OmegaCAM and gravitational lensing

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Computation of CCD Gain with Time Delay Integration Images*

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ABSTRACT — This chapter describes a fast technique for estimating the Conversion Factor or gain of a CCD. It is based on the adjustment of the standard photon transfer curve technique to 2 Time Delay Integration (TDI) images. A similar technique based on one TDI image will be also presented. The data used to test the procedure are taken with the ESO ODT test bench facilities, in the context of characterizing the OmegaCAM CCDs. No modifications to the test bench were needed to employ these techniques. The results obtained using the standard photon transfer method and the two other techniques, developed in this chapter, are compared and this analysis shows that the results from the two new techniques are in very good agreement with the standard method. These techniques are still under development, and possible future improvements will be discussed. Since these fast methods proved reliable, they can be used for simple and efficient gain computations of CCDs.

3.1 Introduction

In optical astronomy CCDs have become the dominant type of detector. The number of CCDs per instrument increases and the characterization of these chips becomes an important task. They should satisfy baseline specifications such as a high degree of linearity for flux measurements, a very good charge transfer efficiency for an accurate point spread function, a high sensitivity to detect and study very faint objects. For the efficient characterization of wide field CCD cameras, such as OmegaCAM, it is important to test each CCD in an automatic and reliable way. A complete procedure has been defined to test all the parameters that characterize a CCD, linearity, quantum efficiency (QE), photon-response non-uniformity (PRNU), charge transfer efficiency (CTE), noise, dark current, cosmetic, cosmetic defects. The same procedure has been applied to all CCDs to enable the analysis and the comparison between them (Christen et al., 2004).

During the CCDs tests, Time Delay Integration (TDI) images have been taken to compute the linearity and the residual non linearity (Cavadore, 2000). In this study we will describe how to use these data to calculate also the conversion factor.

After a brief description of TDI images and their purpose in Section 3.2, the standard techniques to calculate the gain are presented in Section 3.3. In Section 3.4 we present the methods developed to compute the conversion factor from one and two TDI images. In Section 3.5 the first results are discussed. Section 3.6 enumerates possible improvements. The first results are very promising and convinced us to make one step more to confirm the results and to validate these techniques.

3.2 TDI Images, Definition and Purpose.

Contrary to a standard image which is read out entirely after some period of a light collection, a TDI acquisition consists of collecting light and reading out continuously the image on a detector, one row of pixels at a time from the bottom (where the output register is located) of a detector chip.

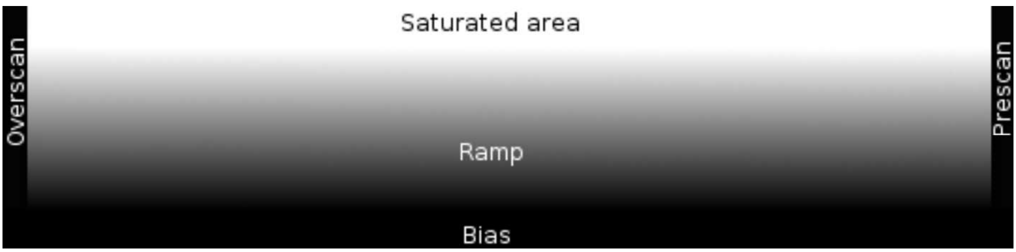

Figure 3.1: Example of a TDI image taken with the ESO test bench. This is a 2148 × 512 pixels size image. The area where the ramp is, is also called in this paper sensitive area.

Under a constant illumination, this reading mode will create an image (see Figure 3.1) with a typical response shown in Figure 3.2. The light sensitive area of such images, flat fielded out, is used in the ESO CCD test procedure to determine the linearity and residual non linearity (Cavadore, 2000). From the sensitive area of flat fielded TDI images, the mean signal of each row is plotted versus the line number. The least square method is used to estimate the best fit line. The estimate of the signal is subtracted from the mean signal computed in each row and the result is divided by the estimate. This manipulation gives the residual non-linearity per line. The CCD is declared linear if all values are between plus and minus one percent.

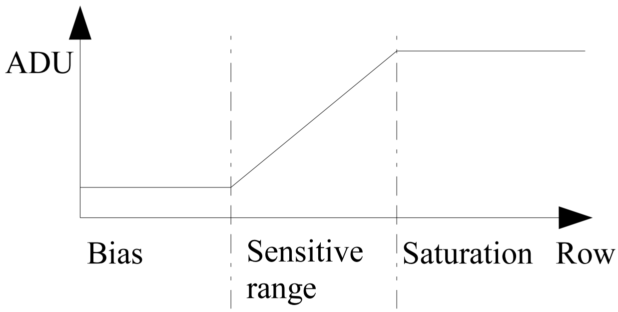

Figure 3.2: Typical response of a TDI image.

