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Modeling and Experimental Investigation on the PRNU Noise of TDI CCD

WANG De-jiang[1,2,3], SHEN Hong-hai[1,2], SONG Yu-long[1,2], ZHAO Jia-xin[2]

(1 *Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun* 130033, *China*)

(2 *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun* 130033, *China*)

(3 *Graduate University of Chinese Academy of Sciences, Beijing* 100049, *China*)

Abstract: Photo response non uniformity (PRNU) noise sets a fundamental limit on image sensor performance, especially under low illumination in remote sensing system. After introducing a complete noise model of time delay and integration charge coupled device (TDICCD), a complete model of TDICCD noise is proposed. Then PRNU noise model for all selectable integration stage is developed, which is linearly related to illumination. Moreover, exposure stages are taken into consideration due to their inherent averaging effect, and relationship between nonuniformity parameter and integration stage is developed. Finally a techinque to identify and measure the PRNU noise in TDICCD is presented by analysis of the output images, and the experimental results are illustrated from test system, measured PRNU noise at different illumination and integration stages are also analyzed.

Key words: Time Delay and Integration Charge Coupled Device (TDI CCD); Photo Response Non Uniformity(PRNU) noise; Noise measurement

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0 Introduction

Time delay and integration mode of operation of a CCD provides increased sensitivity without the sacrifice of spatial resolution, and effective integration time is increased by a factor of N, which is equal to the number of TDI stages, so TDI CCD is widely used in remote sensing system for improving the low light level capability. For example, Chinese lunar orbiting spacecraft Chang′s Ⅱ has been launched successfully, and the most important payload of Chang′e Ⅱ is a TDI CCD stereo camera with 96 stages. Performance of Chang′e Ⅱ camera is characterized by the signal noise ratio (SNR) of TDI CCD mostly, the higher SNR is, the more useful information could be extracted from lunar surface images[1]. Among all noise sources of TDI CCD, photo response non uniformity noise is a special one, since it has a relationship to not only incident flux but also TDI stages.

A number of literatures about CCD noise model are well documented. One PRNU noise model is presented to identify and quantify types of noise in CCD video camera[2-3], its noise evaluation is purely based on frame CCD, so it is not suitable for TDI CCD calibration; a more comprehensive PRNU noise model is well documented[4-5], according to their analysis PRNU noise is caused by differences in detector size, spectral response, and thickness in coating, through TDI CCD inherent averaging effect. PRNU noise is reduced as TDI stage increases, however they only analyze PRNU noise in theory, there is no practical measurements for PRNU noise; L. Chen proposes a method that noise is picked up from image by a specially designed digital high-pass filter[6], but his research is also based on frame CCD camera. Above all there has been little work on the assessment and validation of PRNU noise by experimental evaluation, therefore, in this paper we examine noise sources of the TDI CCD first, then we make a special effort to analyze and evaluate PRNU noise, finally we present a technique for the measurement of TDI CCD PRNU noise according to output images.

1 PRNU noise model of TDI CCD

PRNU noise refers to the pixel to pixel variation that does not change significantly from

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First author: WANG De-jiang(1981—), male, Ph. D. degree candidate, mainly focuses on remote sensing system design. Email: wangdj04@ciomp. ac. cn

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frame to frame. In order to develop PRNU noise model of TDI CCD, we assume that the TDI CCD operates in frame transfer mode in evenly illuminated condition, and photo electrons collected at individual pixel are defined as $x(i,j)$, $1\leqslant i\leqslant M, 1\leqslant j\leqslant N$, where M represents TDI CCD line resolution and N represents number of TDI stage.

When TDI stage is equal to 1, we can express the variance of the PRNU noise as

$$\langle n_{\mathrm{PRNU}}\rangle = U_1 n_{\mathrm{pe}} = \sqrt{\mathrm{var}(x(i,1))} \tag{1}$$

where U_1 is non uniformity ratio of one stage, and n_{pe} is mean value of one line image data.

