鹿林天文台 CCD 相機 PI1300B 的暗電流及增益值測量

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摘要

儀器的狀況可能隨時間改變並影響其效能。爲了確保天文觀測的準確度，我們需定期檢視儀器的表現。本實驗中，我們檢測了鹿林天文台CCD PI1300B的暗電流、增益值及讀出噪音。我們使用平場及暗電流影像來估計增益與讀出噪音，並求得不同CCD冷卻溫度下所表現的暗電流產生率。我們所量測的數據與2005年以前的調查結果 (Kinoshita et al. 2005) 相符合，說明CCD PI1300B仍持續穩定運作。

The Dark Current and Gain Measurements of CCD Camera PI1300B at Lulin Observatory

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Abstract

The condition of the instrument may vary through time, and influences the basic properties and performance of instruments. In order to ensure the stable science operation of observation, the characteristics and performance of CCD needs to be re-examined regularly. We have measured the dark current, gain, and readout noise of CCD camera PI1300B mounted on Lulin One-meter Telescope (LOT) at Lulin Observatory. We have obtained dark and flatfield frames to estimate the gain and readout noise. The dark current generation rates at different CCD cooling temperatures were measured. Results are compared with the previous study (Kinoshita et al. 2005), and it is found to be consistent. The instrument is found to be stably operated.

關鍵字 (Key words): 天文儀器 (instrumentation)、CCD: PI1300B、鹿林天文台 (Lulin Observatory)、暗電流 (dark current)、增益 (gain)、讀出雜訊 (readout noise)

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1. Introduction

Charge-coupled devices (CCD) are the most popular detectors which are used in optical astronomical observations for many advantages. These advantages include low noise, high quantum efficiency, good linearity and high dynamic range. The brief description of the operation of CCD is as follows. The electrons are freed by the energy of incoming photons during the integration. When exposure ends, charges have been collected and the voltage has been converted into digital units. In order to obtain precise measurements for scientific study, observer must know the noise occurred within the instrument first. (Martinez and Klotz 1998; Howell 2000)

The CCD camera PI1300B was mounted on Lulin One-meter Telescope (LOT) at Lulin Observatory being the main instrument after January 2003. Its basic characteristics were surveyed in 2004, and results were reported by Kinoshita et al. (2005). Condition of the instrument may vary with time; so the regular re-estimates are necessary to confirm its stable science operation. We measured the gain, readout noise and dark current generation rate in November 2007 in this work. Table 1 lists the basic properties provided by the manufacturer, Roper Scientific, Inc.

Table 1. The basic properties of CCD PI 1300B provided by the manufacturer (adopted from Kinoshita et al. 2005).

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

2. Measurements and Results

2.1 Gain and Readout Noise

The gain [e^-/ADU] is defined as the number of electrons required to produce a unit of digital number, which is often represented by analog-to-digital unit (ADU), in output image,

$$n_e = G\, n_{ADU} \quad (1)$$

Where n_e is the number of electrons, G is the gain, and n_{ADU} is the value of ADU. The total noise consists of two components. One is the contribution from the Poisson noise, which is square root of the signal. The other is the readout noise. So the relation between total noise N and signal S can be represented as (Motohara et al. 2002; Kinoshita et al. 2005),

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

Where R is readout noise [e^-], the number of electrons introduce into final signal accompanies with data readout. N, S/G and R/G are the total noise, mean signal level, and readout noise, respectively, in the unit of ADU. From Howell (2000), we know that subtracting two flatfields can get the standard deviation which includes both background Poisson and readout noises, and it can be written as,

$$\sigma^2_{F_1-F_2} = 2\left\{\left(\frac{\sqrt{n_e}}{G}\right)^2 + \left(\frac{R}{G}\right)^2\right\} \quad (3)$$

Where $\sigma_{F_1-F_2}$ is the standard deviation of subtracting two flat field frames. Thus, we can estimate the value of gain and readout noise by using flatfields.

