpha \cdot BIAS_i + \alpha \cdot DARK_i \cdot \Delta t$$

where $\alpha \cdot BIAS_i = ADU_i^{M.Bias}$ is known, as well as α and the exposure time Δt, therefore the dark current can be cleared:

$$DARK\left[\frac{e^-}{s}\right] = \frac{ADU_i^{M.Dark} - ADU_i^{M.Bias}}{\alpha \cdot \Delta t} \tag{8}$$

C. Experiment

Given the importance of getting to know the detector's characteristics to obtain a good imaging performance, the purpose of this laboratory experience is to measure the parameters explained above for a bi-dimensional CCD detector. In particular, for the detector inside of a STF-402M camera from SBIG [1][2]. It's an old camera that now is discontinued, but has a really sensitive detector.

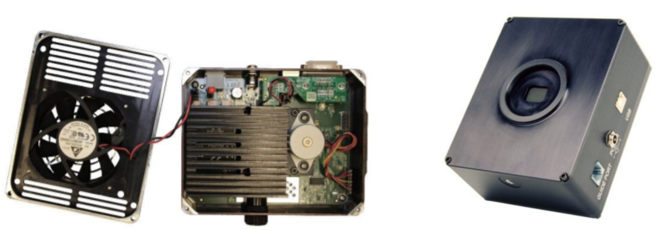

Figure 1. Inside (left) and outside (right) view of the camera.

The detector is a monochrome KAF-0402 imaging sensor[2]. It's an array of 765 (horizontal) X 510 (vertical) pixels and every pixel is a square of $9[\mu m]$X$9[\mu m]$, which results on 0.3 million pixels[1].

Figure 2. KAF-0402 imaging sensor.

The main characteristics that the manufacturers indicate are[2][1]:

Characteristic	Value
Read out Noise	$15\ [e^-]$
Dark current	$10\ [pA/cm^2]$
Quantum efficiency	$45\% - 77\%$
Saturation signal	$100000\ [e^-]$
Min exposure time	$0.09[s]$
A/D Converter	16 bits
A/D Gain	1.5 $e-$ unbinned

II. Method

In this section, information will be provided about the experimental setup, how the experiment was conducted, how data was collected and analysed, etc. Sufficient detail will be given so the experiment can be repeated by someone else. To begin, it is important to make sure that the workplace has controllable illumination and temperature of maximum 25^oC [1].

A. Detector and Software Setup

1) Install on a computer a software to control the camera. We used CCDOps, that is an SBIG platform[2].
2) Connect the camera with the computer, we used an USB serial connection [9].
3) Define the binning on high resolution [9] because for these experiments we decided not to do any special binning.
4) Set the temperature of the detector in the CCDOps settings because the default temperature is 17^{o}C. The temperature must be low (the lower the better). We recommend 0^{o}C so the images are good enough and the detector's fan does not operate at its maximum power. This is a VERY important step and must not be forgotten, otherwise the measurements will have too much electrons produced by heat.

B. Frame Capturing Setup and Measurements

After completing the steps mentioned above, we used the following setups for each measurement.

- **Bias Frame and Dark Frame Setup:**
  1) To turn the illumination of the workplace to the minimum possible we put the camera into a drawer with the lid on.

Figure 3. Camera lid on (left) and inside a dark drawer (right).

  2) We set the exposure time on the *Grab* window of CCDOps tool bar as shon in Figure 4. For the bias frames the exposure time was set to the minimum possible. Even though the camera has a minimum

of $0.09[s]$ of exposure time [2], the program set this automatically to $0.04[s]$. For the dark frames the exposure time was variable.

3) We configured the camera by software to take a dark image: *dark frame "only"* configuration [9]. This means that the internal lid that covers the sensor will not be opened.

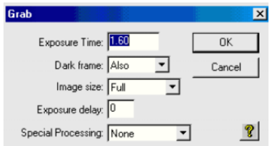

Figure 4. CCDOps *Grab* window. In the first slot the exposure time can be defined. In the second slot the options available are: "Only" (to capture dark frame), "None" (to capture light frame) and "Also" (to capture a light frame and then a dark frame, so the output is the subtraction of light-dark).

Finally, 20 bias frames were captured such as Figure 5.

Figure 5. Example of a bias frame.

Also, 10 pairs of dark frames were captured (see Figure 6) with increasing exposure times of t_{exp} = [0.11 s, 0.20 s] with a step of Δt = 0.01 s between measurements.

Figure 6. Example of a dark frame with 0.18 s of exposure time.

