鹿林天文台 CCD 相機 PI 1300B 在不同溫度下之增益及讀出雜訊之量測

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摘要

進行天文觀測的同時，隨時檢查CCD相機的特性對觀測者而言是相當重要的，如此對科學的結果才可以進行較好的修正。Kinoshita et al. (2005)與Huang et al. (2008)已經完成了一系列研究鹿林天文台一米望遠鏡PI 1300B CCD的工作。在這篇文章中，我們對此CCD的增益及讀出雜訊再作了一次測量，除了在−45°C的工作溫度作測量之外，我們也測量了在不同工作溫度下CCD的表現。在−45°C的工作溫度下，測量出之增益值爲1.98 ± 0.01 e^-/ADU, 讀取誤差爲4.2 ± 0.07e^-。結果大致與之前相關研究相同。從測量資料中，我們得到了一個讀取誤差及CCD溫度的經驗關係式。此關係式中，CCD的讀取誤差與CCD溫度間存在著一個冪次關係。

Measurement for the Gain and Readout Noise of CCD Camera PI 1300B at Different Temperatures in Lulin Observatory

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Abstract

It is very important to check the CCD properties from time to time, because it is essential to the good calibration of scientific data. A series of works had been carried out by Kinoshita et al. (2005) and Huang et al. (2008) for the PI 1300B CCD of Lulin Observatory. We investigated the performance of PI 1300B CCD again for the gain and readout noise in normal operation temperature (-45°C) and higher temperatures. The gain is 1.98 ± 0.01 e^-/ADU and readout noise is 4.2 ± 0.07 e^- at -45° (slow readout mode). The results are consistent with previous works. An empirical relation between the CCD temperature and the readout noise is derived in this work. The readout noise of CCD increases exponentially with the temperature according to our empirical relation.

關鍵字(Keywords)：增益(gain)、讀取雜訊 (readout noise)、PI 1300B CCD、鹿林天文台 (Lulin Observatory)

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1. Introduction

Charged Coupled Device (CCD) camera is the most popular detector for modern optical astronomy. Generally speaking, lower noise, high quantum efficiency, and good linear response are the advantages of CCD. Therefore, CCD has been widely used in the mainstream of optical astronomy. The current CCD facilitated on the Lulin One-meter Telescope (hereafter LOT), of the Lulin Observatory, is Princeton Instruments model 1300B CCD (hereafter PI 1300B CCD, see Table 1 for it's specifications). It has already served for more than five years (since 2004). Past investigations had been carried out by Kinoshita et al. (2005) and Huang et al. (2008) to determine the properties of this CCD. This work is a follow-up investigation of the gain and readout noise of this CCD as time progresses.

As a member institution of the Pan-STARRS 1[a] (hereafter, PS1) science consortium, Institute of Astronomy, National Central University (IANCU)[b] has the full data access right to PS1 data. Follow-up observations are needed for the newly discovered objects, including transient events, asteroids, quasi-stellar objects, and various type of astronomical objects to increase the scientific outputs. LOT is located in one of the best site to follow-up the PS1 observation, because, among the PS1 members, there is no other observatory of PS1 member institutes in Asia. In addition, the latitude of Lulin is similar to that of PS1 site in Hawaii, so that majority of PS1 discoveries are followed up.

Table 1. Specifications of the CCD camera PI 1300B as provided from Roper Scientific, Inc.

Type	Properties
CCD Chip	EEV CCD36-40 (back-side illuminated)
Pixel Number	1340 × 1300
Pixel Size	20μm × 20μm
Imaging Area	26.8mm × 26.0mm
CCD Grade	Scientific Grade; Grade 1
Full Well	200,000 e^-
AD Conversion	16 bits
Sampling Mode	50 kHz (slow mode); 1 MHz (fast mode)
Readout	36 sec @ 50 kHz; 1.8 sec @ 1 MHz
Readout Noise	3 e^- rms @50Hz;10 e^- rms @1MHz
Dark Current	0.1 e^-/sec/pixel @-40°C; 0.5 e^-/hr/pixel @ -110°C

2. Data Acquisition

We followed the method introduced by Kinoshita et al. (2005) to investigate the gain and readout noise of the CCD. Two spotlights were taken as the light source of the flat field. To achieve better flatness of the illuminated screen, the spotlights were faced to the wall and ground of the dorm, so the light from the spotlights would reflect from the wall and ground to the white dorm screen, and then reflect again to the telescope. Bessel U, B, V, R, and I broad band filters and Hα narrow band filter were used for taking the flat field images. We adjusted the intensity of the spotlights and made use of different filters to derive the flat images with different signal levels below 50,000 ADU. We also took dark images which have the same exposure time with the flat field images, which are needed for reducing the data. All flat field and dark images were taken in slow readout mode (50 kHz sampling). In contrast to previous work, we examined gains and readout noises at different operation temperatures, ranging from -45°C to 0°C. The data acquisitions were carried out in Jun. 4, 2009. The log of data acquisition is listed in Table 2.