3.3 Standard Tools to Compute the Conversion Factor

3.3.1 Photon Transfer Curve.

The photon transfer curve is a graphic representation which shows the variance of the signal, σ_{pv}^2, as a function of the average signal, $\overline{S}_{pv}$, for a set of flat-field images. The average signal, $\overline{S}_{pv}$, and the variance σ_{pv}^2 correspond to the average and the variance, respectively of a group of pixels values. The pixels values are expressed in Analog Digital Unit (ADU) and correspond to the number of electrons present in the pixels contained on a CCD array. In such representation σ_{pv} and $\overline{S}_{pv}$ are expressed in ADU. To plot the photon transfer curve, the variance, σ_{pv}^2, is computed at different intensity levels by subtracting a pair of flat-field frames which have the same intensities. From this curve, it is possible to extract the conversion factor and the readout noise (Howell, 2000).

The signal which is measured at the CCD output is composed of electrons, random noise from the Poisson counting statistics and intrinsic noise and it is affected by the readout noise of the electronic chain. We can express the total noise as follows,

$$\sigma_e = \sqrt{\sigma_{pe}^2 + \sigma_{ron}^2} \tag{3.1}$$

where σ_e is the total noise, σ_{pe} is the photon noise and σ_{ron} is the total readout noise. These three components are given in unit of e^-.
Equation (3.1) is re-written following the next steps to express the variance, σ_{pv}^2 (in ADU^2), as a function of the average signal, $\overline{S}_{pv}$ (in ADU).

– We first express the average signal in photo-electrons units, $\overline{S}_{pe}$ (in e^-), as a function of the average signal in ADU, $\overline{S}_{pv}$,

$$\overline{S}_{pe} = g\overline{S}_{pv} \tag{3.2}$$

where g is the conversion factor e^-/ADU.

– The light intensity is usually assumed to be normally distributed. The average signal, $\overline{S}_{pe}$, in photo-electron units is equal to the variance of the signal, σ_{pe}^2 (photon statistics). Equation (3.2) becomes,

$$\sigma_{pe}^2 = g\overline{S}_{pv} \tag{3.3}$$

– The total noise, σ_e, expressed in electrons, is related to the noise in ADU units, σ_{pv}, by,

$$\sigma_e = g\sigma_{pv} \tag{3.4}$$

With equations (3.3) and (3.4), equation (3.1) becomes,

$$\sigma_{pv}^2 = \frac{1}{g}\overline{S}_{pv} + \frac{1}{g^2}\sigma_{ron}^2 \tag{3.5}$$

The average signal in ADU units, $\overline{S}_{pv}$, is related to the variance of the signal in ADU^2 units, σ_{pv}^2, by a linear equation where the slope is the inverse of the conversion factor and the constant term is a function of the total readout noise.

3.3.2 Conversion Factor Determined with two Flat and two Bias Images.

The method used to determine the conversion factor during the OmegaCAM CCDs tests is based on the photon transfer method or variance method. Two flat field and two bias exposures are taken. The bias frames are subtracted from the flat frames. These bias corrected images are divided, one by the other, and the resulting image is multiplied by the average signal of the image in the denominator. The final image will be called I.

$$I = \frac{F_1 - B_1}{F_2 - B_2}\mathcal{M}\left(F_2 - B_2\right) \tag{3.6}$$

where F_1 and F_2 are the flat field images, B_1 and B_2 are the bias images and $\mathcal{M}(F_2 - B_2)$ gives the average of all the pixels values in the image $F_2 - B_2$.

From the image I, $N(= 100)$ sub-windows are selected. In each sub-window i, the average signal, $\overline{S}_i$ and the variance of the signal, σ_i^2, are measured. One has to keep in mind that dividing one flat image by the other produces an image for which the variance is two times the variance that is present for one image. The gain, g_i, of the sub-window i is obtained by dividing the mean signal, $\overline{S}_i$, by the variance, $\sigma_i^2/2$. The gain, g, is the average of all the g_i's and its error is the standard deviation of the 100 computed conversion factors, σ_g, divided by the square root of N,

$$g = \sum_{i=1}^{N}\left(\frac{2\overline{S_i}}{\sigma_i^2}\right) \pm \frac{\sigma_g}{\sqrt{N}} \tag{3.7}$$

3.4 Photon Transfer Curve from TDI Images, Gain.

In this section we describe how to use the photon transfer curve with TDI images to compute the conversion factor. The two techniques developed hereafter are applied afterwards to real data (from the OmegaCAM CCDs) and the results are discussed.