- **Flat Frame Setup:**
  1) We used our cell phone's flashlight as light source.
  2) Then we placed the detector (and the computer to which it was connected) about 4 m away from the light source and made sure they were aligned.
  3) We turned off the lights of the room so it was completely dark except for the light of the flashlight.
  4) We configured the camera by software to take a light image: *Dark Frame "None"* configuration in Figure 4 [9].

10 pairs of flat frames were captured for increasing exposure times in a range of t_{exp} = [0.11 s, 0.20 s] with a step of Δt = 0.01 s between measurements.

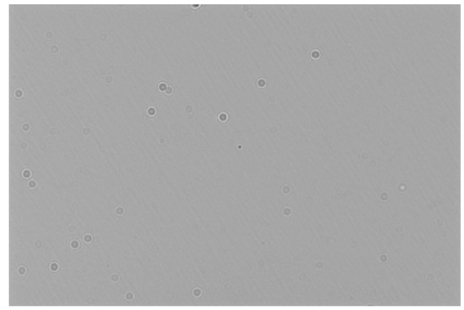

Figure 7. Example of a flat frame with 0.115 s of exposure.

C. Data Analysis

The frames were saved in the computer in FIT format with the CCDOps program and were processed in MATLAB. They were uploaded to MATLAB using *fitsread()* command. Then, the information required to calculate the parameters was extracted using commands such as *mean()* and *std()*. It is important to have in mind that given that the images are in 16 bits it is recommended to work with *double()* data type so there are no overflows in MATLAB.

III. Results and Discussion

1) **Bias Level**
The bias level was computed from a Master Bias Frame formed by 20 bias frames (Figure 8) is:

$$\text{Bias Level} = 1018\ ADU$$

Given that the images are saved on 16 bits, we can have ADU levels between 0 and 65535. Therefore all pixels of the images taken with this camera will have an average offset of 1018 ADUs. This way there will not be any negative values produced by the readout noise.

Figure 8. Master Bias Frame.

2) **Hot Pixels**
The percentage of hot pixels for different exposure times are presented in the following plot:

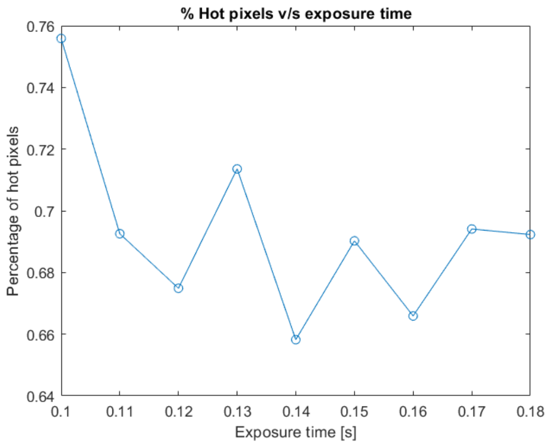

Figure 9. Percentage of hot pixels for different exposure times.

The percentage of hot pixels measured ranges from around 0.65% to 0.76% and the average value of hot pixels is 2704, which corresponds to the 0.69% of the total pixels that the detector has.

Supposedly, for greater exposure times, more heat will build up and probably there will be more hot pixels[2]. However, we can not see a really big and directly proportional relation between the exposure time and the number of hot pixels in Figure 9. We think this is because the time range in which the measurements were taken ($t_{max} - t_{min} = 0.2 - 0.11 = 0.09\ s$ specifically) is too small to notice any correlation. Additionally, the camera has a good refrigeration system that keeps the detector on a stable temperature[2]. Consequently, we think we do not have enough information to make a conclusion of the detector's behaviour on longer exposure times.

As deduced from the above explanation,a source of error in this measurement is the variation of room temperature. Although, in this case, it probably did not affect much because the lab is underground and not many people were present at the time of the measurements. Another source of error is the parasitic light. Even though the laboratory had the lights off, the screen of the laptop used to capture the frames was difficult to hide completely.

3) **Dead Pixels**
The percentage of dead pixels for increasing exposure times are presented below:

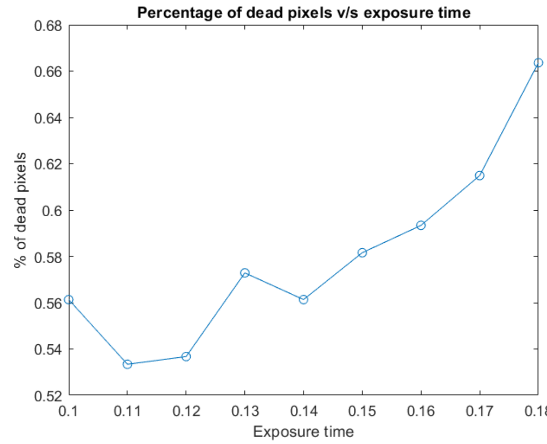

Figure 10. Number of dead pixels for different exposure times.