We followed the method used by Kinoshita et al. (2005), to obtain five flatfields and five dark frames under the same CCD temperature and exposure time. Each frame was divided into 4 regions which every subframe contains 300 × 300 pixels. Fig. 1 is the schematic drawing to show locations of subframes. Using the Eq. (2), we can fit data points to estimate the gain and readout noise values. Fig. 2 and Fig. 3 show the fitting results under CCD temperature of -50°C for the fast readout of 1 MHz sampling (hereafter “fast mode”) and the slow readout of 50 kHz sampling (hereafter “slow mode”), respectively. The comparison between previous work and our measurement are collated in Table 2.

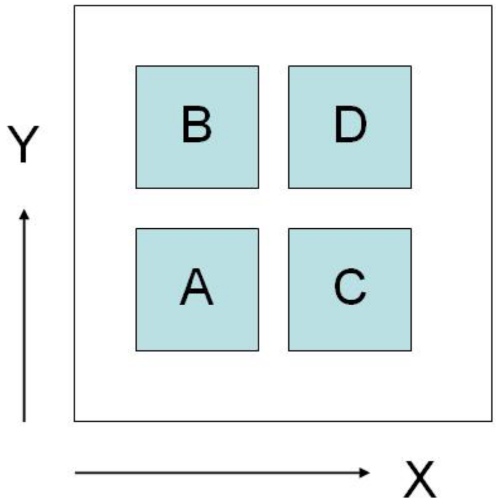
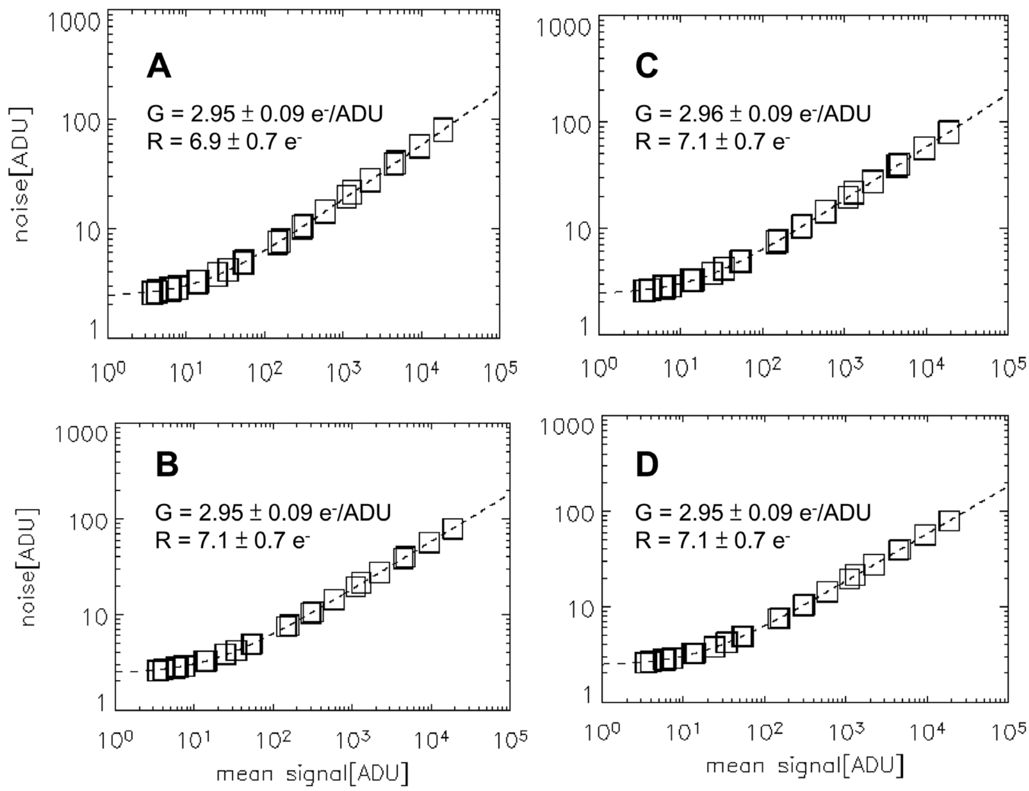


