Optik 124 (2013) 4832–4835

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Effects of electron multiplication on the CCD SNR in remote sensing application

Dejiang Wang [a,b,c,*], YongSen Xu [a], Yuan Yao [a], Zhengping Xu [a], Houtian Hung [a]

[a] Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, PR China
[b] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, Changchun 130033, China
[c] Graduate School of the Chinese Academy of Science, Beijing 100084, PR China

ARTICLE INFO

Article history:
Received 18 September 2012
Accepted 15 February 2013

Keywords:
Electron multiplication
Charge coupled device
Signal to noise ratio

ABSTRACT

A mathematical model describing the effect of electron multiplication (EM) gain on the detector signal to noise ratio (SNR) is presented, and then two types of experiment have been made to test their relationship. The experimental results of the radiometric calibration and imaging in practice both show that the initial EM gain amplification makes the most significant improvement on the EM charge coupled device (CCD) SNR, while as the gain factor continues to increase, the EMCCD SNR improvement will become negligible.

© 2013 Elsevier GmbH. All rights reserved.

1. Introduction

The SNR of the images captured in the remote sensing application is usually detector readout noise dominated [1]. Taking larger aperture and longer integration time are the two common methods to improve the CCD SNR [2]. Unfortunately, the primary mirror diameter for the space camera is limited by the volume and mass constraints of the launch vehicles as well as the scaling laws of manufacturing costs, and the longer exposure time will result in excessive motion between photo sensitive pixels and the objects, which leads to the system modulation transfer function degradation greatly [3]. The advent of electron multiplying CCD pushes the boundaries of detection limits for imaging application. The EMCCD multiplies the photo-electrons by a factor G before they reach the readout stage. Due to this multiplication the readout noise is G times smaller when it is expressed in photo-electrons. Then it is possible to overcome the readout noise G times faster than with a conventional CCD [4–7]. However, increasing the gain factor too much will reduce system dynamic range dramatically, and the system's SNR will not improve further [8]. So there is an urgent requirement on how to determine the appropriate gain factor, by which not only will the SNR improve as much as possible, but also the dynamic range should keep higher enough such that the EMCCD could be applied in the environment with wide irradiation variation.

* Corresponding author at: Dongnanhu Road No. 3888, Changchun 130033, PR China. Tel.: +86 431 86176158; fax: +86 431 85680049.
E-mail address: wangdj04@ciomp.ac.cn (D. Wang).

0030-4026/$ – see front matter © 2013 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2013.02.037

2. Theoretical details

In the EMCCD-based cameras, there are several sources of noises [9]. Photon shot noise is the noise associated with the random arrival of photons at any detector, and it exists because of the discrete nature of light and electrical charge. The dark current noise is generated inside the sensor, and the rate of generation depends exponentially on temperature. While the readout noise is due to the readout electronics of the sensor and the analogue to digital converter, and the readout noise is always present and increases with increased readout speed. In our analysis, the CCD noises can be divided into the aforementioned three main categories. Since most SNR metrics compare the mean target signal with the standard deviation of the noise, thereby the EMCCD SNR formulation is expressed as

$$SNR = \frac{n_{pe}}{(F^2 n_{shot}^2 + n_{dark}^2 + G_1^{-2} n_{read}^2)^{1/2}} \tag{1}$$

where n_{pe} is the number of photoelectrons, n_{shot} is the number of the shot noise equivalent photoelectrons, n_{dark} is the number of dark current noise equivalent photoelectrons, n_{read} is the number of read out noise equivalent photoelectrons, and F is the noise factor which quantifies the noise that is introduced by the gain process itself, and G is the electron multiplication gain factor.

From Eq. (1) we could see obviously that the proportion of the read noise to the EMCCD total noise will decrease with the electron multiplication gain, hence the EMCCD SNR will increase accordingly, and its augmenter with the gain factor is given by

$$\Delta SNR_{G_1,G_2} = \frac{n_{pe}}{(F^2 n_{shot}^2 + n_{dark}^2 + G_1^{-2} n_{read}^2)^{1/2}} - \frac{n_{pe}}{(F^2 n_{shot}^2 + n_{dark}^2 + G_2^{-2} n_{read}^2)^{1/2}} \quad (2)$$

where G_1 represents the original gain factor, and G_2 represents the enlarged gain factor. Generally the SNR is expressed in decibels, so that Eq. (2) is rewritten as

$$\Delta SNR_{g_1,g_2} = 10 \log \left(1 + \frac{G_1^{-2} - G_2^{-2}}{F^2 n_{shot}^2 n_{read}^{-2} + n_{dark}^2 n_{read}^{-2} + G_2^{-2}}\right) dB \quad (3)$$

