Postprint: Performance Study of the CCD Camera on the 65cm Reflecting Telescope at Nanjing University

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Abstract

In June 2021, the performance of the backend detector—the Charge-Coupled Device (CCD) system—of the 65cm reflecting telescope system used for undergraduate experimental teaching at Nanjing University was practically measured using the dome flat-field method, yielding the shutter function of the CCD camera. Simultaneously, the linearity of the CCD camera was tested through flat-field sequence exposures. The results indicated that the readout values of the CCD camera ranged from 0 to 61900 Analog-Digital Units (adu), with a non-linearity of less than 1%. Furthermore, the gain of the CCD camera was determined to be 1.02 e-/adu, and the readout noise was 13 e-. However, for observations of point sources such as stars, saturation occurs when pixel values exceed 38000 adu. Therefore, when employing this CCD camera for observational studies of point sources (e.g., stars), appropriate exposure times must be selected to prevent saturation of stellar images. In actual astronomical observations, the shutter function obtained from this study can be utilized to calibrate observed images, thereby effectively improving photometric accuracy.

Full Text

Performance of the CCD Camera on the 65cm Reflective Telescope at Nanjing University

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Abstract

In June 2021, we conducted performance measurements of the Charge-Coupled Device (CCD) system on the 65cm reflective telescope at Nanjing University’ s

Zuodijiang Observatory using the dome flat-field method. We obtained the CCD camera' s shutter function and tested its linearity through a series of flat-field exposures. The results demonstrate that the CCD camera exhibits less than 1% nonlinearity across a readout range from 0 to 61,900 Analog-Digital Units (ADU), with a gain of approximately 1.02 e^-/ADU and readout noise of 13 e^-. However, for point-source observations such as stars, saturation occurs when pixel values exceed 38,000 ADU. Therefore, appropriate exposure times must be selected to avoid star image overflow when using this CCD camera for point-source observations. In practical astronomical observations, the shutter function derived from this study can be used to calibrate observed images, effectively improving photometric accuracy.

Keywords: CCD; shutter function; linearity; detectors; astronomical telescope

Introduction

Astronomy is a discipline that intimately links observational and theoretical research, representing a perfect union of modern science and high technology. The development of astronomy has always been inseparable from telescopes, and modern astronomical telescopes depend critically on detectors. Since Galileo invented the astronomical telescope in 1609 [1], astronomers for over two centuries relied on telescopes and visual observation, recording their discoveries through sketches [2]. In 1839, American chemist John Draper captured the first photograph of the Moon, marking the beginning of photographic technology in astronomical observations and the gradual establishment of astronomical photometry techniques. Following the development of electronics in the 20th century, optical signals began to be converted into electrical signals, leading to the emergence of photoelectric devices such as photomultiplier tubes and ushering astronomy into the era of photoelectric photometry [3]. Photographic plates offered the advantage of large detection areas and long exposure capabilities but suffered from nonlinear response. Photoelectric photometry provided high sensitivity and linearity but with small detection areas. In 1969, Bell Laboratories invented the CCD, which combined the advantages of both photographic plates and photoelectric photometry. By 1975, scientific-grade CCD cameras were applied to astronomical telescopes and quickly became widely used in optical astronomy, fundamentally transforming observational methods. By the 1990s, optical astronomical detectors had been almost entirely replaced by scientific-grade CCDs.

The widespread adoption of scientific CCD cameras in astronomy stems not only from their ability to produce digital images [4] but also from their excellent performance characteristics including high sensitivity, low noise, exceptional linearity, and large dynamic range [3]. These properties enable the detection of fainter celestial objects. However, while scientific CCD cameras offer superior performance, their characteristics can change with environmental conditions and over time. Although manufacturers provide some performance parameters upon purchase, they conventionally do not supply detailed parameters such as shutter characteristics or linearity for individual pixels. When observing bright objects requiring short exposures, the impact of shutter performance on photometric precision must be considered, necessitating that observers independently measure their CCD camera' s performance parameters [5, 6]. This paper presents characteristic measurements of the PIXIS 2048B CCD camera used on Nanjing University' s 65cm telescope, analyzing its shutter function and linearity to facilitate necessary corrections for precision photometry.

Section 1 briefly describes the measurement methods for shutter function and linearity, Section 2 presents the observations and results, Section 3 discusses the findings, and Section 4 summarizes the work.

1.1 Shutter Function

Astronomical CCD camera systems require a shutter mechanism. Since the shutter operates independently of the optical system, it provides additional flexibility in controlling the amount of signal charge beyond what the optics alone can achieve [7]. Astronomical CCD shutters come in two types: iris and curtain. The PIXIS 2048B CCD camera employs an iris shutter. In iris-shutter CCD cameras, the shutter opens first at the center of the CCD target surface and closes last at the center, resulting in different actual exposure durations between central and edge pixels. Furthermore, shutter operation speed is limited, making shutter effects particularly noticeable during short exposures. When observing relatively bright targets that require short exposures, CCD shutter characteristics must be measured to understand their impact and apply necessary corrections.