Fig. 1: Sketch of subframes of four regions. Coordinates of four regions are listed as following in the unit of pixel. Region A (301 ≦ X ≦ 600, 301 ≦ Y ≦ 600); Region B (301 ≦ X ≦ 600, 701 ≦ Y ≦ 1000); Region C (701 ≦ X ≦ 1000, 301 ≦ Y ≦ 600); Region D (701 ≦ X ≦ 1000, 701 ≦ Y ≦ 1000).

Fig. 2: The gain and readout noise of different regions for fast mode. Horizontal and vertical axes are the mean signal and noise in the unit of ADU, respectively. G represents gain and R indicates readout noise. Dashed curves are the least square fits to the data using Eq. (2). We used 240 data points to fit, and these data points are roughly uniformly distributed over the signal level.



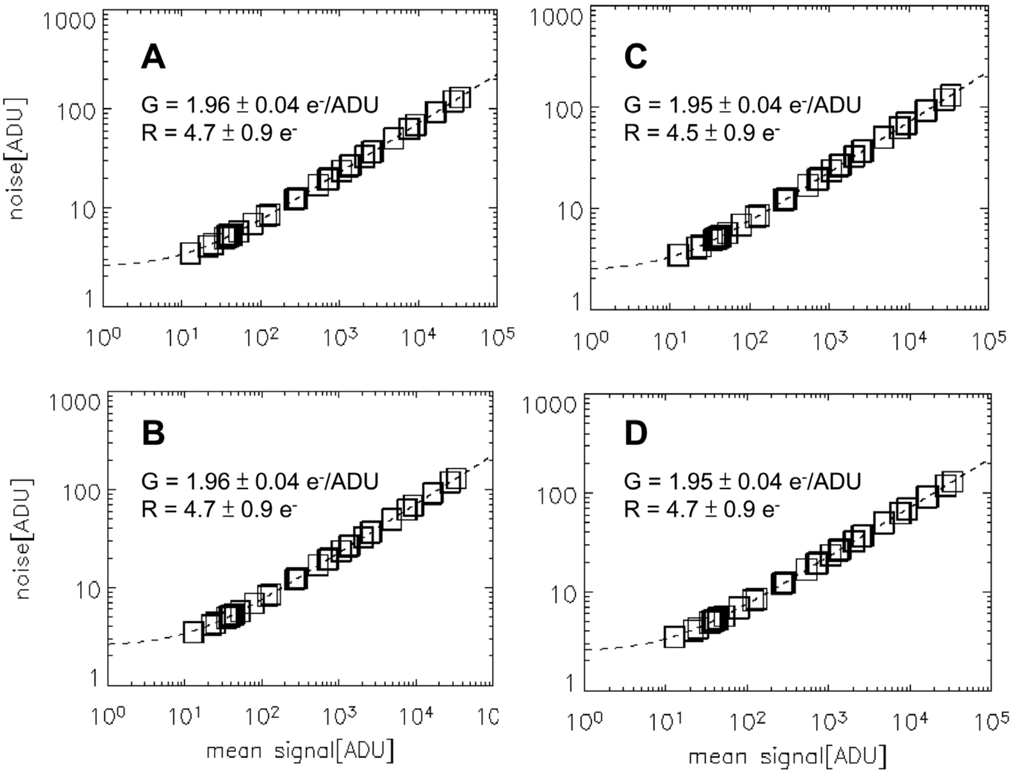


Fig. 3: The gain and readout noise of different regions for slow mode. Legend is as the same as Fig. 2.

Table 2. The average gain and readout noise of CCD PI1300B at -50°C.