Let G_3 represents another gain factor, and $G_3 > G_2 > G_1 > 1$, $G_3 - G_2 = G_2 - G_1$, then the SNR increment between G_2 to G_1 and G_3 to G_2 is expressed as

$$\Delta SNR_{G_1,G_2} - \Delta SNR_{G_2,G_3} = 10 \log \left(1 + \frac{G_1^{-2} - G_2^{-2}}{F^2 n_{shot}^2 n_{read}^{-2} + n_{dark}^2 n_{read}^{-2} + G_2^{-2}}\right) - 10 \log \left(1 + \frac{G_2^{-2} - G_3^{-2}}{F^2 n_{shot}^2 n_{read}^{-2} + n_{dark}^2 n_{read}^{-2} + G_3^{-2}}\right) \quad (4)$$

For deducing simplicity, assuming that

$$F^2 n_{shot}^2 n_{read}^{-2} + n_{dark}^2 n_{read}^{-2} = k_1 \cdot G_2^{-2} = k_2 \cdot G_3^{-2} \quad (5)$$

where k_1 and k_2 represent the proportionality factor. Substituting Eq. (5) into Eq. (4), we obtain

$$\Delta SNR_{G_1,G_2} - \Delta SNR_{G_2,G_3} = 10 \log \left(1 + \frac{G_1^{-2} \cdot G_2^2 - 1}{k_1 + 1}\right) - 10 \log \left(1 + \frac{G_2^{-2} \cdot G_3^2 - 1}{k_2 + 1}\right) \quad (6)$$

As we know, the logarithmic function is a monotone increasing function, therefore comparison of $\Delta SNR_{G_1,G_2}$ and $\Delta SNR_{G_2,G_3}$ is equivalent to comparison of $(G_1^{-2} \cdot G_2^2 - 1)/(k_1 + 1)$ and $(G_2^{-2} \cdot G_3^2 - 1)/(k_2 + 1)$. Since $G_3 > G_2 > 1$, so that $k_1 < k_2$, then we obtain

$$\frac{G_1^{-2} \cdot G_2^2 - 1}{k_1 + 1} - \frac{G_2^{-2} \cdot G_3^2 - 1}{k_2 + 1} > \frac{(G_2^2 - G_1 G_3)(G_2^2 + G_1 G_3)}{(k_1 + 1) G_1^2 G_2^2} \quad (7)$$

Substituting $G_3 - G_2 = G_2 - G_1$ into the right side of Eq. (7), we obtain

$$\frac{(G_2^2 - G_1 G_3)(G_2^2 + G_1 G_3)}{(k_1 + 1) G_1^2 G_2^2} = \frac{(G_1 + G_3)(G_2^2 + G_1 G_3)}{4(k_1 + 1) G_1^2 G_2^2} > 0 \quad (8)$$

Therefore $(G_1^{-2} \cdot G_2^2 - 1/k_1 + 1) - (G_2^{-2} \cdot G_3^2 - 1/k_2 + 1) > 0$, then from Eq. (6) we know that $\Delta SNR_{G_1,G_2} > \Delta SNR_{G_2,G_3}$, which indicates that the gain amplification in the initial stage makes more contributions to the CCD SNR improvement, while as the gain factor keeps increasing, the benefits to the CCD SNR will decrease gradually, and eventually to zero. In that case, the EMCCD SNR will approach its theoretical maximum value

$$\max(SNR) = \frac{n_{pe}}{(F^2 n_{shot}^2 + n_{dark}^2)^{1/2}} \quad (9)$$

3. Results and discussion

In this letter, we test the influence of electron multiplication gain on the EMCCD SNR by two types of experiment. The first experimental devices are depicted in Fig. 1. An integrating sphere is used to provide even illuminations. A customized EMCCD and its driving circuit are mounted on a guide rail, which is separated from the ground by the optics vibration isolation platform. The detail descriptions of the tested EMCCD are summarized in Table 1.