When TDI stage turns to$N$, we can write the variance of the PRNU noise as

$$\langle n_{\mathrm{PRNU}}\rangle = U_N(Nn_{\mathrm{pe}}) = \sqrt{\mathrm{var}(\sum_{j=1}^{N} x(i,j))} \tag{2}$$

where U_N is non uniformity ratio of N stage, and Nn_{pe} is mean value of summation of N lines data.

Theoretically, correlation factor of PRNU noise between two adjacent rows ranges from zero to one. When PRNU noise of every row is uncorrelated (correlation factor is equal to 0), Eq. (2) becomes

$$\langle n_{\mathrm{PRNU}}\rangle = \sqrt{\sum_{j=1}^{N}\mathrm{var}x(i,j)} = n_{\mathrm{pe}}\sqrt{\sum_{j=1}^{N}U_1^2} = \frac{U_1}{\sqrt{N}}(Nn_{\mathrm{pe}}) \tag{3}$$

When correlation factor is 1, which means every row is identical to each other completely, Eq. (3) becomes

$$\langle n_{\mathrm{PRNU}}\rangle = \sqrt{\mathrm{var}(Nx(i,1))} = U_1(Nn_{\mathrm{pe}}) \tag{4}$$

As TDI stage increases, non uniformity ratio is expressed as

$$\frac{U_1}{\sqrt{N}} \leqslant U_N \leqslant U_1 \tag{5}$$

2 PRNU Noise measurement method

In this section we will describe a method for noise measurement of TDI CCD. The organization of sampled data is illustrated in Fig. 1.

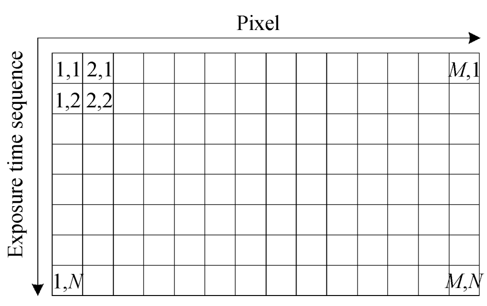

Fig. 1 The organization of sampled data

According to Holst analysis[4-5], the output of digitized TDI CCD camera image is described by

$$D(i,j) = I(i,j) + I(i,j)\times\mathrm{PRNU} + N_{\mathrm{ps}}(I(i,j)) + N_{\mathrm{PFN}}(i,j) + N(i,j)_{\mathrm{dark}} + N(i,j)_{\mathrm{read}} + N(i,j)_{\mathrm{rst}} + N(i,j)_{\mathrm{Q}} \tag{6}$$

where $I\times\mathrm{PRNU}$ is the photo response non uniformity noise, $N_{\mathrm{ps}}(I)$ is the photo shot noise, N_{PFN} is the fixed pattern noise, N_{dark} is the dark current noise, N_{read} is the circuit readout noise, N_{rst} is reset noise, N_{Q} is ADC quantization noise, and N represents the exposure time of TDI CCD, and M represents the resolution of TDI CCD.

We know that noises could be divided into two types: spatial variance and temporal variance, for simplicity, Eq. (6) can be expressed as

$$D(i,j) = I + N_{\mathrm{T}}(i,j) + N_{\mathrm{S}}(j) \tag{7}$$

where N_{T} represents zero mean temporal noise with a variance of σ_{T}^2, N_{S} represents zero mean spatial noise with a variance of σ_{S}^2, and $\overline{I}$ represents mean value of $I(i,j)$, which is given by

$$\overline{I} = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} D(i,j) \tag{8}$$

As proposed in Ref. [6], the spatial noise is expressed as

$$\hat{\sigma}_{\mathrm{S}}^2 = \frac{1}{M-1}\sum_{j=1}^{M}\hat{N}_{\mathrm{S}}^2(j) \tag{9}$$

Then the expectation of $\hat{\sigma}_{\mathrm{S}}^2$ is given by

$$E(\hat{\sigma}_{\mathrm{S}}^2) = \sigma_{\mathrm{S}}^2 + \frac{M-1}{N}\sigma_{\mathrm{T}}^2 \tag{10}$$

Eq. (10) is a biased estimation, however, error of the estimation decreases as quantity of samples increases, so when N becomes large enough, error of the estimation turns to be negligible.