		This work	Kinoshita et al. 2005
Fast mode	**Gain**	2.95 ± 0.05	3.0
	Readout noise	7.0 ± 0.3	7.1 – 7.4
Slow mode	**Gain**	1.95 ± 0.02	2.0
	Readout noise	4.6 ± 0.5	4.4 – 4.5

2.2 Dark Current

Dark current electrons are electrons generated by thermal influence within instrument. It is usually represented for the generation rate per second per pixel [e^-/s/pix], and has highly correlation with CCD temperature. The theoretical behavior of thermal electron production rate D against temperature can be expressed as Howell (2000),

$$D = CT^{\frac{3}{2}} \exp\left(\frac{-E_g}{2kT}\right) \qquad (4)$$

$$E_g = 1.557 - \frac{7.021 \times 10^{-4} T^2}{1108 + T} \qquad (5)$$

Where T is temperature, E_g is the band gap energy for silicon, k is the Boltzmann constant, and the C value depends on CCDs.

We took dark frames using slow mode at the temperature from 0°C to -50°C. Six dark and six bias frames were taken for each temperature setting, then we subtracted bias from dark frames to calculate the dark current generation rate. Fig. 4 is our measurement and we use Eq. (4) to fit the data points. For CCD PI1300B, we get the C value = 7.24 × 10^7. Because the gain depends on the temperature, we used linear fitting to estimate gain values under different CCD temperature conditions, and the fitting result is showed in Fig. 5.

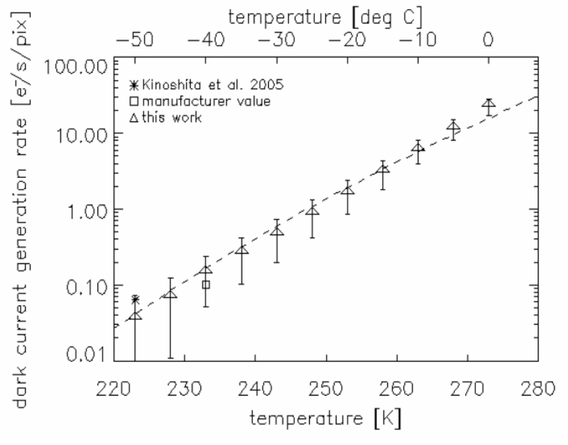


Fig. 4: Dark current performance of CCD PI1300B againsts the CCD cooling temperature. The dashed line is the fitting curve using Eq. (4).

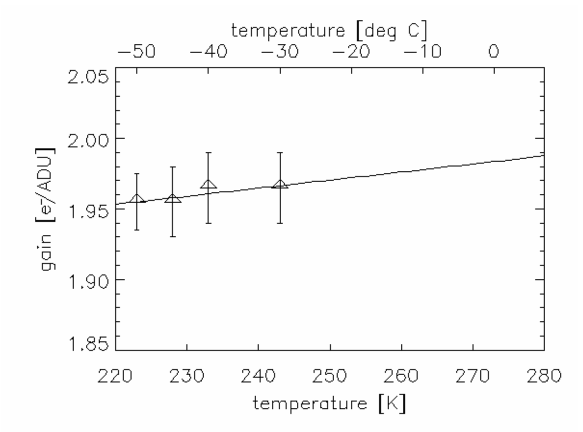


Fig. 5: Gain values at CCD temperature -50, -45, -40, -30°C are labeled as triangle symbols with error bars. The solid line is the linear fitting of these four gains, and we applied this fitting result to estimate dark current in Fig. 4.

3. Discussion

3.1 Comparison with the previous work

We can compare our results with the previous work by Kinoshita et al. (2005). For gain and readout noise, we divide four regions in each image frame in our processing as Fig. 1 shows. This method can help us to check uniformity of the CCD. From the results showed in Fig. 2 and Fig. 3, the CCD PI1300B still performs uniformity well. Our measurements, both for slow and fast mode, are within or quite similar with the range of previous work.