In general, the operation temperature of PI

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[a] Panoramic Survey Telescope & Rapid Response System. http://pan-starrs.ifa.hawaii.edu/public/
[b] http://www.astro.ncu.edu.tw

1300B CCD is set to -45°C in summer and -50°C in winter. The setting temperature (-45°C) in summer time sometimes could not be sustained at the same level by the current water cooling system, and this maybe due to the aging of the cooling system. Observers of LOT need to be aware of the cooling system for the PI 1300B CCD.

Table 2. The log of the data acquisition.

Date	Temperature (°C)	Number of frames
2009/06/04	-5	60
2009/06/04	-10	75
2009/06/04	-20	55
2009/06/04	-35	60
2009/06/04	-30	55
2009/06/03	-45	75

3. Method of Analysis

The dome flat field images were subtracted by the dark images with the same exposure time, so the bias and dark components were removed. We followed the method in Motohara et al. (2002), and Kinoshita et al. (2005), by defining the gain value as:

$$n_e = Gn_{ADU} \tag{1}$$

where n_e is the number of electrons, G is the gain value, and n_{ADU} is the ADU count of the CCD. In a CCD image, the noise is composed of two parts, the photoelectric Poisson noise and the readout noise. The relation between the signal and noise is listed as the following equation (Motohara et al, 2002).

$$N = \sqrt{\frac{S}{G} + \left(\frac{R}{G}\right)^2} \tag{2}$$

where N is total noise in ADU, R is readout noise (the number of electrons introduce into final signal during data readout) in e^-, and S is the signal of the image in ADU. The relation between the deviation of the difference image from the flat field pairs, electron signals, gain, and readout noise could be presented as:

$$\sigma^2_{F_1F_2} = 2\left[\left(\frac{\sqrt{n_e}}{G}\right)^2 + \left(\frac{R}{G}\right)^2\right] \tag{3}$$

where $\sigma^2_{F_1F_2}$ is the standard deviation of the subtracted images.

After subtraction of the two images, the noise level will grow by a factor of $\sqrt{2}$. The noise level (N) could be derived by dividing $\sqrt{2}$ to the deviation level of the subtracted image. The mean signal level (S) is the average of the image pair. Since we have the signal and noise values, we fitted the data of different ADU levels by Equation (2), and the gain and readout noise values were derived.

In order to check the uniformity of the CCD properties, we divided the CCD images into nine sub-regions (401 × 401 pixel^2 for each) (Figure 1, and Table 3). The readout noise and the gain values are calculated in each sub-regions. The results for the CCD operation temperature of -45°C are demonstrated in Figure 2. We summarized all the results in Table 4.

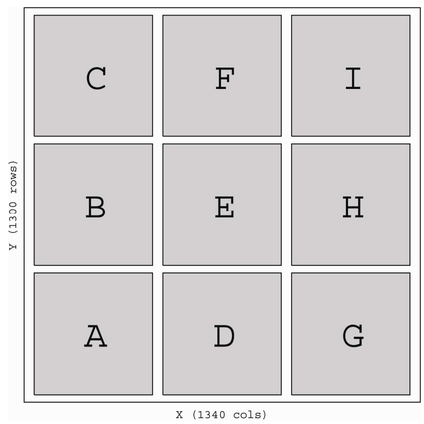

Fig. 1: Illustration for the nine regions used for the statistical calculation for the signal and noise levels. The coordinates of each sub-region could be found in Table 3.

Table 3. Ranges of different regions. An entire frame has been divided into nine regions with the same area (401 × 401 pixel^2). x_{min} and x_{max} are the minimum pixel and maximum pixel of the column, and y_{min} and y_{max} are the minimum and maximum pixel of the rows, respectively.

