A Performance Study of the CCD Cameras of the Joint Laboratory of Optical Astronomy

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Abstract A performance study of several CCD cameras of the Chinese Joint Laboratory of Optical Astronomy (CJLOA) is presented. The main results are: 1) We propose a modified classical method to analyse the linearity of CCD cameras. This method is more sensitive and accurate as well as more intuitive, especially in measuring around the 0.1%–0.2% range of nonlinearity. 2) To illustrate the advantage of the method, the linearity performance of the CCD cameras at CJLOA has been measured and analysed. 3) For the CCD systems tested, there is no unique formula to represent the correlation over the entire CCD frame between the deviation from linearity and the pixel value, i.e., different pixel has different correction even though their pixel values are the same. 4) For the BFOSC (BAO Faint Object Spectrograph Camera) Loral CCD camera and the Tek CCD camera at the 1.56-m reflector, blooming (bleeding) happens long before saturation, and we suspect whether it could have resulted from the charge transfer efficiency (CTE) not being high enough.

Key words: instrumentation: detectors — telescopes

1 INTRODUCTION

There are three optical reflectors belonging to the Chinese Joint Laboratory of Optical Astronomy (CJLOA), the 2.16-m at Xinglong, the 1.56-m at Zo-se, and the 1-m in Kunming. All three are equipped with CCD detectors. A study has been made on the performance of the CCD cameras during our photometry observations from 1997 to 2002. The cameras we checked are as follows: the #1 and #2 CCD cameras on the 1-m reflector equipped with Tek 1024×1024 chip (pixel size 24 micron), both from Princeton Instruments (PI), Inc.; the camera on the 1.56-m reflector with a Tek 2048×2048 (24 micron) and the one of BFOSC (Yao & Huang 2002) on the 2.16-m reflector with a Loral 2048×2048 (15 micron), both integrated at Lick Observatory using their control electronics, the same that is used on the 10-m Keck telescope. Sect. 2 describes a modified classical method we used for a linearity study of the cameras and presents the results obtained— this is the main part of this article. Additionally, Sect. 3 discusses the charge transfer efficiency (CTE). Our conclusion is given in Sect. 4.

2 NON-LINEARLITY

One of the most important features of the CCD is its linearity. When the CCD was first introduced into the astronomical community in the 1980s, the linearity was generally carefully checked by the makers, and the users were told that the CCD system is always linear up to near the saturation point. However, nonlinear response appearing long before saturation was reported in the literature more than once (see, e.g., Walker 1993). Now we are told that there are two sources of nonlinearity, floating diffusion nonlinearity (in the sense node of the chip) and MOSFET nonlinearity (in the on-chip amplifier), and the two may add together (Janesick 2001). Obviously, not every CCD system was carefully checked before delivery to the user. The users have to make the check themselves. This is also the case with the CCD cameras of the CJLOA.

As far as we know, the usual way of dealing with the non-linearity in the observatories is as follows. a) Take a series of dome flat field exposures of increasing durations. b) Subtract the bias and correct the shutter-timing error (if necessary). c) Take a sub-region (in any part of the frame) or the whole CCD frame (without bad pixels) to obtain the average value of the sub-regions (or the whole frame). d) Plot the "counts - exposure" curve (the so-called transfer curve), note where deviation from linearity appears and how large it is. Some observatories give count levels for 0.1% and 1% nonlinearity separately, e.g., KPNO (Armandroff et al. 1996). e) Use a polynomial to fit the "counts - exposure" plot, and give the coefficients of the polynomial (or a Look Up Table) to enable the user to correct the non-linearity, e.g., Robinson et al. (1989), Walker (1993), Irwin & Lewis (1999), Irwin (2000), Tinney (cgt@aaoepp.aao.gov.au, 2003).

2.1 Our Method

We also followed the above classical method to check the CCDs at CJLOA. Here the Stetson method (Stetson 1989) was used to determine the shutter function to correct the shutter-timing error. In addition, a calibration exposure is always inserted into the series to monitor the variation of the light source and correct its influence (because the illumination of the light source at CJLOA sometimes varies continuously and not monotonically, the obtained counts - exposure plot may be distorted even in the linear part of the transfer curve). A sample series consists of a succession of exposures of 5s, 10s, 5s, 15s, 5s, 20s, 5s, 25s, 5s, 30s, ..., the 5s being the calibration exposures. For each dome flat we calculate the average of the two adjacent calibration exposures. Compare this average with that of the first calibration exposure, a ratio is obtained. Multiply by this ratio the exposure time of the dome flat, then use the modified time to plot the transfer curve (less effective for abrupt variations of the light source). A straight line is fitted to the linear part of the transfer curve by least squares and the nonlinearity in the nonlinear part is estimated.