3.4.1 Photon Transfer Curve with Two TDI Images.

To acquire two TDI images, the test bench is set at the setting used to record flat images and the shutter is opened after the readout has started. The monochromators are set to a wavelength of 630 nm and 10 nm bandwidth. In this condition the PRNU of the 44-82 e2V CCDs are negligible (~1%). Most of the noise is a photon noise. Equivalently important is the illumination of the CCD. The ESO test bench produces a flat illumination with fluctuations less than 1%, so it is not necessary to flat field the TDI images. Otherwise the method described in this chapter is still applicable but it would involve more computation process stages.

The principle and the mathematical tools are the same as in the standard photon transfer curve technique (see section 3.3.1). To extract the variance of the signal and the average signal from the TDI images the following manipulations have to be carried out.

– To compute the average signal, the two TDI images are averaged. In the sensitive area the average of the pixels values of each row is calculated and the bias subtracted, $\overline{S}_{pv,i}$. The average signal is given in ADU.

– To compute the variance one TDI image is subtracted from the other (see Figure 3.3). In the sensitive area the variance, σ^2, is calculated for each row. The variance is divided by two to obtain the variance of the signal for the line in a single frame, $\sigma^2_{pv} = \sigma^2/2$.

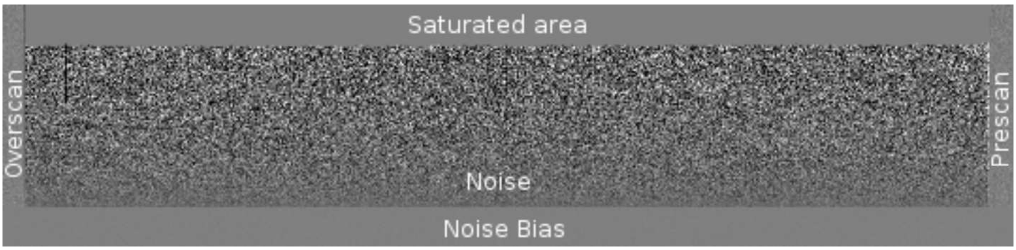

Figure 3.3: Example of a noise pattern after subtraction of two TDI images. Similar patterns are observed with same characteristics when we apply the pixel to pixel subtraction method (see section 3.4.2).

We have now for each row the signal, $\overline{S}_{pv,i}$, and the variance $\sigma^2_{pv,i}$. The plot of the $\overline{S}_{pv,i}$, $\sigma^2_{pv,i}$ pairs produces the so-called photon transfer curve. Next, we perform a best linear fit on these data. The slope yields the inverse of the conversion factor and the y-axis intercept is a function of the readout noise but it is better to obtain this parameter from bias frames.

Comments: To use this technique (2 TDI images subtraction) the test bench must be able to open the shutter systematically at a very specific moment during the CCD reading. The best option is to send the open shutter command each time a certain line of the CCD is read, in order to ensure that the ramps in the TDI images start at the same line. With the ESO test bench we actually have a precision of ± 4 lines or even better.

3.4.2 Photon Transfer Curve with One TDI Image.

The major problem with determining the gain of TDI images is the precise repetition of the data acquisition. It can be difficult to start the integration always at the same line index if the shutter suffers from random delay when opening. To circumvent this problem, the photon transfer curve with one TDI image can be used (Janesick, 2001). The mean and the variance of the ramp are calculated for each line and the pairs of points (intensity, variance) are plotted.

In normal circumstances, in a flat field image for example, the computed variance does not provide the shot noise but instead, it yields the shot noise plus the pixel to pixel non uniformity variation. In the case of a TDI image, the quantity of electrons in a pixel is the sum of all the elementary fluxes which the pixel received during its complete transfer till the output register. The pixel intensity in the output image is thus barely affected by the pixel to pixel non uniformity, except in the first few lines read out. Employing this technique, which uses only one TDI image, the first twenty rows (minimum) of the sensitivity area must be discarded in order to determine the gain. In these first lines, pixel-to-pixel non-uniformities bias the computations of the variance, and due to the propagation of the errors, also the estimation of the gain.