Measurement methods for shutter correction include the dome flat-field method proposed by P.B. Stetson and the twilight sky flat-field method proposed by P. Surma [8]. The dome flat-field method is simple and accurate, requiring only a stable light source without needing to determine the flat-field function itself [9]; therefore, we employed this method for shutter function measurement.

Shutter correction requires first determining the shutter function, which is obtained similarly to flat-field correction. For a pixel at column i and row j with response coefficient $a(i,\ j)$, illuminated by stable dome flat-field light with intensity $L(i,\ j)$, we measure the actual output $I(i,\ j)_1$ and $I(i,\ j)_2$ using two different integration times t_1 and t_2:

$$I_1 \equiv I(i,j) \cdot t_1 = a(i,j) \cdot L(i,j) \cdot (t_1 + \Delta(i,j))$$

$$I_2 \equiv I(i,j) \cdot t_2 = a(i,j) \cdot L(i,j) \cdot (t_2 + \Delta(i,j))$$

where the shutter function *Δ(i, j)* (for the PIXIS 2048B CCD, $i = 1,..,2048$; $j = 1,..,2048$, with *(i, j)* representing the pixel at column i and row j) represents the time delay caused by shutter effects—the difference between the programmed integration time and the true integration time *T(i, j)*. Since *a(i, j)* and *L(i, j)* remain constant, their effects can be eliminated. Dividing equations (1) and (2) yields:

$$\frac{I_1}{I_2} = \frac{t_1 + \Delta(i,j)}{t_2 + \Delta(i,j)}$$

Rearranging gives the shutter function:

$$\Delta(i,j) = \frac{I_2 \cdot t_1 - I_1 \cdot t_2}{I_1 - I_2}$$

Thus, the true exposure time for the pixel at column i and row j is:

$$T(i,j) = t + \Delta(i,j)$$

1.2 Linearity

CCD linearity refers to the degree of linear relationship between incident light intensity variations and CCD response within the dynamic range. It is typically characterized by linearity—the relationship between the electrical signal produced by the CCD camera and the incident light intensity. In typical video or television applications, CCD linearity is not a major concern, with deviations up to 20% being acceptable [10]. However, in imaging science, response linearity is a critical parameter that must be considered. Ideally, each pixel should function as a high-fidelity photon detector, producing electrical signals precisely proportional to incident light intensity. Therefore, ensuring CCD linearity is essential for quantitative imaging science applications. High-performance scientific CCD cameras exhibit nonlinearity of less than 0.1% across their entire dynamic range [8], with excellent response uniformity between pixels.

CCD linearity is a crucial metric for astronomical detectors; poor linearity means observed images will be distorted, complicating information processing. Our linearity measurement method involves: acquiring a series of flat-field images with different exposure times t to obtain pixel response values V (measured values); performing linear function fitting between V and t to obtain the linear function; calculating the difference between measured values V and linear function values V' at corresponding t—this difference represents the deviation from linearity. The percentage deviation is our calculated nonlinearity:

$$\text{NL} = \frac{V_{t_i} - V'_{t_i}}{V'_{t_i}} \times 100\%$$

Depending on the precision requirements of different data processing tasks, regions where NL exceeds a certain threshold can be identified as nonlinear.

2 Observations and Results

2.1 Observational Setup

The Undergraduate Teaching Center Laboratory of Nanjing University' s School of Astronomy and Space Science operates a 65cm optical telescope at the Zuodijiang Observatory (geographic coordinates: 118°57 34 E, 32°07 45 N). The telescope' s detector is a PIXIS 2048B CCD camera primarily used for undergraduate experimental observations in courses covering atmospheric extinction, pixel scale, and differential photometry of variable stars. While these projects initially aimed to train students' observational and data processing skills with modest precision requirements—where CCD shutter and linearity effects were incorporated into experimental error analysis—demands for precision have increased with enhanced teaching quality initiatives, graduate student involvement, and collaborative observation programs. To better understand CCD performance for precise photometry and determine appropriate exposure times, detailed knowledge of the CCD camera' s parameters is essential.

During May-June 2021, we measured the shutter function using the telescope' s internal flat-field lamp. The I-filter, at which the CCD is most sensitive, was selected for measurements with short and long exposure times of 1s and 10s, respectively. The CCD' s maximum readout value is 65,535 ADU; 1s exposures yielded approximately 5,000 ADU after bias subtraction, while 10s exposures produced approximately 50,000 ADU. The shutter function measurement sequence consisted of: five consecutive 1s exposures, two 10s exposures, and another five 1s exposures. Ten bias images were taken before and after this sequence for processing and to verify CCD stability. Throughout the measurement process, the CCD temperature and flat-field lamp illumination were maintained stable.