The results so obtained are not accurate because we lack highly stabilized light sources at CJLOA. When a specification of 1% at some count level is reported, this is only an estimate of the nonlinearity. This difficulty in measuring small nonlinearity is generally recognized, even the PI company once pointed out (PI company 1998) that "it is so difficult to measure the non-linearity of these CCDs that the 1% linearity specification usually means 'the CCD is more linear than the test fixture'".

Needless to say, it is even more difficult to measure 0.1% nonlinearity using the classical method. Besides, it is not easy to use the classical method to answer the question: can a unique polynomial fit the nonlinear part of the transfer curve over the entire CCD frame?

A Performance Study of CCD Cameras

In the attempt to answer these questions we modified the classical method a little to make it more sensitive, more accurate, and more intuitive. Our modification is as follows:

Make full use of the inhomogeneity of the illumination of the dome flat field (in ideal case the CCD should be placed in the laboratory and image a series of well designed screen with inhomogeneous pattern onto the CCD chip. The inhomogeneity should range from 15% to 200%). After subtracting the bias and correcting the shutter-timing error, a shorter exposure image (which should be in the linear range of the CCD) is divided into longer ones and the resultant quotients are inspected. In this way the linearity analysis becomes intuitive image reduction with all the advantages of the latter.

Inhomogeneous illumination is bad for flat fielding purpose, but it is just what we need to show the non-linear response of the CCD. In the classical method, the number of exposures is limited (giving limited points in the transfer curve). By contrast, by using the inhomogeneous frame the intensity varies continuously from low to high through all the intermediate values. So the effect of one exposure here is equal to a large number of exposures in the classical method.

Both in the classical and our methods the pixels in a sub-region are averaged when plotting the transfer curve because the measurement of nonlinearity is a "macro" task rather than a "micro" pixel to pixel search for bad pixels. Similarly, the quotient should be smoothed, say, using the IRAF command "median" and display the image more smoothly. In addition, if the calibration exposure is suitable as the denominator in the image division, they may be combined into an averaged image to improve the signal to noise ratio of the division.

When the quotient is loaded onto the screen of the computer (pseudo color display is preferred), the entire image will show the same uniform color if the two images in the numerator and denominator are both in the linear range, otherwise, the linear regions will show a uniform color, while the nonlinear regions will show a pattern with different colors because, generally, the deviation from linearity will be larger at higher intensity regions of the frame. What the pattern shows is the difference in the degree of non-linearity. Using an image examination command, e.g., the IRAF command "imexamine", one can cut any slice in the plot and analyse it.

Now we put this procedure mathematically. Denote by im_1 and im_2 the two dome flats, im_1 is in the linear range and im_2 has some nonlinear sub-regions. Check two sub-regions on each of the images, denote by Sm_1 and Sm_2 the averaged counts of the two sub-regions on the image im_1 , by tm its exposure time, by S_1 and S_2 the corresponding averages on the image im_2 , by t the time of im_2 . Suppose S_1 is in the linear range and S_2 in the nonlinear range. We first suppose the light source is stable, then:

$$Sm_1 = a_1 \cdot tm \,, \tag{1}$$

$$Sm_2 = a_2 \cdot tm \,, \tag{2}$$

$$S_1 = a_1 \cdot t \,. \tag{3}$$

Here a_1 and a_2 are constants. Denote by LR the degree of nonlinearity (%) of S_2 . We have,

$$LR = 100 \left(\frac{a_2 \cdot t - S_2}{a_2 \cdot t} \right). \tag{4}$$

Because

$$a_2 = Sm_2/tm\,,\tag{5}$$

 \mathbf{SO}

$$LR = 100\left(1 - \frac{S_2}{a_2 \cdot t}\right) = 100\left(1 - \left(\frac{S_2}{Sm_2}\right) / \left(\frac{t}{tm}\right)\right).$$
(6)

In fact, Eq. (6) is similar to the formula (2.22) in Janesick's book (2001), where LR is called "linearity residual". When the light source is not stable (in our practice it varied from 1% to 5% in most cases), then

$$S_1 = \beta \cdot a_1 \cdot t \,. \tag{7}$$

Here β is a factor describing the variation of the light source,

$$\frac{S_1}{Sm_1} = \frac{\beta \cdot a_1 \cdot t}{a_1 \cdot tm} = \beta \frac{t}{tm} \,.$$