3.5 Results and Comparison.

3.5.1 Results

To test the performance of these two methods for the gain computation, TDI images from seven CCDs have been used. Based on the procedure developed above, the photon transfer curve is plotted for each CCD and for each method (see an example of this plot in Figure 3.4). The conversion factor is then calculated. The gain obtained from one and two TDI images and that, yielded by the standard variance method are tabulated in Table 3.1. We observe that the results produced by the two techniques based on the TDI images are in very good agreement with those yielded by the variance method used in the OmegaCAM test procedure. The maximum difference in this set is 1.5%.

The gain, computed using the variance method in the OmegaCAM procedure, has been compared to the gain obtained employing the ^{55}Fe method (reference technique). The results show that both techniques are in accordance. Further confidence in the method is related to non-linearity. When this defect is observed in the standard photon curve, the photon curve from TDI images shows the defect too. An example of non-linearity can be observed in Figure 3.5 (Downing et al., 2006).

3.5.2 Comparison

In the technique based on one TDI image, we assume that the total noise is not affected by the noise from the pixel-to-pixel non uniformity. Next, we assume that the square-root of the computed variance corresponds to the photon noise. This hypothesis is not correct. The noise from the PRNU still exists, even if the noise is smoothed because of the successive transfer of charges, and it affects the total noise (see, for example, Figure 3.6). Figure 3.6 shows that the ratio of the variance determined per line in the method based on one TDI image, and the variance obtained from the method based on two TDI

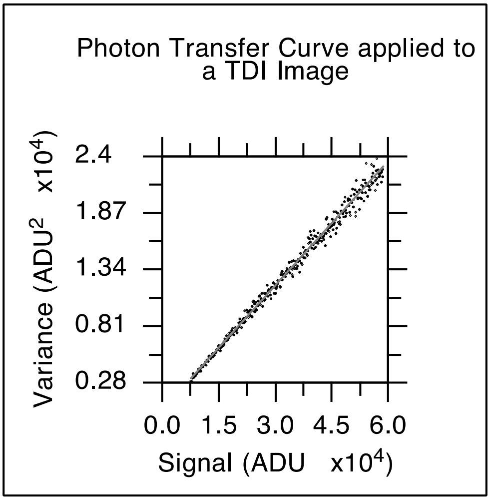

Figure 3.4: Example of a photon transfer curve realized with two TDI images. A similar pattern is observed with the technique based on one TDI image.

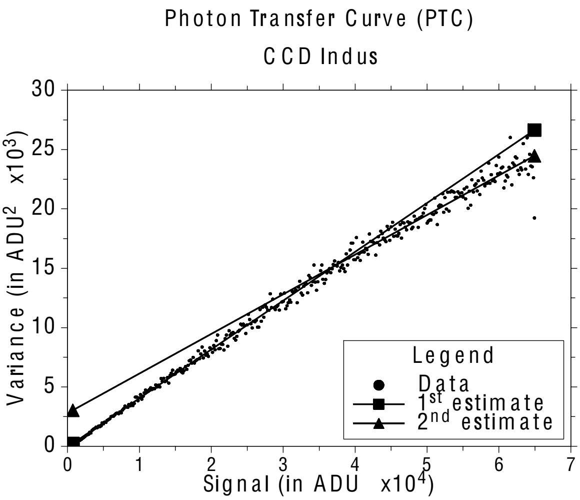

Figure 3.5: The photon transfer curve (variance versus average signal) of one of the OmegaCAM CCD candidates is obtained using the technique based on the two TDI images. This plot clearly shows the presence of non-linearity. The first estimate is a linear fit based on the lower half ($<$ 32,000 ADU) of the signal data. The second estimate is a linear fit based on the upper half ($>$ 32,000 ADU) of the signal data. Similar results have been obtained with the standard photon transfer curve method.