For dark current generation rate, we pick the values from previous work and the manufacturer to check our results. Both the previous work (D = 0.064 e^-/s/pix at -50°C) and the manufacturer value (D = 0.1 e^-/s/pix at -40°C) are within the error range of our measurements. Because we lack direct gain measurements except for -30, -40, -45, -50°C conditions, we adopted gain values from linear fitting based on these four measurements. It may cause errors, especially we have no actual measurements for temperature higher than -30°C.

The influence of dark current can be reduced with lower CCD temperature. Using Eq. (4) and (5), we can estimate dark current generation rate at lower CCD temperature. If the CCD camera can achieve the operation temperature of -100°C, dark current generation rate will be about 0.015 e^-/hr/pix. In other words, effect of dark current is negligible even under long time exposure as one hour.

3.2 Comparison with other instrument

In order to show the comparison between PI1300B and other instruments, here we also summarize the signal-to-noise ratio (SNR) calculations of PI1300B and the other CCD camera once used by LOT.

The previous CCD camera mounted on LOT was AP8, which was manufactured by Apogee Instruments Inc., and became backup camera after PI1300B has started to serve as a main instrument. Kinoshita et al. (2004) has measured its basic performance. AP8 only has one readout mode for 35 kHz sampling. Its gain was estimated as 4.4 ± 0.4

e⁻/ADU, and the readout noise was 15.7 ± 4.7 e⁻. The dark current generation rate of AP8 was measured as 0.49 e⁻/s/pix for the CCD temperature -45°C. Comparing to AP8, PI1300B has much lower readout noise and dark current generation rate. We can use the CCD Equation as Eq. (6) to estimate difference of signal-to-noise ratio between these two CCDs (Mortara and Fowler 1981; Howell 2000),

$$\frac{S}{N} = \frac{N_S}{\sqrt{N_S + n_{pix}(N_B + N_D + N_R^2)}} \qquad (6)$$

Where N_S is the total number of photons from the target, n_{pix} is the number of pixels for calculation, N_B is the total number of photons per pixel from background sky, N_D is the total number of dark current electrons per pixel, N_R is the total number of electrons per pixel from readout noise. First of all, we assume 300 seconds integration in V-band for a source which magnitude is 20 and seeing is 1.5 arcseconds, and then we insert dark current generation rate and readout noise to calculate the ratio of PI1300B to AP8. Under the condition defined above, PI1300B at slow mode achieves 1.1 times higher signal-to-noise ratio than that of AP8.

Similar calculations under different conditions can be made. Fig. 6 shows the signal-to-noise ratios of PI1300B and AP8 with different integration time for a 20 magnitude target. We take ratios of SNRs achieved by PI1300B and AP8, and then Fig. 7 is constructed. Fig. 7 demonstrates the ratio of SNRs achieved by PI1300B and AP8 for different target magnitudes under the integration time of 30, 60, 120, and 300 seconds. We can see that the ratio of SNRs achieved by PI1300B and AP8 are about 1.06 for magnitude range between 12 to14, and become larger when fainter objects are observed. For example, the difference is as large as 15% for 18 magnitude target with 120 seconds integration time. The parameters for the calculation of SNR and limiting magnitude are listed in the Table 3.

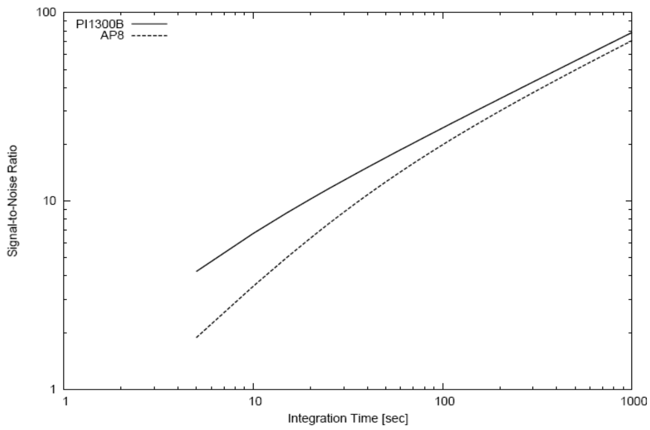


Fig. 6: The signal-to-noise ratio of PI1300B and AP8 versus different integration time for a 20 magnitude target.