Note that β has the same value for S_1 and S_2 because they are on the same CCD frame, so

$$LR = 100\left(\frac{\beta \cdot a_2 \cdot t - S_2}{\beta \cdot a_2 \cdot t}\right) = 100\left(1 - \frac{S_2}{\beta \cdot a_2 \cdot t}\right) = 100\left(1 - \left(\frac{S_2}{\beta \cdot Sm_2}\right) \middle/ \left(\frac{t}{tm}\right)\right).$$
(8)

Because

$$\beta = \left(\frac{S_1}{Sm_1}\right) / \left(\frac{t}{tm}\right),\tag{9}$$

therefore

$$LR = 100\left(1 - \left\{\left(\frac{S_2}{Sm_2}\right) \middle/ \left(\frac{t}{tm}\right)\right\} \cdot \left\{\left(\frac{t}{tm}\right) \middle/ \left(\frac{S_1}{Sm_1}\right)\right\}\right) = 100\left(1 - \left(\frac{S_2}{Sm_2}\right) \middle/ \left(\frac{S_1}{Sm_1}\right)\right).$$
(10)

Here $\frac{t}{tm}$ is known already, $\frac{S_2}{Sm_2}$ and $\frac{S_1}{Sm_1}$ are measured directly from the quotient, so LR is obtained. It is not influenced by the variation of the light source (unnecessary to know the value of β).

Generally, a difference as small as 0.1%-0.2% in LR can be clearly distinguished in the quotients. If the linear and 0.1% nonlinear sub-regions co-exist in the same quotient, then any 0.1% nonlinearity is measured directly. If the intensity range of the dome flat includes both the linear part and the 1% nonlinear part, then the 1% nonlinearity can be measured from the same frame too. As to the question of unique polynomial fitting of the nonlinear part of the whole CCD frame, it may also be answered in the following examples by image reduction technique. It may have been noticed that all the above discussion contain a hidden basic assumption, namely, that the reciprocity law holds, i.e., if $E_1 \cdot t_1 = E_2 \cdot t_2$ (here E is the illumination and t the exposure time), then their responses in the CCD are the same. To illustrate our modified method, we now discuss the CCD systems at the 1-m reflector in more detail.

2.2 The 1-m Reflector

The Tek 1024 #1 CCD system was last used in 1998. Its linearity was checked in 1997. The PI company provided 3 readout rates, 50, 100 and 150 kHz. We tested the #1 CCD at 100 kHz with gain $5 e^{-}$ /adu and readout noise $7.5 e^{-}$. The test was done on 1997 October 27 and repeated on the next night. The light source of the dome flat at the 1-m reflector can be adjusted by the user, a pity is that the inhomogeneity of the illumination was only adjusted to about 15%. The 5s exposure was selected as the calibration exposure because its average is about 7000 adu which is low enough to be located at the linear level and high enough to have a good signal to noise ratio. The exposure series consisted of 5s, 10s, 5s, 15s, 5s, 20s, 5s, 20s, 5s, 30s, 5s, 35s, 5s, 40s, 5s, 45s, 5s. The plot between the counts and exposure using the classical

400

method is shown in Fig. 1: there are only nine points in the figure (each point is the average of the whole exposed frame). The number of bad pixels of this Tek CCD is small (< 10), so the average value of each point (using about 1 million pixels) in Fig. 1 has a high precision and the scatter about the curve is mainly due to the variation of the light source.



Fig. 1 Transfer curve of Tek #1 CCD on the 1-m reflector.

Unfortunately, the deviation from linearity (> 1%) does begin at about 20 000 adu. It is not sure where the 1% nonlinearity happened, but it is sure that the LR is larger than 1% at 20 000 adu (from two repeated nights' measurements). At 50 000–60 000 adu the nonlinearity is about 3%–4%. Such nonlinearity is much worse than the 1% specification over the full dynamic range given in the PI manual. According to the PI manual, the full well of #1 CCD is 420 400 e⁻, 20 000 adu only uses 24% of the full well capacity, even 60 000 adu only uses 71%. Certainly the deviation from the specification is too large! All the observations using #1 CCD seriously suffer from non-linearity.

Next we make the image reduction. Now that our modified method uses image reduction, a large number of figures is inevitable. In order to save print space of the journal many figures have to be shown in "http://www.chjaa.org" only.

We make the following figures: Figs. 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2h and 2i. They are scans along the respective diagonals of the 5s, 10s, 15s, 20s, 25s, 30s, 35s, 40s and 45s. All of them are used to illustrate the inhomogeneous intensity distributions (Figs. 2c–2g see http://www.chjaa.org).

Figure 3a is the quotient of one 5s exposure divided by another 5s exposure (not shown because it is a homogeneous noise image with no pattern). Figures 3b, 3c, 3d, 3e, 3f, 3g, 3h and 3i are the quotients of the corresponding exposures 10s, 15s, 20s, 25s, 30s, 35s, 40s and 45s divided by the 5s, respectively. They show qualitatively the patterns on the quotients.