CCD nickname	Gain (e^-/ADU) From one TDI Image	From two TDI Images	Variance method
225kpix/s Low Gain readout mode			
Reticulum	2.60 ± 0.01	2.58 ± 0.01	2.59 ± 0.02
ColumbaII	2.51 ± 0.01	2.50 ± 0.01	2.52 ± 0.02
Lepus	2.64 ± 0.01	2.62 ± 0.01	2.58 ± 0.01
MicroscopiumII	2.50 ± 0.01	2.50 ± 0.01	2.51 ± 0.01
Musca AustralisII	2.62 ± 0.01	2.60 ± 0.01	2.62 ± 0.01
225kpix/s High Gain readout mode			
Carina	0.52 ± 0.01	/	0.52 ± 0.01
Canis Major	0.54 ± 0.01	/	0.54 ± 0.01

Table 3.1: Estimate of the conversion factor using three different methods. In column one we list the gain computed with one TDI image, in column two is listed the gain from two TDI images and in column three is reported the gain obtained with the photon transfer technique. The low gain mode and the high gain of FIERA have been used (~2.5e$^-$/ADU and ~0.54e$^-$/ADU respectively.)

images has a slight negative slope. The line starts at a value larger than 1.0 (the number of transfers of charges is small) and converges to 1.0 when the number of transfers is high ($y = 1.0173 - 4.1\,10^{-3} N_{row}$ in the case of Figure 3.6). Because of this bias at the beginning of the curve, some precautions have to be taken with the method based on one TDI image. To reduce the systematic error induced by the PRNU in the method developed around one TDI image, the points located at the beginning of the ramp are not taken into account while estimating the best fit. In our analysis the first twenty points in the sets of pairs ($\overline{S}_i$, σ_i^2) in the photon transfer curve have been discarded to estimate the gain (see Table 3.1). When this precaution is taken, we observe that the gain obtained with the one TDI image technique is slightly higher than the gain computed with two TDI images. These results show that it is feasible to use one TDI image to compute the gain if we remove the first lines. Nevertheless using two images is safer.

3.6 Future Work

Encouraged by these first results, we will develop a complete procedure to obtain the gain using the TDI images. Furthermore an extensive comparison with the ^{55}Fe method will be performed. This new procedure will include a preliminary work. An analysis of a CCD has to be done in order to create a map of cosmetic defects (hot pixels, bad pixels, bad columns, area with a low sensitivity compared to the rest of the chip,...). The flagged pixels will be discarded in the computation of the signal and the variance. This procedure has to be able to flat field out TDI images. In addition, an automatic detection procedure of the sensitive area (the ramp) has to be developed. Currently these parameters are provided by the users. Finally, an automatic detection of the beginning of a non-linearity regime has to be created (see Figure 3.5). If all criteria are fulfilled

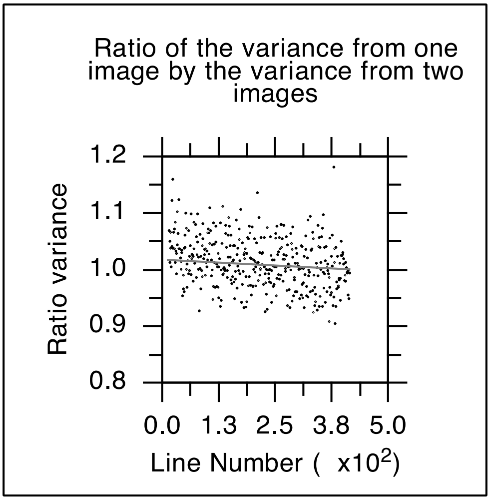

Figure 3.6: This plot shows that the ratio of the variance from one image and the variance from two TDI images is not scattered around 1.0. The variance from one image is affected by the PRNU compared to the variance from two TDI images.

this method can be used in procedures to tune the voltage of the CCD automatically in order to find the best performance of the chip.

3.7 Conclusion

This chapter described a fast technique for the estimation of the conversion factor (gain) of the CCD. The method is based on the photon transfer curve adjusted to one or two TDI images. The technique has been tested on data taken at ESO Garching by the Optical Detector Team (ODT) to characterize the OmegaCAM CCDs. The TDI images are taken during the ESO CCD test procedure to obtain the linearity of the chips. The preliminary results for the gain determined using these data are very promissing. They are in agreement with the results yielded by the standard gain computation method.

The technique developed in this chapter is advantageous because it could use the ESO Testbench without any modification, providing many more points for the photon transfer curve, (here about 400 points per plot compared to ~20 usually) and in addition, it proved to be very quick. Only one or two TDI images and a set of flat field images, if necessary, are required to compute the conversion factor.

Since the gain computation based on the new technique is faster than the standard one, it is appropriate to use it during the tuning of CCDs (i.e. voltage adjustment). This technique, even if further work is needed to improve it, already proved reliable and it can be used for simple and efficient gain computations of CCDs.