Region Name	X Range (x_{min}:x_{max})	Y Range (y_{min}:y_{max})
A	35:435	25:425
B	35:435	450:850
C	35:435	875:1275
D	470:870	25:425
E	470:870	450:850
F	470:870	875:1275
G	905:1305	25:425
H	905:1305	450:850
I	905:1305	875:1275

Table 4. Readout noises in different regions (in e^-).

Region	-45°C	-35°C	-30°C	-20°C	-10°C	-5°C	-0°C
A	4.87 ± 0.43	5.16 ± 1.22	7.59 ± 0.53	8.61 ± 0.28	14.20 ± 0.62	19.57 ± 0.79	24.15 ± 0.78
B	4.96 ± 0.36	5.92 ± 0.33	8.58 ± 0.45	10.25 ± 0.32	17.83 ± 0.66	23.80 ± 0.79	30.37 ± 1.01
C	5.23 ± 0.41	6.53 ± 0.48	9.82 ± 0.57	11.86 ± 0.34	21.13 ± 0.72	28.10 ± 0.88	36.49 ± 1.32
D	4.58 ± 0.35	5.16 ± 0.37	7.32 ± 0.45	8.34 ± 0.29	13.85 ± 0.58	18.83 ± 0.74	23.53 ± 0.74
E	4.67 ± 0.31	5.65 ± 0.37	8.27 ± 0.43	9.92 ± 0.33	17.36 ± 0.64	22.89 ± 0.75	29.49 ± 0.96
F	5.05 ± 0.36	6.28 ± 0.55	9.45 ± 0.46	11.57 ± 0.34	20.70 ± 0.71	27.42 ± 0.85	35.52 ± 1.27
G	4.46 ± 0.39	4.96 ± 0.52	7.12 ± 0.57	8.17 ± 0.30	13.58 ± 0.58	18.36 ± 0.72	23.19 ± 0.74
H	4.44 ± 0.29	5.22 ± 0.91	7.98 ± 0.51	9.64 ± 0.32	16.95 ± 0.65	22.08 ± 0.72	28.67 ± 0.95
I	4.89 ± 0.33	6.10 ± 0.44	9.21 ± 0.55	11.38 ± 0.34	20.33 ± 0.72	26.65 ± 0.83	34.85 ± 1.26

Table 5. Fitted parameters of different rows for the empirical relation, Equation (4).

Regions	*a*	*b*	*c*
Top Row	20.38 ± 0.96	0.0654 ± 0.0092	3.53 ± 0.95
Middle Row	26.56 ± 1.01	0.0626 ± 0.0070	3.13 ± 1.01
Bottom Row	32.59 ± 1.18	0.0625 ± 0.0066	3.19 ± 1.18

Table 6. Comparison to previous works (at slow readout mode (50 kHz)).

Works	Gain (e^-/ADU)	Readout Noise (e^-)	Temperature (°C)
Kinoshita (2005)	2.0	4.4-4.5	-50
Huang (2008)	1.95 ± 0.02	4.6 ± 0.5	-50
This work	1.98 ± 0.01	4.2 ± 0.07	-50 (extrapolated)