2.1 Sensor irradiance

Let us denote the raw signal that would be registered by the sensor due to incoming light as $D(i,j), i=1,\cdots,m, j=1,\cdots n$, where m is the same scene captured by pixel j at different exposure time, and n is the resolution of the TDI CCD. Since time averaging will remove temporal noises, so photo shot noise, dark current noise, circuit readout noise and reset noise could be effectively removed when m is large enough

$$D'(j) = \frac{1}{m}\sum_{1\leqslant i\leqslant m} D(i,j) \tag{11}$$

Meanwhile line averaging will remove spatial noise along TDI CCD array, so the expected value of I over all pixels for TDI CCD is written as

$$\hat{I} = \frac{1}{n}\sum_{1\leqslant j\leqslant n} D'(j) = \frac{1}{n\times m}\sum_{1\leqslant i\leqslant m, 1\leqslant j\leqslant n} D(i,j) \tag{12}$$

2.2 PRNU noise estimation

There are two steps for extracting PRNU

noise. First, temporal noises, such as photo shot noise (N_{ph}), dark current noise (N_{dark}), circuit readout noise(N_{read}) and reset noise(N_{rst}) could be removed by time averaging, so Eq. (6) becomes:

$$D'=I+I\times \mathrm{PRNU}+\mathrm{FPN}+N_{\mathrm{Q}} \quad (13)$$

Then the amplitude of PRNU noise for a particular irradiance can be calculated by subtracting I, N_{FPN} and N_{Q}.

Moreover, TDI devices, due to their inherent averaging, as integration stage increases, PRNU noise is decreased, meanwhile amplitude of PRNU parameter is also decreased. If PRNU noise of each TDI stage is uncorrelated, we could have the following deduction. Assuming PRNU parameter is K when TDI stage is 1, then PRNU parameter becomes $K/\sqrt{N}$ when TDI stage is N[7-8].

3 TDI CCD PRNU noise calibration

The experimental layout is depicted in Fig. 2. An integrating sphere is used to provide evenly illuminations. A customized CCD and its driving circuit are mounted on a guide rail, which is separated from the ground by the optics vibration isolation platform. The captured image data are transmitted to the work station through Camera Link Interface, also the camera configuration parameters are controlled by external acquisition software through the interface. The CCD native resolution is 12 bit, and yields an output signal in the 0 ～ 4 096 counts range at each pixel. The experiment is made at an ambient temperature approximately 22 ℃, which ensures that temperature dependent noise will remain stable during the measurement procedure.

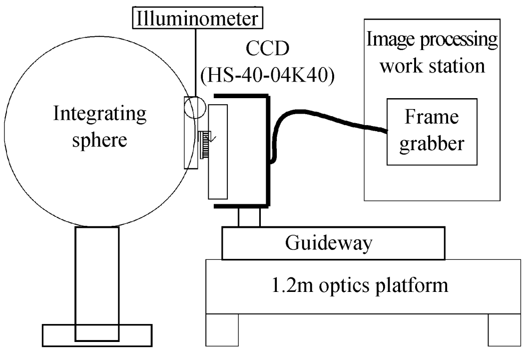

Fig. 2 Practical experimental system

Since resolution of the ADC is 12, so ADC quantization noise has a uniform probability distribution over the range $[-\frac{1}{2}DN, \frac{1}{2}DN]$ with a variance $\frac{1}{12}DN$.