The percentage of dead pixels measured ranges from around 0.53% to 0.66% and the average value of dead pixels is 2262, which corresponds to the 0.58% of the total pixels that the detector has.

Dead pixels are usually the result of a manufacturing defect. If a defect prevents a pixel from receiving power, the pixel will remain black at all times. For instance, bumping into or knocking over a display device, may damage the power connection to one or more of its pixels, in which case a dead pixel can occur [10]. Therefore, before measuring the dead pixels we would tend to think that they were going to be constant. However the curve shows an increasing behaviour along with the exposure time which will be attributed to the detector's non-linearities and sources of errors (such as experimental setup errors, room temperature variations, dust, etc).

4) **Noisy Pixels**
The percentage of noisy pixels for different exposure times are presented below:

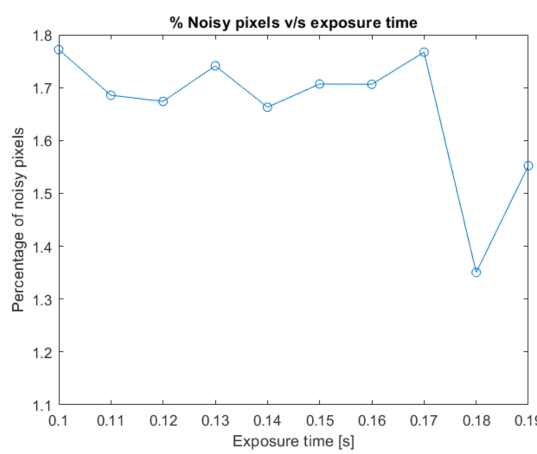

Figure 11. Percentage of noisy pixels for different exposure times.

Moreover, in the following table, the data is also summarised:

Exposure Time (s)	N° of Noisy Pixels	% of Noisy Pixels
0.11	6913	1.77
0.12	6576	1.69
0.13	6531	1.67
0.14	6793	1.74
0.15	6488	1.66
0.16	6659	1.71
0.17	6657	1.71
0.18	6894	1.77
0.19	5269	1.35
0.2	6056	1.55

Table I
Number and percentage of noisy pixels for different exposure times considering dark and flat frames.

The percentage of noisy pixels measured ranges from around 1.3% to 1.8% and the average value of noisy pixels is 6483, which corresponds to the 1.6% of the total pixels that the detector has. Noisy pixels include hot and dead pixels, therefore it makes sense that a bigger percentage was obtained.
To visualise the noisy pixels, a binary image (Figure 12) was created where the pixels in white represent the noisy pixels for a certain exposure time.

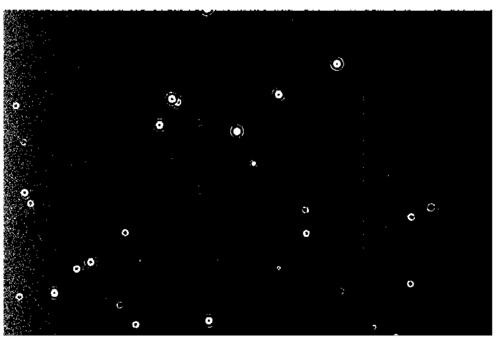

Figure 12. Example of noisy pixels (white pixels) in the image.

We can observe that in the left side of Figure 12, there is a vertical strip of accumulated noisy pixels, so it could be wise to avoid including them when imaging a scientific object. Also, there are many noisy pixels scattered around the frame in circular clusters which are produced by the specks of dust.

Actually, one source of error in the measurements of dead pixels and noisy pixels was the dust that was observable when taking flat frames as seen in Figure 7. It can cast shadows often called "dust donuts" due to their appearance in centrally-obstructed systems. Compressed air can help reduce dust donuts, but it is often difficult to completely eliminate them [2].