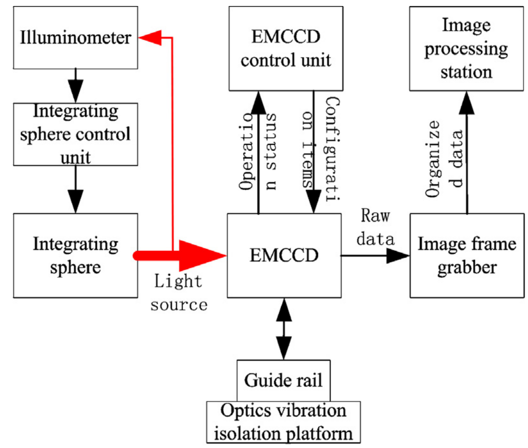

Fig. 1. The block diagram of the calibration experiment.

The captured images are transmitted to the work station through Camera Link Interface, and the camera configuration parameters are adjusted by external acquisition software through the interface. In order to have a stable and continuous light source, a calibrated illuminometer is used to make a relative calibration of the beam exiting from the integrating sphere. As long as the illumination uniformity of the light beam exceeds the given threshold, the integrating sphere control unit will generate the corresponding corrected parameters which ensure that the integrating sphere could provide a highly uniform illumination. Due to that the temperature has a significant influence on the EMCCD noise measurement accuracies, such as the dark current noise, the read out noise, the experiment is made at an fixed ambient temperature of 22 °C.

Using the CCD noise measurement technique proposed in Refs. [10,11], we illustrate the relative magnitudes of the aforementioned three noise components in Fig. 2. A slight trend can be seen that the photon shot noise has $n_{shot} \approx \sqrt{n_{pe}}$ as expected from Poisson sampling theorem for sampling of discrete quanta, and since the sensor temperature are relatively stable and the charge readout speed is fixed during the calibration procedure, the dark current noise and the readout noise are 0.2 and 12.1e^{-1}, respectively, which accords well with the sensor factory reports.

Substituting the noise models illustrated in Fig. 2 to the SNR representation shown in Eq. (1), we illustrate EMCCD electron multiplying gain versus SNR in Fig. 3. We could see that the SNR improves a lot as the gain increases when G is in the range of 1–3, but the SNR curve becomes effectively flat showing no apparent trend of increment with the gain when G is greater than 4. The reason is that as G increases, the proportion of readout noise to the total EMCCD noise is reduced gradually, and ultimately to be a negligible level. Thus the EMCCD SNR will increase with G in the initial stage. But, when G exceeds some threshold, the amount of EMCCD total

Table 1
The factory features of the tested EMCCD.

Parameter	Value
Sensor format	1024 × 1024
Pixel size (μm)	13
Full well capacity (e^{-1})	45,000
Quantum efficiency	65%
Full frame rate (frames/s)	30
Dynamic range	8500 (without electron multiplication gain)
Multiplicative noise factor	1.41
Read out noise (e^{-1})	12 (without electron multiplication gain)

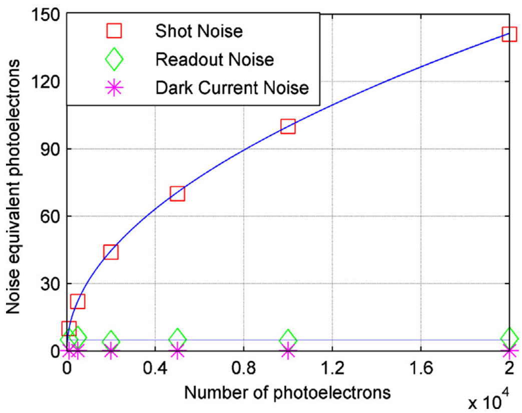

Fig. 2. EMCCD equivalent noise as a function of the photoelectrons, where electron multiplying gain factor equals to one. Data points correspond to individual measurements, while the solid lines represent the predicted curves.