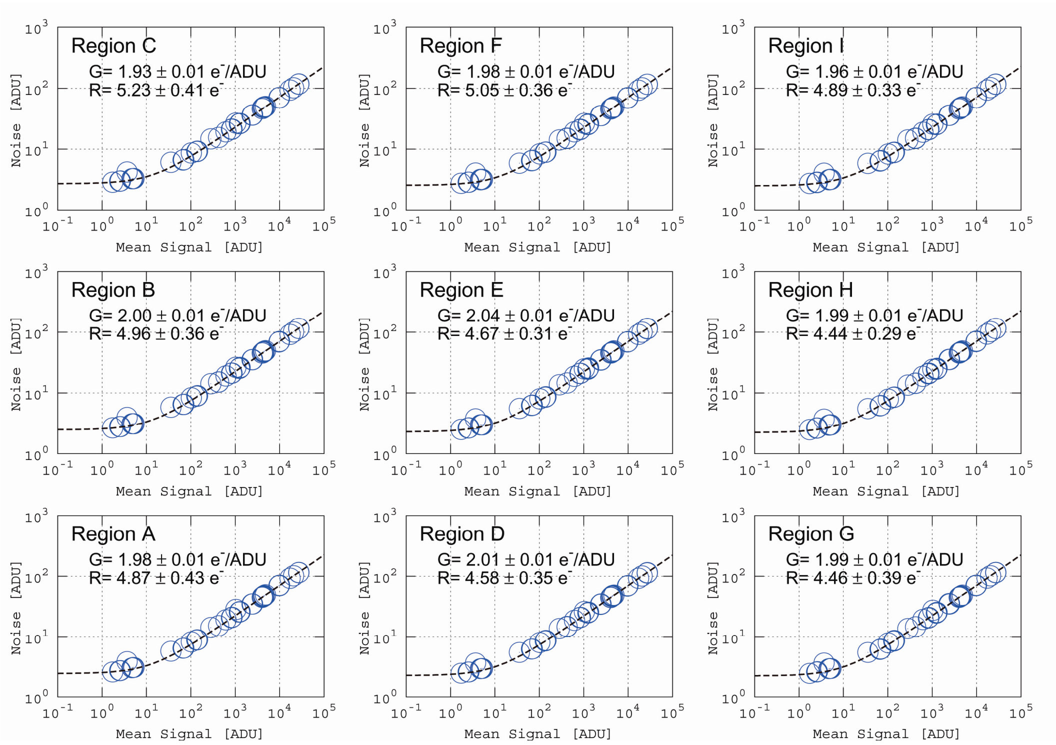

Fig. 2: Signal versus noise plot for different sub-regions in -45°C. The fitted results of gains (*G*) and readout noises (*R*) are listed in each sub-figure.

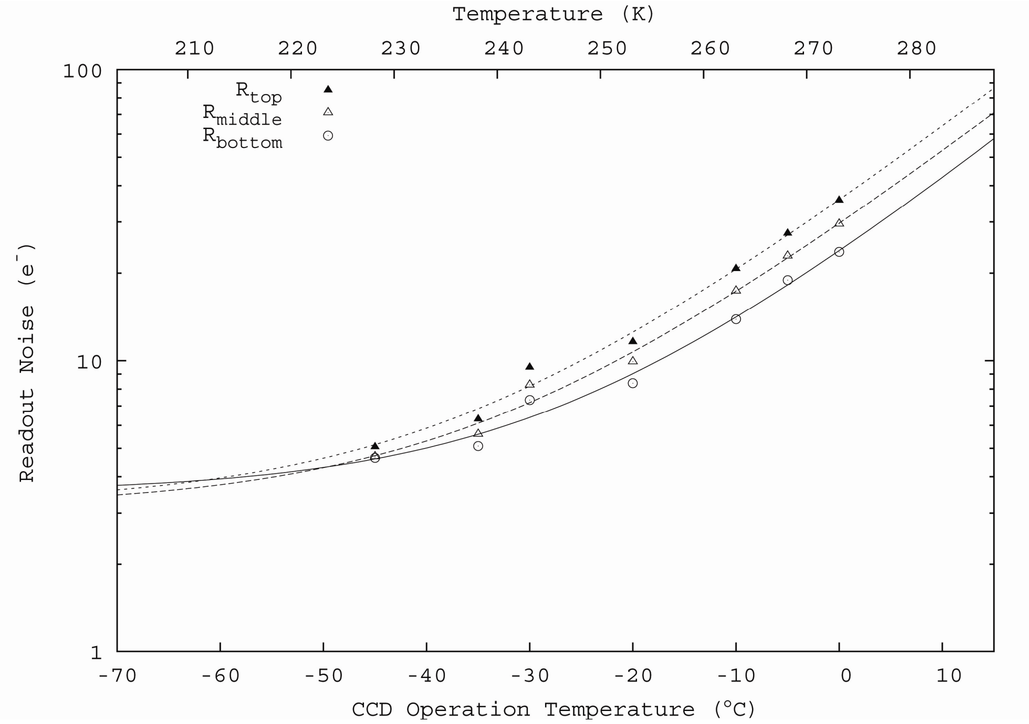

Fig. 3: Readout noise in different temperatures by rows. Readout noise in top row (R_{top}, combinations of regions: C, F, I, filled triangle), in middle row (R_{middle}, regions: B, E, H, open triangle), and in bottom row (R_{bottom}, regions: A, D, G, open circle). The fitted empirical models are in short dashed line (top row), long dashed line (middle row), and solid line (bottom row).

4. Results and Discussion

4.1 Temperature Dependence of Readout Noise

The readout noise is composed of two inseparable components (Howell 2000). The first component is from the amplifier and the analog-to-digital converter. The second component is from the spurious electrons which enter into the system during the entire readout process. Therefore, it's difficult to give the physical relation between the temperature and readout noise, hence, we try to derive an empirical relation from the results presented in Table 4 (see Figure 3).