According to noise measurement methods described in section 2, the PRNU parameters are 0.0024752, 0.0015689, 0.0011369 and 0.0009016 for 16, 32, 64 and 96 TDI stages respectively.

$$\begin{aligned}
\mathrm{PRNU}_{16}&=0.0024752E(x)-0.011548\\
\mathrm{PRNU}_{32}&=0.0015689E(x)+0.17085\\
\mathrm{PRNU}_{64}&=0.0011369E(x)-0.042205\\
\mathrm{PRNU}_{96}&=0.0009016E(x)-0.01325
\end{aligned} \quad (14)$$

PRNU noise for the sensor is defined as the best-fit line for PRUN noise values. According to Eq. (14), we illustrate PRNU noise in Fig. 3, it increases approximately linearly with sensor irradiance[9].

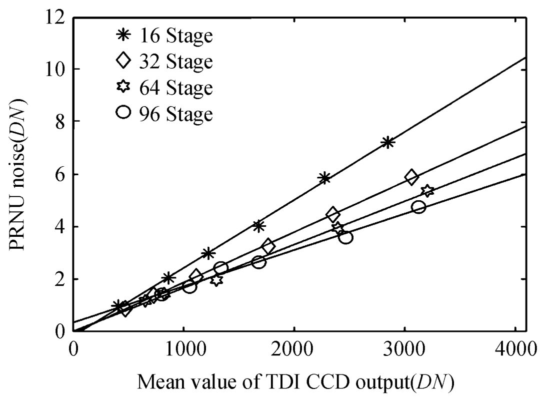

Fig. 3 PRNU noise for the tested camera

16, 32, 64 and 96 TDI stage could be normalized to 1, 2, 4 and 6, while normalization of the experimental PRNU parameters are 1, $\sqrt{1.6}$, $\sqrt{3.1}$, $\sqrt{7.3}$. According to sub section 2. 4 analysis[10-13]. If PRNU noise in each TDI stage is uncorrelated, when TDI stage is 1, 2, 4, 6, the corresponding PRNU parameter is 1, $\sqrt{2}$, $\sqrt{4}$, $\sqrt{6}$. Obviously, there are some differences between assumption and experimental results. This is because there exist some correlations for PRNU noise in adjacent TDI stage[14-16], therefore we should calibrate PRNU noise for all of TDI stage in practice.

4 Conclusion

In conclusion, a PRNU noise model and a technique for evaluation have been developed for TDI CCD camera. The noise components are grouped into measurable quantities and measured on a commercially available TDI CCD camera. The PRNU noise information can be used in many aspects, for example an edge detection algorithm could be benefit from the knowledge of PRNU noise, and another natural application for this technique is to design of PRNU noise removal filter. So far this technique has been used in design and evaluation of practical aerial TDI CCD cameras, and more than 40 TDI CCD have been calibrated using this method, all of the calibrated TDI CCD perform well in their different applications.

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TDI CCD 光子响应非均匀性噪音分析与测量

王德江[1,2,3],沈宏海[2],宋玉龙[1,2],赵嘉鑫[2]

(1 中国科学院长春光学精密机械与物理研究所 中国科学院航空光学成像与测量重点实验室,长春 130033)

(2 中国科学院长春光学精密机械与物理研究所,长春 130033)

(3 中国科学院研究生院,北京 100049)

摘　要:探测器光子响应非均匀性噪音会降低低照度情况下遥感成像系统的成像质量.针对这一现象,本文首先结合探测器的物理性质,对各种噪音源进行了研究;建立了 TDI CCD 不同级数下的光子响应非均匀性噪音模型,随着曝光量的增加,光子响应非均匀性噪音也线性增加.其次根据曝光级数越多 TDI CCD 对非均匀性噪音的平滑效应越明显这一现象,提出一种光子响应非均匀性系数与曝光级数之间的关系式,并给出了利用 TDI CCD 输出图像提取光子响应非均匀性噪音的方法.最后建立了试验系统,通过试验对测试获得的光子响应非均匀性噪音与理论分析计算得出的结果进行了分析.

关键词:时间延迟积分电荷耦合器件;光子响应非均匀性噪音;噪音测量