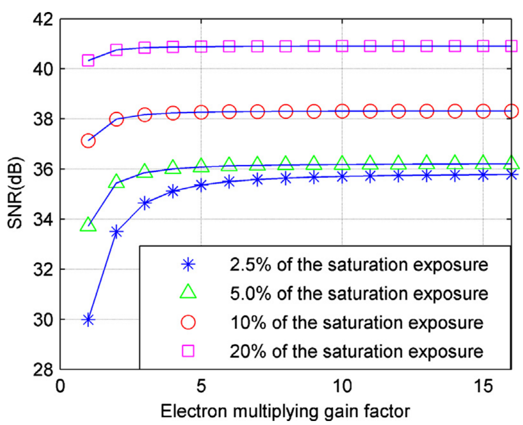

Fig. 3. EMCCD SNR versus electron multiplying gain under different low illumination environments.

noise and pixel mean intensity will both increase proportionally to G, so the SNR will remain stable.

In order to demonstrate the contributions of different gain factors to the SNR improvement vividly, we illustrate a percentage diagram in Fig. 4. It can be seen obviously that the amount of the SNR increment caused by increasing G from 1 to 2 accounts for a majority amount of the total SNR increment.

The SNR is a common metric used to tell the image quality and radiometric performance of a remote sensing system [12]. However, when a camera designer specifies a SNR value, it is not always sure how it relates to the image quality of the system. Then the image quality improvement caused by the gain adjustment is accessed by a real aerial camera. The experimental devices are depicted in Fig. 5, which mainly consists of the light source, the bar target pattern, the collimator, the optics vibration isolation platform, and the EMCCD with 1500 mm lens. The optics and detector design parameters as well as the imaging conditions are listed in Table 2.

Employing the light source, the bar target, the collimator as well as the optics vibration isolation platform, the drone beam is generated which seems that the object is emitting at infinity, and the beam will go through the camera's entrance pupil. Then the influence of the electron multiplication gain could be evaluated.

Fig. 6(a)–(d) shows a series of sectional views of the bar target with integration time of 30 ms, which is commonly used in practical remote imaging application, where the illumination is relatively lower. In order to facilitate image interpretability comparison, it

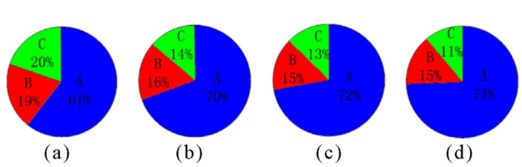

Fig. 4. SNR increment caused by different gain factor. Part A represents SNR improvement when G increases from 1 to 2; part B represents SNR improvement when G increases from 2 to 3; part C represents SNR improvement when G increases from 3 to 16. (a) 2.5% of the saturation exposure, (b) 5% of the saturation exposure, (c) 10% of the saturation exposure, (d) 20% of the saturation exposure.

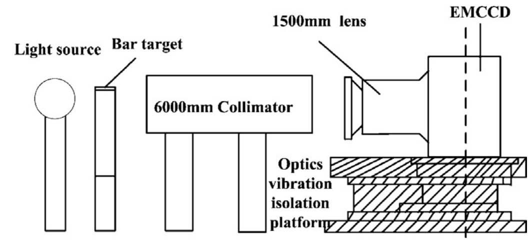

Fig. 5. The block diagram of the practical imaging experiment.

Table 2
Optics and detectors parameters of the remote sensing camera used for the imaging experiment.

Parameters	Value
Focal length (mm)	1500
F-number	5.6
Spectral band pass (μm)	0.4–0.9
Optics transmission	0.7
Camera output resolution (bit)	12
Integration time (ms)	30

