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1 Introduction

Janesick¹ provides a method for determining the amplification of a CCD camera when only access to the raw images is provided. Once the amplification is known, the digital pixel values can be converted into physically meaningful units such as interacting photons or numbers of electrons. However, the equation that is provided ignores the contribution of dark current. For CCD cameras that are cooled well below room temperature, this is not a problem, however, the technique needs adjustment for use with room temperature cameras. This article describes the adjustment made to the equation, and a test of this method.

2 Theory

Janesick provides a method to determine the amplification or camera gain with only access to the raw image under two specific lighting conditions and making the assumption that the amplification has low variance.

According to Janesick, the equation that determines the average signal for a CCD is:

$$S(DN)=PQE\eta_i S_v A_{CCD} A_1 A_2 \quad (1)$$

Where:

$S(DN)$: average signal for a group of pixels

P : average number of incident photons per pixel

QE_f : quantum efficiency or interacting photons / incoming photons

η_i : number of electrons generated, collected and transferred per interacting photon

S_v : sensitivity of the sense node V/e-

A_{CCD} : output amplifier gain V/V

A_1 : gain of the signal processor V/V

A_2 : gain of the ADC DN/V

Unfortunately, the values of most of the constants are unknown. Even for scientific CCDs measuring the individual constants accurately enough that the overall amplification can be determined may be difficult. However, even without this

¹ Scientific Charge-Coupled Devices, by James R. Janesick, 2001, SPIE Publications, pg 98-101 ISBN: 978-0819436986

information with some assumptions the overall gain can be measured indirectly using a method described in Janesick. For doing this, two different gains are defined:

$$K = \frac{1}{S_v A_{CCD} A_1 A_2} \text{ Camera gain in units of e-/DN}$$

$$J = \frac{1}{\eta_i S_v A_{CCD} A_1 A_2} \text{ Camera gain in units of (interacting photons)/DN}$$

K is used to calculate what digital pixel value will be measured if there is one electron in the physical pixel. J is used to calculate what digital pixel value will be measured if one photon hits and puts all its energy in one physical pixel.

If the photon energy is low enough, at most one electron will be generated per photon. When this condition is true determining the camera gain is possible. Visible light ranges from red with wavelengths of about 7000Å to violet with wavelengths of about 4000Å. The equation $E = \frac{hc}{\lambda}$ where h is the Planck constant 4.136e-15 eV seconds and c is the speed of light 2.998e8 meters per second can be used to convert wavelengths to energies. The photons for red have about 1.77 eV of energy, and the photons of violet have about 3.10 eV of energy. If the incoming photon wave lengths are greater than 4000Å (that is, photons that are less energetic than 3.10 eV violet light photons) then the photons have only enough energy to ionize at most 1 electron is per incoming photon, so $\eta_i = 1$. The equation²:

$$S(DN) = \frac{P_I}{K} \quad (2)$$

can then be used where P_I is the number of interacting photon's per pixel $P_I = QE_f P$. For photons with more energy than violet, roughly one electron-hole pair is generated for every 3.65 eV of the photon's energy in silicon at room temperature.³

When the CCD chip is at room temperature there is noise even in the absence of light, the equation needs to be modified to become:

$$S(DN) = \frac{P_I}{K} + R \quad (3)$$

where R is the average dark noise digital number that is read after the ADC. This equation explicitly adds R to Equation 2, which allows the equation to properly calculate the value when dark noise is a significant fraction of the $S(DN)$ value. This addition allows the equation to be used for room temperature cameras.

Next calculate the variance of Equation 3 using the error propagation formula and partial derivatives:

$$\sigma_{S(DN)}^2 = \left[\frac{\partial S(DN)}{\partial P_I} \right]^2 (\sigma_{P_I}^2) + \left[\frac{\partial S(DN)}{\partial K} \right]^2 (\sigma_K^2) + \left[\frac{\partial S(DN)}{\partial R} \right]^2 (\sigma_R^2) \quad (4)$$

² Equation 2.5, Janesick

³ pg 27, Janesick

$$\frac{\partial S(DN)}{\partial P_I} = \frac{1}{K} \quad (5)$$

$$\frac{\partial S(DN)}{\partial K} = -\frac{P_I}{K^2} \quad (6)$$

$$\frac{\partial S(DN)}{\partial R} = 1 \quad (7)$$

Combining Equations 4-7 gives:

$$\sigma_{S(DN)}^2 = \left(\frac{1}{K}\right)^2 \sigma_{P_I}^2 + \left(-\frac{P_I}{K^2}\right)^2 \sigma_K^2 + \sigma_R^2 \quad (8)$$

If we assume that variance in the camera gain is small, that is $\sigma_K^2=0$, then the variance becomes:

$$\sigma_{S(DN)}^2 = \left(\frac{1}{K}\right)^2 \sigma_{P_I}^2 + \sigma_R^2 \quad (9)$$

Since P_I is the count of the photons that interact, it can be modeled as a Poisson distribution and then $\sigma_{P_I}^2 = P_I$ so the variance becomes:

$$\sigma_{S(DN)}^2 = \frac{P_I}{K^2} + \sigma_R^2 \quad (10)$$

Solving Equation 3 for P_I gives:

$$(S(DN)-R)K = P_I \quad (11)$$

Combining Equations 10 and 11 gives:

$$\sigma_{S(DN)}^2 - \sigma_R^2 = \frac{[S(DN)-R]K}{K^2} \quad (12)$$

so

$$K = \frac{S(DN)-R}{\sigma_{S(DN)}^2 - \sigma_R^2} \quad (13)$$

Therefore, to measure K , the camera gain in e-/DN, we need to measure four things: 1) the average signal $S(DN)$ in light with no high energy photons, 2) the variance of that signal $\sigma_{S(DN)}^2$, 3) the average signal when the camera has no light R , and 4) the variance of that signal σ_R^2 . Then K can be calculated.