5) **Conversion Factor**
The conversion factor is obtained from the following graph:

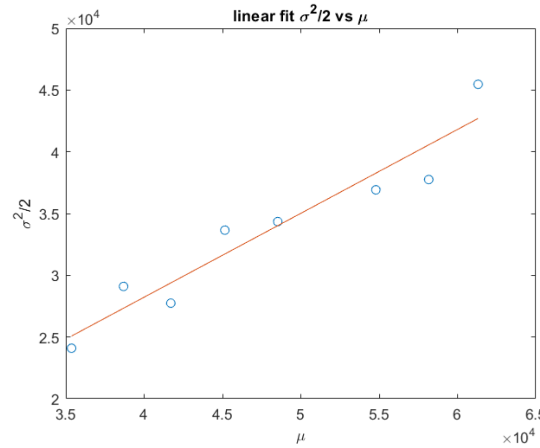

Figure 13. $\sigma^2/2$ vs μ for flat frames taken at different exposure times with a linear fit equal to: $\sigma^2/2 = 0.7\mu + 1059.2$.

where the linear fit gives a slope of:

$$\text{Conversion Factor} = \alpha = 0.7\ ADU/e-$$

Which means that the gain is:

$$\frac{1}{\alpha} \sim 1.429\ \frac{e-}{ADU}$$

From an online store [11] we found in the specifications of an SBIG STF402 Monochrome CCD Camera that A/D Gain is: 1.5 e- unbinned, 2.0 e- binned 2x2, 3x3. All the images captured for this experiment were unbinned, therefore the result has a 4,7% of error with respect to the manufacturer's value.

6) **Read-Out-Noise**
The experimental Read-Out-Noise obtained was:

$$RON = 11.77\ ADU$$

Using the conversion factor to express the RON in electrons:

$$RON = 11.77\ [ADU] \cdot 1.429 \Big[\frac{e-}{ADU}\Big] = 17\ e^-$$

According to the detector´s data sheet[1]:

$$RON = 15\ e-$$

which gives a 13.3% of error. From this result (only 2 e- of difference!), it can be concluded that subtracting two bias frames effectively reduces the detector's structural errors.

7) **Dark Current**
The dark current computed from a Master Dark Frame of 0.1 seconds of exposure time was:

$$Dark\ current = 9\ \frac{e^-}{s}$$

Then, considering that the above result is the average dark charge in one pixel, we can normalize the value by the área of one pixel. i.e:

$$\frac{9\ e^{-}/s}{9\mu m \text{ x } 9\mu m} = \frac{9\ e^{-}/s}{81 \cdot 10^{-12}\ m^2}$$

Now, if we recall that the absolute value of the charge of one electron is $1.6 \cdot 10^{-19}\ C$, the Dark Current can be expressed in a more general way as:

$$\frac{9 \cdot 1.6 \cdot 10^{-19}\ A}{81 \cdot 10^{-12}\ m^2} \cdot \frac{10^{12}}{10^4} = 1.78 \frac{pA}{cm^2}$$

According to the detector's data sheet [1], the dark current is

$$10 \frac{pA}{cm^2}$$

Therefore the experimental dark current is far from the theoretical value. The main problem with dark current is that it accumulates at a different rate in every pixel. Some pixels are "hot" and others are "cold". Fortunately, the effect of hot and cold pixels can be easily removed by subtracting a dark frame [2].

IV. Conclusion

On this report we were able to characterize a CCD detector using an STF402M camera from SBIG with a KAF402 detector, a really sensitive electronic device. We measured bias, flat and dark frames to obtain the values of bias level, dark current, conversion factor, read out noise and the numbers of dead, hot and noisy pixels. The bias level is 1018 ADU of a total of 65535 ADU. Also, $\mathbf{0.69}\%$ of the pixels that the detector has are hot pixels, $\mathbf{0.58}\%$ are dead pixels and $\mathbf{1.6}\%$ are noisy. It was not possible to deduce a correlation of the quantity of these pixels with respect to the exposure time, which leads us to notice the non-linearity of the detector. Analysing other characteristics, the read out noise experimentally calculated based on the bias frames was $17e^{-}$, which only has 2 electrons of difference with the RON that the datasheet presents[1]. Whereas the dark current experimentally calculated was $1.78\frac{pA}{cm^2}$ which is not really near to the sensor datasheet[1]. This is probably because the main problem with dark current is that it accumulates at a different rate in every pixel. Some pixels are "hot" and others are "cold". Fortunately, the effect of hot and cold pixels can be easily removed by subtracting a dark frame [2].

Even though we knew theoretically how to take the measurements, it was a hard experience. For instance, the setup for the flat frames was not easy to make and required a lot of trial and error to get good and representative images. We empirically learned the different effects on the detector caused by a plane and a perturbed wavefront and understood the importance of being in an isolated dark room to minimize the noise caused by temperature variations and unwanted background light (common sources of error).

Another important lesson from this lab experience is about the importance of picking a convenient exposure time to obtain a good image. When the detector is exposed for a long time, it receives more signal and has more information to make the image. However, this has a price: on longer exposures the dark current increases and the risk of saturation is higher for every additional unit of time.

Now that we know how to obtain calibration frames, the next step is to use them to process a scientific image and improve the output performance.

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