Figures 4a, 4b, 4c, 4d, 4e, 4f, 4g, 4h and 4i are scans along the diagonals of the corresponding Figs. 3a–3i, they show the nonlinearity quantitatively (Figs. 4c–4g see http://www.chjaa.org). Most of the features on these figures are self-explanatory. We note:

a) Inspecting the smoothed trace along the scan in the Fig. 4a we estimate its fluctuation $< \pm 0.002$, in accord with the statistical error. The average of the scan ($\neq 1.0$) only reflects the fluctuation coming from the light source.



Fig. 2 Scan along the diagonal of the 5s (a), 10s (b), 15s (c), 20s (d), 25s (e), 30s (f), 35s (g), 40s (h) and 45s (i) exposure dome flat (c, d, e, f and g see http://www.chjaa.org).



Fig.3 Quotient of the 10s (b), 15s (c), 20s (d), 25s (e), 30s (e), 35s (f), 40s (h) and 45s (i) divided by the 5s.

b) The scan has become uneven in Fig. 4b (if Fig. 3b is shown in pseudo color, it will have no uniform single color). Note the minimum at $x \approx 1050$. This is real because it is always minimum in the other figures (Figs. 4c, 4d, 4e, 4f, 4g and 4h). In order to use Eq. (10), take the scan at $x \approx 1400$ as the first sub-region, suppose it is in the linear range, its $\frac{S_1}{Sm_1} = 2.002$, take the scan at $x \approx 1050$ as the second sub-region, $\frac{S_2}{Sm_2} = 1.999$, then LR = 0.15%. $S_2 \approx 14\,600$ adu, therefore the counts should not exceed 14 600 adu if 0.15% nonlinearity is wanted. Note that the above calculation may underestimate the degree of nonlinearity because we take the sub-region at $x \approx 1400$ which is in the linear range. Its intensity is $\approx 13\,000$ adu already but in Fig. 2a the highest intensity is only 7300 adu. We are not sure if it is still linear between 7300 adu and 13 000 adu due to the lack of exposure. This is not the fault of the method we used. In addition, we are lack of experience in making the inhomogeneous illumination of the dome flat.

c) Because the intensity range of the dome flat was only $\approx 15\%$, there were no exposures in which the linear sub-regions and the 1% nonlinear sub-regions exist on the same frame, so we could not measure the exact count level at 1% LR. This is not the fault of the method itself either.

d) If one wants to estimate the approximate LR with the Eq. (8), β must be known. It can be estimated as the ratio of the calibration exposures mentioned at the beginning of the previous subsection. Due to the abrupt variation of the light source, an accurate β is unavailable (taking $\beta = 1.0$ is a rather rough estimation).



Fig. 4 (a) Scan along the diagonal of the quotient of one 5s; (b) Scan along the diagonal of Fig. 3b; (h) Scan along the diagonal of Fig. 3h; (i) Scan along the diagonal of Fig. 3i.

e) There is no unique polynomial to fit the entire CCD frame for the #1 CCD. The deviation from linearity does not allow a single 'deviation – counts' correlation.

If a unique polynomial exists, then equal intensities should have equal LR, i.e., the points having equal y values in Figs. 2* should also have equal y values in Figs. 4*. In addition, the higher the counts in Figs. 2*, the larger the LR (the smaller the $\frac{S}{Sm}$) in Figs. 4*. However, this is not the case. For example, note the lowest minimum at 200 < x < 300 and the highest maximum at $x \approx 700$ in all the Figs. 2*. This lowest minimum should be the highest maximum and the highest maximum should be the lowest minimum in all the corresponding Figs. 4.*. Actually, the lowest minimum is always at $x \approx 1070$ instead of x = 700 (except in Fig. 4i), and the sub-region around x = 250 never becomes maximum (on the contrary, it becomes local minimum in Figs. 4c, 4d, 4e, 4f, 4h and 4i).

Figure 4i is obtained by dividing the 5s into the 45s, where the intensity varies from about 55500–63500 adu. Though the lowest minimum is at x = 700, the maximums at $x \approx 10$, 600, 1240 are not understandable. We notice that there are no bad pixels at these sub-regions. All of these mean that there does not exist a single relationship over the entire CCD frame. Different sub-regions have different relationships.