3 Further Notes

Removing the assumption that $\sigma_K^2=0$ is difficult, since it adds an additional variable that needs to be determined. Neither has a rigorous method to test the validity of this assumption been found.

The following can be used to give an estimate of the number of photons produced. One candela is the luminous intensity of a source that emits 1/683 watt per steradian at 540e12 hertz. A 540e12 hertz photon is 2.23 eV, or 3.58-19 joules, so a candela emits 5.14e16 photons per second.⁴

4 Experimental Method

In a scientific CCD, measuring the four values is fairly simple. Take two pictures, one with only low energy light, such as red light, and one without any light at all. Then, measure the average pixel value in the red light one for $S(DN)$ and its variance for $\sigma_{S(DN)}^2$, and measure the average pixel value for dark for R and its variance for σ_R^2 .

For the experiments with digital cameras, the same basic method can be used. Red LEDs were used as the source of light, and the camera and the LEDs were placed in an enclosed box to keep out other light. For the dark picture, the cameras were placed in the same box with the LEDs turned off and a black sheet of paper or the lens cap were placed over the lens to keep out light. For the light picture, the light from the Red LEDs was reflected off of a white paper in the enclosed box to get a reasonably uniform light distribution.

Unlike a scientific CCD, the values cannot be used directly from the camera. The primary problem is that to get color, each pixel of the CCD has a different color filter placed overtop of it. The majority of the variance from pixel to pixel actually comes from the effect of different color filters. The color filters are arranged in various patterns⁵, so a utility program was made to separate the different colors that occurred. This separation greatly reduced the apparent variance.

There still is additional non-photon counting variance in the color separated images. One cause of this seems to be location dependent variance in the amount of dark current and/or the amplification. The other variance is from the different amount of light that falls on different parts of the sensor. Since the lens for some of the digital cameras was permanently attached, it focused the light different amounts on different parts of the sensor. This variance was decreased by separating the picture into an 8x8 grid and then calculating the camera gain for each grid portion separately.

5 Results

Three cameras were tested, a Canon Powershot A640, a Nikon D40 and a Olympus SP-550UZ. The Nikon and the Olympus's 'raw' image mode actually shifted the output of the ADC so that the lowest value was zero. This adds another unknown variable to the equation, so the value of K could not be determined by the method. It

⁴ $=(4*\pi/683)/3.58\text{e-}19)$

⁵ Dave Coffin's raw photo decoder's source code ddraw.c contains examples of these.

is possible that the value of K could be determined by some modification of the method.

Table 1: Powershot 640 Data

	1s iso80	5s iso80	1s iso800	5s iso800
Mean (e-/DN)	5.880	5.011	0.5371	0.5462
Standard Error	0.1784	0.0485	0.0033	0.0046
Median	5.038	5.105	0.5369	0.5711
Standard Deviation	4.036	1.098	0.0756	0.1035
Sample Variance	16.29	1.205	0.0057	0.0107
Kurtosis	192.1	9.063	-0.4836	9.491
Skewness	11.14	-0.0505	-0.1201	-0.6911
Range	78.39	12.64	0.4221	1.113
Minimum	-1.066	-1.076	0.3070	0.0937
Maximum	77.33	11.56	0.7291	1.208
Sum	3010.	2566.	275.0	279.6
Count	512	512	512	512
95% CI for the Mean				
low	5.529	4.916	0.531	0.537
high	6.230	5.106	0.544	0.555

Table 1 is K values and statistics from the Powershot A640 with 1 second exposures and 5 second exposures at iso 80 and iso 800 values. The pixel locations were put in eight bins to separate out the color filter effects and 8x8 grid locations to separate out the sensor location dependent effects, resulting in 512 calculations of K . The values are in units of e-/DN. If these are correct, then the difference between two digital numbers at iso 80, is 5 electrons. So if you have a reading of 20, at iso 80, there were about 100 electrons produced from 100 photons in the physical pixel. On the other hand, at iso 800, if the pixel has a reading of 20, there were about 10 electrons that came from 10 photons. Assuming that the amplification does not induce significant amount of noise, the noise that is seen on high iso settings in digital cameras does seem to be related to the counting statistics from incoming photons.

Since the Powershot camera uses a 10 bit ADC, at iso setting 80, it measures up to 5115 electrons⁶ before it saturates the pixel, and at iso setting 800, it measures up to about 580 electrons before the maximum value is measured.

Since the values of the amplification K are near constant with different times of exposure, but vary with different ISO settings, it seems to indicate that Equation 13 works for determining the amplification of the camera.

6 Open Questions

Amount of noise produced in amplification (how constant is K)? Can this be done with raw cameras that zero the lowest value?

⁶ =5*1023

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