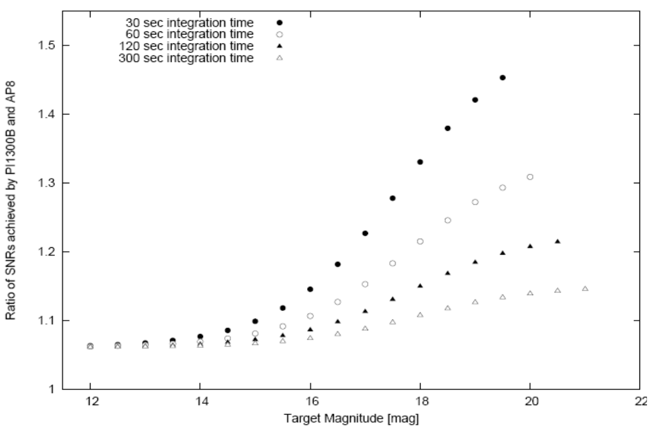


Fig. 7: The ratio of SNRs achieved by PI1300B and AP8 versus target magnitude. Different symbols of data points represent different integration time.

4. Conclusion

We have measured the gain, readout noise of CCD camera PI1300B at 1 MHz and 50 kHz readout mode. Under the CCD cooling

Table 3. Parameters for the Calculation of the relation between SNR and limiting magnitudes.

	AP8	PI1300B
Quantum Efficiency	0.8	0.9
Dark current [e$^-$/s/pix]	0.49	0.07
Readout noise [e$^-$]	15.7	4.6
Pixel scale [arcsec/pix]	0.619	0.516
PSF size [arcsec]	1.5	
Aperture size [arcsec]	2.25 (PSF size × 1.5)	
Central wavelength of V-band [Å]	5500	
Bandwidth of V-band [Å]	900	
Zero magnitude flux at V-band [W /m^2/micron]	3.58×10^{-8}	
Sky background brightness at V-band [mag./arcsec^2]	21.0	

temperature of -50°C, the average gains are 1.95 ± 0.02 and 2.95 ± 0.05 e$^-$/ADU for slow and fast mode, respectively; The average readout noise is 4.6 ± 0.5, and 7.0 ± 0.3 e$^-$ for slow and fast mode, respectively. We have also measured the dark current generation rate for slow mode at difference cooling temperatures. The average value is 0.04 ± 0.04 e$^-$/s/pix for -50°C. Our measurements are consistent with previous study (Kinoshita et al. 2005), and it is found the instrument is stably operated.

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References

Howell, S. B., 2000, *Handbook of CCD Astronomy*, Cambridge University Press

Kinoshita, D.; Chen, C.-W.; Lin, H.-C.; Lin, Z.-Y.; Huang, K.-Y.; Chang, Y.-S.; Chen W.-P., 2005, *ChJAA*, 5, 3, 315.

Kinoshita, D.; Huang, K.-Y.; Wu, Y, -L.; Chang, Y.-S.; Urata, Y., 2004, *Annual Report of Lulin Observatory (2003)*, 30.

Martinez, P. and Klotz, A., 1998, *A Practical Guide to CCD Astronomy*, Cambridge University Press.

Mortara, L and Fowler, A., 1981, *Proc. SPIE*, 290, 28.

Motohara, K; Iwamuro, F.; Maihara, T.; Oya, S.; Tsukamoto, H.; Imanishi, M.; Terada, H.; Goto, M.; Iwai, J.; Tanabe, H.; Hata, R.; Taguchi, T.; Harashima, T., 2002, *PASJ*, 54, 2, 315.