It was reported by Walker (1993) "Stetson found that the data obtained with the Tek 2048 CCD shows evidence for non-linearity of the CCD system at the level of almost 2 percent per magnitude. ... To a good approximation the raw data can be linearized" by a simple formula $I = I(raw) \times [A + B \times I(raw)/32767]$. A similar formula is used by others (Robinson et al. 1989; Irwin 2000; Tinney 2003). Unfortunately, this is not the case for the 1-m's Tek #1 CCD. Of course, this conclusion is based on the viewpoint of high precision photometry. We may roughly estimate the error. Take $\beta = 1.0$ in Fig. 4i, then LR varies from about 2.4%–4.0%. If a mean polynomial is used, the resultant nonlinearity may be reduced to $\approx \pm 1\%$.

If the users do not need high precision they may ignore such non-linearity, or high intensity exposures should simply be discarded. Trying to correct it pixel by pixel accurately is difficult. We had no chance to check this CCD at rate 50 kHz because of its break.

On the contrary, if the 1% nonlinearity specification is satisfied, the Tek 1024 #2 CCD is good (this CCD system was measured at readout rate 50 kHz only, the gain = $3.9 \text{ e}^-/\text{adu}$, read out noise 5.1 e^-). Figure 5a is determined for the whole CCD frame obtained on 1998 September 20. It is quite clear the non-linearity is $\leq 1\%$ up to 60 000 adu. In fact, some pixels got highest illumination so their maximum was about 65 000 adu but they are still linear (Fig. 5b, see web, which belongs to a sub-region [935:945, 340:359] of Fig. 5a). Here the gain was $3.9 \text{ e}^-/\text{adu}$ so the linear range is at least 254 000 electrons. The linearity of this CCD system was checked again 3 years later on 2001 September 20 at the same gain (the measured value is $3.8 \text{ e}^-/\text{adu}$ with readout noise 5.7 e^-), the good linearity ($\leq 1\%$) was still kept (Fig. 5c see http://www.chjaa.org).

However, it is different when the 0.1% specification is measured. For the data obtained on 1998 September 20, 10s was taken as the calibration exposure, the average is about 5100 adu. We make similar figures to those for the #1 CCD and do the image reduction, but only some figures are given here to save space (all in http://www.chjaa.org).

These figures are: Figs. 6a, 6b and 6c: scans along 830-th row of the 40s, 50s and 60s respectively. Figures 7a, 7b and 7c: scans along the same row on the corresponding quotients of the 40s, 50s and 60s divided by the 10s.

When the 20s, 30s and 40s exposures are divided by the 10s, there is no pattern in the scan of the quotients. The pattern appears in Fig. 7b (50s divided by the 10s) and longer exposures.

The minimum intensity is 19500 adu in Fig. 6b. Inspecting Fig. 6a, the intensity $< 21\,000$ adu is in the linear range, so we take $\frac{S_1}{Sm_1} = 4.974$, $\frac{S_2}{Sm_2} = 4.969$, $(S_2 \approx 26\,000$ adu), then from Eq. (10) LR $\approx 0.1\%$.

In order to keep the linearity better than 0.1% the intensity should be less than $\approx 26\,000$ adu. As for the data on the 2001 September 20, though the 1% linearity is still kept, we are puzzled by the measuring of the 0.1% linearity. Figure 8 shows the scan along the diagonal of the quotient of two 6s exposures, the scan is even within \pm 0.001. Figures 9a, 9b and 9c show the scans of the 12s, 18s, 36s along the corresponding diagonals. Figures 10a, 10b and 10c show the corresponding diagonal scans of the quotients of the 12s, 18s and 36s divided by the 6s, respectively (Fig. 8, 9a–9c, 10a–10c see http://www.chjaa.org).

Figure 10a shows also even within ± 0.002 , but Fig. 10b shows the difference in y value ~ 0.005 already. Still a pity is that the intensity range of the dome flat is only $\approx 9\%$, the minimum intensity in Fig. 9b does not link the maximum in Fig. 9a. Assuming the sub-region around x = 0 is linear and taking $\frac{S_1}{Sm_1} = 3.003$, $\frac{S_2}{Sm_2} = 2.999$, then we have LR = 100 (1 - $\frac{2.999}{3.003}$) = 0.13%, according to Eq. (10). Note the maximum intensity in Fig. 9b is only ~ 10400 adu! Therefore, the exposure should be controlled to less than 10400 adu if 0.1% linearity is required. This 0.1% nonlinearity happens too early compared with that measured using the data of 1998 September 20. Is this due to the circuit of the CCD system being aged after three years' continuous operation? Repeating the measurements is needed.

We are not sure if a unique polynomial can correct the nonlinearity of #2 CCD for the whole frame to a precision of 0.1%-0.2%. We have not checked the CCD at rate 100 kHz, and also we have no chance to check the nonlinearity at gain = $7.8 \text{ e}^-/\text{adu}$.