Simultaneously, we measured the CCD camera' s linearity using a flat-field lamp with optically designed uniform output. After allowing the lamp to stabilize for half an hour, we began acquisition, initially taking flat-field images every few minutes and calculating mean values until they remained constant. During flat-field image acquisition, the exposure sequence was divided into image acquisition and monitoring sequences, as shown in , with monitoring sequences interspersed among image acquisition sequences. Based on the measured shutter function, we selected minimum exposure times starting from 5s up to saturation at 180s. The complete exposure sequence was: 10s; 5s; 10s; 15s; 10s; 20s; 10s; 25s; 10s; 30s; 10s; 35s; 10s; 40s; 10s; 45s; ···; 10s; 180s, where the interspersed 10s exposures served as monitoring frames. If the light source brightness drifted, these monitoring images helped track variations and minimize their impact.

2.2 Results

2.2.1 Shutter Function We processed the observational data using the standard IRAF software [11] to obtain the camera' s shutter function (SHUTTER.fits) and contour map, shown in [Figure 2: see original paper] (where different contour lines represent various shutter correction values). The measured shutter function reveals a maximum value of approximately 0.04 seconds at the center and a minimum of about 0.006 seconds at the edges, indicating a difference of approximately 0.04 seconds between central and edge exposure times. Consequently, to achieve photometric precision better than 1% across the entire image, exposure times must exceed 4 seconds; for precision better than 0.1%, exposures must exceed 40 seconds.

[Figure 1: see original paper] and [Figure 2: see original paper] provide schematic diagrams for semi-quantitative assessment of shutter effects across the CCD. For quantitative correction, image processing is required [12]. In practical observations, 'SHUTTER' represents the shutter function. For a target image obtained with exposure time t, after subtracting the CCD bias ('BIAS') and applying flat-field correction to obtain 'IMAGE' , any image processing software such as IRAF can perform:

$$\mathrm{IMAGE}_0 = \left[\frac{\mathrm{IMAGE}}{(\mathrm{SHUTTER} + t)}\right] \cdot t$$

This yields the shutter-corrected image 'IMAGE_0' .

The shutter function can be used for an extended period, but repeated shutter operations may cause mechanical aging, necessitating periodic re-measurement.

2.2.2 Linearity Data processing revealed the CCD' s linearity characteristics, shown in [Figure 3: see original paper] and [Figure 4: see original paper]. [Figure 3: see original paper] displays measured linearity values and the fitted curve, while [Figure 4: see original paper] shows the percentage deviation from linearity. The results clearly demonstrate that the PIXIS 2048B CCD camera maintains nonlinearity below 1% up to 61,900 ADU across its dynamic range of 0 to 65,535 ADU. It should be noted that [Figure 3: see original paper] and [Figure 4: see original paper] represent linearity measurements for extended sources (dome flat-fields). Although linearity is maintained up to 61,900 ADU for flat-fields, point-source (stellar) observations behave differently. Between January and May 2021, we repeatedly observed the open cluster M67 in Cancer. For the bright star HD 75700 (08:51:49 +11:53:38) in M67, a 5s exposure produced a surface brightness distribution [Figure 5: see original paper] and radial profile [Figure 6: see original paper] showing saturation at approximately 38,000 ADU. Therefore, image portions exceeding 38,000 ADU cannot be used for point-source photometry.

This premature saturation represents a limitation of this CCD camera, restricting the dynamic range for point-source photometry and hindering Point Spread Function analysis. However, by controlling exposure times to prevent overexposure of bright stars, high-precision photometry of point sources remains achievable [13]. We used the MaxImDL control program for image acquisition, the same software employed at Kitt Peak Observatory. To investigate the cause of premature overflow, we consulted with experts from the Yunnan Observatory 1m telescope and the National Astronomical Observatory 2.16m telescope. The Yunnan 1m telescope experiences varying overflow behavior with different CCD models: a previous 1024$\times$1024 PI CCD camera showed no premature overflow, while a newer ANDOR CCD exhibits this issue, which persists despite various attempts at resolution. At the National Astronomical Observatory 2.16m telescope, using MaxImDL, premature overflow can be mitigated by adjusting binning parameters, though this approach did not resolve the issue in our case. Massey et al. encountered similar situations with older RCA CCD data at Kitt Peak, attributing it to "subtle charge transfer problems" [13]. Whether premature overflow stems from charge transfer issues, CCD chip problems, or control software requires further investigation.

Conclusion

Although manufacturers provide reference performance parameters for CCD instruments, users must independently measure relevant parameters to thoroughly understand their equipment. Our measurement methodology offers reference and guidance for new CCD users. This study characterized the PIXIS 2048B CCD camera on Nanjing University' s 65cm reflective telescope, determining its shutter function, linearity, gain, and noise. The measured shutter function is now stored on the observatory computer and will be provided to data processors alongside observational data when necessary. The CCD camera maintains nonlinearity below 1% from 0 to 61,900 ADU, with a gain of approximately 1.02 e^-/ADU and readout noise of about 13 e^-. These measured parameters will guide students and researchers in selecting appropriate targets, setting observation parameters, and performing data corrections in future experimental teaching and research observations, enabling better equipment performance and more effective research.

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Note: Figure translations are in progress. See original paper for figures.