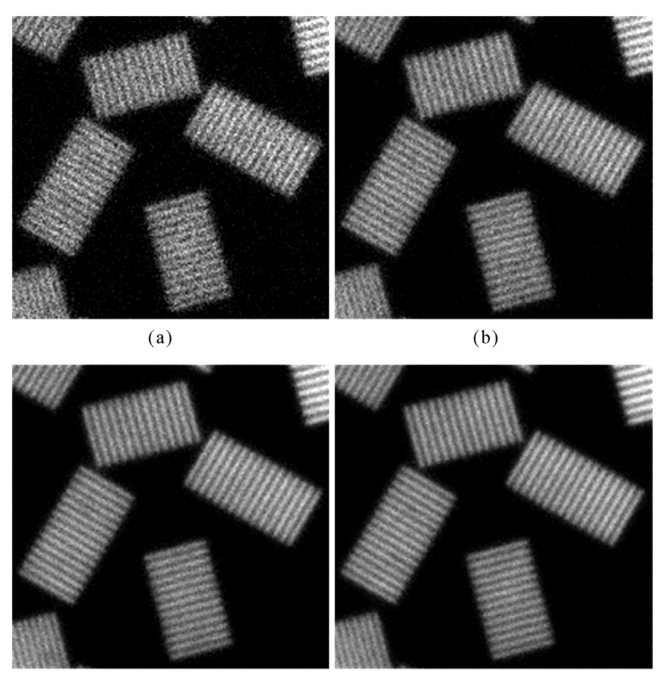

Fig. 6. The captured bar target pattern. (a) $G=1$ and $D=8$; (b) $G=2$ and $D=4$; (c) $G=4$ and $D=2$; (d) $G=8$ and $D=1$; where G represents the electron multiplying gain factor, and D represents the digital gain factor.

is required that the product of the electron multiplying gain factor and digital gain factor is a constant value. Then we could see apparently that Fig. 6(a) exhibits too much mosaic effect, while Fig. 6(b)–(d) tell more details of the target pattern, especially near the edge of the bar. Moreover, it is hard to distinguish differences among Fig. 6(c) and (d) with unaided eyes. Noting that the digital gain has no effect on CCD SNR, so the imaging experimental results confirm the aforementioned conclusion once again, it is that when G increases in the initial stage, the image quality improves a lot, while as G continues to increase, the image quality improvement becomes inconspicuous.

4. Conclusion

In conclusion, the effects of electron multiplying gain on EMCCD SNR and contributions of different gain factors to SNR improvement are analyzed thoroughly and then illustrated through two types of experiment, especially under the low illumination in remote sensing applications. The result of the theoretical analysis accords well with the laboratory calibration as well as the imaging experiment in practice. The experiments results show that the CCD SNR will improve significantly when the gain factor enlarged in the initial stage, and the amount of SNR increment accounts for more than half of the whole SNR growth. But as the gain factor increases more, the SNR improvement will become inappreciable.

References

[1] P.J. Pool, D.G. Morris, D.J. Burt, R.T. Bell, A.D. Holland, D.R. Smith, Application of electron multiplying CCD technology in space instrumentation, Proc. SPIE 5902 (2005), 59020A/1-59020A/6.
[2] N.J. Miller, M.P. Dierking, B.D. Duncan, Optical sparse aperture imaging, Appl. Opt. 46 (2007) 5933–5943.
[3] D.J. Wang, T. Zhang, H.P. Kuang, Clocking smearing analysis and reduction for multi phase TDI CCD in remote sensing system, Opt. Express 19 (2011) 4868–4880.
[4] L. Zhang, L. Neves, J.S. Lundeen, I.A. Walmsley, A characterization of the single-photon sensitivity of an electron multiplying charge-coupled device, J. Phys. B 42 (2009) 114011–114011/12.
[5] Y. Reibel, M. Jung, M. Bouhifd, B. Cunin, C. Draman, CCD or CMOS camera noise characterization, Eur. Phys. J. D 21 (2003) 75–80.
[6] G.T. He, X.Z. Wang, D.L. Li, J.M. Hu, A high-speed image sensing technique with adjustable frame rate based on an ordinary CCD, Optik 119 (2008) 548–552.
[7] X. Tian, S.Y. Zhou, P. Chen, Luminance adaptation model for increasing the dynamic range of an imaging system based on a CCD camera, Optik 122 (2011) 1367–1372.
[8] P.H. Wu, N. Nelson, Y. Tseng, A general method for improving spatial resolution by optimization of electron multiplication in CCD imaging, Opt. Express 18 (2010) 5199–5212.
[9] G. Zonios, Noise and stray light characterization of a compact CCD spectrophotometer used in biomedical applications, Appl. Opt. 49 (2010) 163–169.
[10] K. Irie, A.E. Mckinnon, K. Unsworth, I.M. Woodhead, A technique for evaluation of CCD Video camera noise, IEEE Trans. Circ. Syst. Video Technol. 18 (2008) 280–283.
[11] D.J. Wang, T. Zhang, Noise analysis and measurement of time delay and integration charge coupled device, Chin. Phys. B 20 (2011) 087202/1–087202/6.
[12] S.A. Cota, C.J. Florio, D.J. Duvall, M.A. Leon, The use of general image quality equation in the design and evaluation of imaging systems, Proc. SPIE 7458 (2009) 1–20.