2.3 The 1.56-m Reflector

For the Tek $2048 \times 2048 \ \#1$ CCD of the 1.56-m the linearity (1%) is good up to about 60 000 adu for the gain index 0 ($2.4 \, e^-$ /adu, read out speed 'slow') (Yao & Zhang 2003). According to the manual of the Princeton company (1998), the full well capacity of the Tek CCD with 24 micron pixel is 300 000–350 000 electrons. Therefore, the linear range is about 45% of the full well.



Fig. 5 (a) Transfer curve of Tek #2 CCD on 1-m reflector (use the whole frame, measured on 1998-09-20).

Fig. 11 Transfer curve of Tek #1 CCD on 1.56-m reflector (gain index 0, readout speed 'medium').

100

In order to know the largest possible linear range this CCD system was checked at gain index 0 and read out speed 'medium' (corresponding to gain $=4.6 \,\mathrm{e^-/adu}$) on 2003 July 26

(the circuit of this CCD system has been modified in June of 2003). A total of 31 dome flat field exposures in the order 10s, 15s, 10s, 20s, 10s, 25s, 10s, 30s, 10s, 35s, 10s, 40s, 10s, 45s, 10s, 50s, 10s, 55s, 10s, 60s, 10s, 65s, 10s, 70s, 10s, 75s, 10s, 80s, 10s, 85s and 10s was obtained. The transfer curve is shown in Fig. 11. Each point in the figure represents the average of the whole image. In this figure "good linearity" (< 0.1%) is kept up to about 38 000 adu for the 65s exposure. The nonlinearity is 3% at about 40 000 adu (the 70s exposure), 5.6% at about 47800 adu (the 85s exposure).

However, Fig. 11 does not describe the whole character. When the 10s is divided into the 45s (and shorter exposure) images, the quotients are homogeneous within 0.1%, as shown by the scan along the diagonal of the quotient (Fig. 12, see http://www.chjaa.org). However, the 50s/10s quotient (Fig. 13b) is quite different. Figure 13c is the scan along the diagonal of Fig. 13b. Figure 13a is the scan along the diagonal of the 50s itself.

We note:

(a) the minimum points in Fig. 13a do not always correspond to the maximum points in Fig. 13c, which means the nonlinearity over the whole frame can not be represented by a single correlation (a unique formula).

(b) Using Eq. (10), the nonlinearity in the subregion $1100 \le x \le 1500$ is about 0.2%.

(c) The fluctuation of the scan between x = 1100 and 1700 in Fig. 13a is smaller than in the other part, this is because blooming happens in these sub-regions of the image corresponding to intensity $\approx 31\,000$ adu.



Fig. 13 (a) Scan along the diagonal of the 50s dome flat; (b) Quotient of the 50s divided by the 10s; (c) Scan along the diagonal of Fig. 13b.

(d) For the longer exposures the situation becomes even worse. Figure 14a shows the 55s exposure, Fig. 14b shows the quotient of the 55s divided by the 10s, Fig. 14c shows the scan along the diagonal of Fig. 14b and Fig. 14d shows the scan of the Fig. 14a itself. Note the nearly vertical black stripes in Fig. 14a (also see below). We omit the 60s and longer exposures for brevity.



Fig. 14 (a) Image of the 55s dome flat; (b) Quotient of the 55s divided by the 10s. (c) Scan along the diagonal of Fig. 14b; (d) Scan along the diagonal of Fig. 14a.

Here the important point is that blooming happens at about 31 000 adu, so the discussion on the degree of nonlinearity becomes meaningless because the image is distorted by the blooming. The seemingly good linearity for the exposures 55s, 60s and 65s in Fig. 11 is of no use. Users should not expose their CCD frames higher than $31\,000\,\text{adu}$ ($14\,260\,\text{e}^-$) for the gain index 0, readout speed 'medium'.

2.4 BFOSC

The circuit of this Loral CCD system has been changed more than once, the previous change was in 2000 (also made at Lick). We first give the analysis of the old circuit. In order to avoid using the non-linear range the CCD system was made digital saturated at 32767 adu (gain \approx $1.6 \,\mathrm{e^{-/adu}}$, readout noise $\approx 12 \,\mathrm{e^{-}}$). Only the range of $\leq 31\,000$ adu was checked by us on 2000 August 26. The exposure series consisted of 2.4s, 4s, 8s, 16s, 32s, 64s, 96s, 128s, 160s, 192s and 208s. No calibration exposure was inserted. Analysing the average of the whole CCD frame showed a seemingly good linearity ($\leq 1\%$) up to at least 28 000 adu (Fig. 15). The light source used was a built-in integrating sphere whose illumination was very inhomogeneous as shown by the scan along the diagonal of the 64s exposure useful in the nonlinearity analysis (Fig. 16a). Divide the 64s by the 32s and scan the resultant image along the diagonal results in Fig. 16b. The scan is basically flat. However, a similar scan, Fig. 17, for the 96s/64s quotient shows clear non-linearity. The maximum intensity for the 96s is about 13800 adu, the minimum is about 10 000 adu. With 10 000 adu still linear, we use Eq. (10) and obtain LR = 0.2%. Therefore, the exposure should be controlled to be less than 13800 adu if 0.2% linearity is required.