The readout noise for PI 1300B CCD is not uniform. From the results shown in Table 4, we found a gradient of readout noise which is parallel to the readout direction. Therefore, we grouped the sub-regions in row directions (perpendicular to the readout direction) to analyze the readout properties of the CCD. The empirical relation between CCD temperature (T) and readout noise (R) could be described as the following relation:

$$R = a \times e^{bT} + c \qquad (4)$$

where T is temperature in Celsius, and R is the readout noise in e^-. The readout noise grows exponentially with increasing CCD temperature. The fitted parameters, *a, b*, and *c* are listed in Table 5.

4.2 Comparison of the gain and readout noise with previous works

In Table 6, we compared our results of the gain and readout noise to previous works presented in Kinoshita et al. (2005) and Huang et al. (2008). The gain value in slow readout mode is about 2 e^-/ADU, which is identical in different operating temperatures. Because our operating temperature is different from other works, we extrapolated the readout noise value to -50°C from equation (5), and the expected readout noise is 4.2 e^-, which is consistent with previous result.

4.3 Uniformity of Readout Noise

We divided the CCD pixels into nine sub-regions when performing the analysis for the uniformity check. The gain value is almost constant in entire CCD region, but the readout noise is not. The readout noise is higher in top regions (C, F, I) and lower in bottom regions (A, D, G). This suggests the readout noise is depending on the row, and nearly uniform among different columns. Because the non-uniformity is parallel to the readout direction, one possible reason is the additional electrons accumulated during the transfer of the photoelectrons from pixel to pixel, and the other possible reason is that the amplifier is heated when converting e^- into voltage.

In order to check the uniformity of the readout noise, the uniformity coefficient developed by Christiansen in 1942 (Vories and Von Bernuth, 1986) is introduced, which is stated below:

$$CU = 100 \times \left[1 - \frac{\sum |R_i - m|}{\sum R_i}\right](\%) \qquad (5)$$

where *CU* represents the uniformity of the entire CCD, R_i is the readout noise of the *i*th region, and m is the mean value of R_i. The result of uniformity check is shown in Table 7. The non-uniformity becomes a more serious problem for higher CCD operation temperature.

According to the fitted parameters in Table 5 and Equation (4), the expected readout noises for the 9 sub-regions in different temperatures could be derived. We expect that the uniformity will be larger than 97% when T < -51.2°C, and reach the maximum, ~ 97.96%, at T ~ -55.9°C.

Table 7. Christiansen uniformity coefficient (*CU*) of the readout noise in different operation temperatures.

Temperature (°C)	*CU* (%)
-5	86.85
-10	86.25
-20	88.47
-30	90.51
-35	91.48
-45	95.23

4.4 CCD Cooling Temperature

We identified an important issue for the data acquisition under the current configuration of the CCD camera. The cooling temperature of -45°C sometimes could not be sustained at the same level by the current water cooling system in summer. It is possibly due to the aging or the vacuum level of the cooling system. The performance of the CCD cooling system might be decayed by time or affected by other factors. If the observers would like to use PI 1300B CCD, they should notice about this issue. From the private communication to the staff members of Lulin Observatory, another set of CCD cooling system will be setup soon. The cooling ability and stability are expected to perform better than the current one. We will keep tracking on the performance and the characteristics investigation of the new instruments once it is ready.

5. Summary

We had evaluated the gain and readout noise for PI 1300B CCD again. The gain is 1.98 ± 0.01

e^-/ADU and readout noise is 4.2 ± 0.07 e^- at -45°C (slow readout mode). The CCD readout noise will grow exponentially with its operation temperature. When the temperature is less than -51.2°C, the uniformity of readout noise is expected to be larger than 97%, and reaches the maximum, ~ 97.96%, at T ~ -55.9°C.

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Reference

Howell, S. B., 2000, *Handbook of CCD Astronomy*, (ISBN 0-521-64834-3), Cambridge University Press.

Huang, H.F., Kinoshita, D., Shih, C.Y., 2008, *JTAM*, 6, 18.

Kinoshita, D., Chen, C.W., Lin, H.C., Lin, Z.Y., Huang, K.Y., Chang, Y.S. and Chen, W.P., 2005, *ChJAA*, 5, 315.

Motohara, K. et al., 2002, *PASJ*, 54, 315..

Vories, E.D. and R.D. von Bernuth, 1986, *Trans. Am. Soc. Agric. Eng.*, 29, 1325.