When the exposure increases, the scan becomes curved. Figure 18 shows the scan for the 128s/64s quotient. The maximum intensity for the 128s is about 18400 adu. Figure 19 is for the 160s/64s quotient. The maximum intensity for the 160s is about 23 000 adu. Figure 20 is for the 192s/64s quotient. The maximum intensity for the 192s is about 27500 adu. Figure 21 is for the 208s/64s quotient. The maximum intensity for the 208s is about 29600 adu.

Obviously, the longer the exposure, the stronger the curvature in the scan of the quotient. Note at the right end of longer exposures, the scan curves downward. This is the most obvious feature in these figures showing that the non-linearity can not be represented by a unique relationship over the whole CCD frame (Figs. 15–21, except Fig. 17, see http://www.chjaa.org).

The new Lick circuit with a much faster read out speed (the same Loral chip) was installed in July of 2002. A dome flat field series of 5s, 0.4s, 5s, 0.8s, 5s, 1.6s, 5s, 3s, 5s, 6.5s, 5s, 8.1s, 5s, 9.6s, 5s, 11.1s, 5s, 12.6s, 5s, 14.1s, 5s, 15.6s, 5s, 17.1s, 5s, 18.6s, 5s, 20.1s, 5s and 21s was obtained on 2002 August 13 to analyse the linearity. As shown in Fig. 22 the CCD is seemingly linear in the range $0-28\,000$ adu at gain $=1.7\,\mathrm{e}^{-1}$ /adu. Once again this plot does not describe the whole character. The points in the plot represent the average over the whole CCD frame only. When the pixels are inspected individually, the situation is quite different. Up to exposure 17.1s the quotients between two exposures are homogeneous, but no longer so for longer exposures. Figure 23a is the image of the 18.6s itself, the scan along the 677-th column of Fig. 23a is shown in Fig. 23b. The maximum intensity in Fig. 23b is about 25800 adu. The 18.6s/5s quotient is not homogeneous already in the central region (Fig. 23c). Figure 23d is the scan along the 677-th column of Fig. 23c. According to Eq. (10), the nonlinearity is about 0.1%. Note the local minimum at about x = 700 in Fig. 23b does not correspond to the local maximum in Fig. 23d. In fact, blooming begins to happen at these sub-regions, though the degree of blooming is not severe. Note here the intensity is only $\approx 25\,000$ adu $(42\,500\,\mathrm{e}^{-})!$ Figure 24a shows the dome flat image of the 20.1s, the central part of Fig. 24a begins to bloom upward more clearly than that in Fig. 23a (in this published small figure the white color pixels with vertical tails are especially obvious). The scan along the 677-th column of Fig. 24a is shown in Fig. 24b, its maximum is about 28 000 adu. The 20.1s/5s quotient is shown in Fig. 24c, the scan along the 677-th column of Fig. 24c is shown in Fig. 24d. It is evident that the longer the exposure, the worse the results. We omit the worse results for the exposure 21s (Figs. 22–24d see http://www.chjaa.org).

In order to inspect the non-linearity at higher level, supplementary dome flats (the same gain) were obtained on the next night, as the new circuit is made digital saturated at 65535 adu, an exposure series of 5s, 22.5s, 5s, 24s, 5s, 25.5s, 5s, 27s, 5s, 28.5s, 5s, 30s, 5s, 31.5s, 5s, 33s, 5s, 34.5s, 5s, 36s, 5s, 37.5s, 5s, 39s, 5s, 40.5s, 5s, 42s, 5s, 43.5s, 5s, 45s, 5s, 46.5s, 5s, 48s, 5s, 49.5s, 5s and 51s (the exposure condition is a little different on the two nights, so the 5s of the first night is not equal to the 5s of the second night). Unfortunately, the situation for this Loral CCD at high level is very bad, and users are not recommended to use these high intensities. The results are as follows.

(a) The longer the exposure, the larger the central blooming area. When the intensity is higher than about 30 000 adu the pattern of the dome flat is almost entirely distorted.

(b) The degree of non-linearity changes from sub-region to sub-region. As shown in Fig. 25.
(c) The pixel size of this Loral CCD is 15×15 micron, less than the 24×24 of the Tek. It is understandable that the pixel full well of the former is less than that of the latter. However, it can not explain why the linearity at some pixels of this Loral chip is much better, e.g., the average of the sub-region [1650:1750, 1150:1350] (see Fig. 25). At the lower left corner sub-region [1:30, 112:152], the linearity is good for every pixel up to our highest intensity (about 50 000 adu), as shown in Fig. 26 (see http://www.chjaa.org, which is the pixel of 2-th column and 114-th row) obtained from our pixel by pixel analyses.

Of course there does not exist a single correlation which fit the conditions of non-linearity over the entire CCD frame. It is well known that for a well developed photographic plate one single characteristic curve is enough to represent the relationship between density and exposure over the whole plate (though the precision is not high), but for the CCDs we checked, it is not the case.



BFOSC gain index 85:1085.1000:1200 5 [20:140.1000:1200] [1650:1750,1150:1350 [660:800,1846:2046] [660:800,330:530] adu ($\times 10^4$) [50:1500.250:2046] 3 2 0 10 30 40 20 50 Exposure (s)

Fig. 17 Scan along the diagonal of the quotient of the 96s by the 64s.

Fig. 25 Transfer curves measured at different sub-regions of Loral CCD at BFOSC.

3 CHARGE TRANSFER EFFICIENCY (CTE)

We are only CCD users and we have no device to measure the CTE at our observing stations at Xinglong, Zo-se or Kunming. According to the PI manual, the CTE of their Tek CCD systems is higher than 0.9999999. In practice we have not found any obvious trouble in the CTE from their systems. However, the following pieces of indirect evidence made us suspect whether the CTE of the CCD systems at BFOSC and the 1.56-m reflector is high enough to ensure satisfactory performance.

(1) The lower middle strong cosmic ray in Fig. 27 (see http://www.chjaa.org) has a value of 31778 adu (300s dark exposure, gain= $2.4 \,\mathrm{e^-/adu}$), note its vertical tail (it belongs to the Tek #1 CCD of the 1.56-m reflector). Sorensen et al. (2000) have pointed out that this kind of phenomenon is due to poor CTE.

(2) According to Sorensen et al. (2000), the white color points having vertical tails in Fig. 24a (BFOSC Loral CCD) show poor CTE. They are not the bleeding from full well pixels!

(3) In addition, almost the whole pattern in Fig. 24a begins to bloom vertically and in our unpublished longer exposure more white color points show vertical tails and the whole pattern blooms more strongly than in Fig. 24a. We ask: is this due to the poor CTE too?

(4) How to explain the nearly vertical (but not exact vertical) black stripes in Fig. 14a and in even longer exposures? They are also not the bleeding from full well pixels!

We pick out the sub-regions [150:450, 1700:2000] (corresponding to the upper left corner) from the whole series of images on 2003 July 26 and analyse the nonlinearity, the result is shown in Fig. 28 (see http://www.chjaa.org). Note the good linearity at low level and the strange nonlinearity (above the straight line rather than below) at intensities higher than 36 000 adu. It looks as though electrons blooming from the lower pixels gather over the upper part of the image, but the intensity here is still less than 46 000 adu ($212\,000\,e^{-}$).

There are two types of saturation: A/D (digital) saturation which produces flat-topped stars and pixel full well saturation which leads to blooming (Howell 2000 and the references therein). The phenomena mentioned here are not related to either type. If pixel full well is defined as the point where image pixels start to bloom into adjacent pixel, then the well of this Tek 2048 \times 2048 CCD at the 1.56-m reflector would be too shallow! For a gain $4.6 \,\mathrm{e^-/adu}$, $31\,000$ adu is only $14\,260 \,\mathrm{e^-}$, far below the full well specification of all Tek CCDs reported as yet. A similar discussion applies to the BFOSC Loral CCD system. We wait for explanations from CCD experts.

4 CONCLUSIONS

(1) The method used to analyse the non-linearity in this paper deserves to be better known.

(2) As far as we know, there has been little attention paid to the character of CCDs at high levels. It may be unnecessary to do so in spectroscopic work (except in emission line objects), but the case is different in direct imaging, especially in bright star photometry, e.g., Delta Scuti variables. This paper may be a useful guide to users to control their exposure times to avoid using the non-linear range of the CCDs when their work requires high precision.

(3) It seems that there are still some problems to be resolved for the BFOSC CCD system and the one on the 1.56-m reflector if users want to work at high levels while doing accurate photometry.

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410