

## The Mini-SiTian Array: Evaluation Camera System (Postprint)

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### Abstract

The Mini-SiTian project, which is a pathfinder for the SiTian project, utilizes three 30 cm telescopes equipped with commercial CMOS cameras (ZWOASI6200MM Pro) to simulate a large-area time-domain survey. Due to the avoidance of the traditional mechanical shutter, the CMOS camera is favorable in time-domain survey projects. In the future, the SiTian telescope array will employ a two-by-two scientific-grade mosaic CMOS camera to survey a 10,000 degree square area every 30 minutes. Therefore, the performance of CMOS directly determines the detection capability of SiTian telescopes for transient sources, and a comprehensive understanding of the performance of CMOS cameras is crucial. In this research, laboratory testing was conducted to thoroughly evaluate three cameras by assessing several critical parameters, including bias stability, dark current, pixel anomalies, linearity, gain, and read noise. We find exceptional short-term bias stability with standard deviations below 0.02 ADU, negligible dark current of approximately 0.002 e<sup>-</sup> pixel<sup>-1</sup> s<sup>-1</sup> at 0°C, and excellent linearity with nonlinearity consistently below  $\pm 0.5\%$ , and a small proportion (0.06%–0.08%) of pixels with anomalous responses. Furthermore, our analysis demonstrates uniform gain values across all cameras, ranging from 0.252 to 0.255 e<sup>-</sup> ADU<sup>-1</sup>, with low readout noise, measured to be below 1.6 e<sup>-</sup> using conventional methods. We also propose a novel method for pixel-level gain and read noise calculation for CMOS sensors, which revealed a narrow gain distribution and a low median read noise of 1.028 e<sup>-</sup> for one of the cameras. The laboratory testing of the ZWOASI6200MM Pro cameras indicates their potential to meet the requirements of time-domain surveys for the Mini-SiTian project.

## Full Text

### Preamble

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### Abstract

The Mini-SiTian project serves as a pathfinder for the SiTian project, utilizing three 30 cm telescopes equipped with commercial CMOS cameras (ZWO ASI6200MM Pro) to simulate a large-area time-domain survey. CMOS cameras are particularly favorable for time-domain surveys due to their avoidance of traditional mechanical shutters. In the future, the SiTian telescope array will employ a two-by-two scientific-grade mosaic CMOS camera to survey a 10,000 square degree area every 30 minutes. Consequently, CMOS performance directly determines the detection capability of SiTian telescopes for transient sources, making a comprehensive understanding of CMOS camera performance crucial. In this research, we conducted laboratory testing to thoroughly evaluate three cameras by assessing several critical parameters: bias stability, dark current, pixel anomalies, linearity, gain, and read noise. We find exceptional short-term bias stability with standard deviations below 0.02 ADU, negligible dark current of approximately  $0.002 \text{ e}^- \text{ pixel}^{-1} \text{ s}^{-1}$  at  $0^\circ\text{C}$ , excellent linearity with nonlinearity consistently below  $\pm 0.5\%$  ADU<sup>-1</sup>, with low readout noise measured below  $1.6 \text{ e}^-$  using conventional methods. We also propose a novel method for pixel-level gain and read noise calculation for CMOS sensors, which reveals a narrow gain distribution and a low median read noise of  $1.028 \text{ e}^-$  for one of the cameras. The laboratory testing of the ZWO ASI6200MM Pro cameras indicates their potential to meet the requirements of time-domain surveys for the Mini-SiTian project.

**Key words:** instrumentation: detectors – surveys – telescopes

## 1. Introduction

Complementary Metal-Oxide Semiconductor (CMOS) technology emerged in the 1960s alongside Charge-Coupled Device (CCD) technology (Bigas et al. 2006). This technology is based on integrated circuits comprising both n-type and p-type metal-oxide Semiconductor Field-Effect Transistors (MOSFETs). Conventional CMOS image sensors have limitations such as low quantum efficiency, high dark current, small dynamic range, and limited full well capacity (Bigas et al. 2006). However, recent advancements have addressed many of these issues. Modern CMOS sensors exhibit several notable advantages, including compact size, lightweight design, cost-effectiveness, and high readout speed. These benefits are largely attributed to the integration of individual amplifiers within each pixel. This architectural innovation allows each pixel to independently amplify the signal from its photodiode, resulting in a higher signal-to-noise ratio and enhanced processing speed (Princeton Instruments 2016; Karpov et al. 2021; Alarcon et al. 2023).

Due to these numerous advantages, CMOS technology is extensively utilized in digital cameras, mobile phones, and monitoring equipment. However, in optical astronomical observation, CCD maintains dominance due to its superior sensitivity for faint objects and high-precision measurements. These advantages, along with excellent performance in time-domain astronomy for detecting variable phenomena, make CCDs ideal for diverse and demanding astronomical applications (e.g., Gunn et al. 1998; Ma et al. 2012; Wang et al. 2017). Consequently, telescopes employing CMOS sensors as detectors remain relatively uncommon.

Nevertheless, compared to CCDs, CMOS detectors present unique opportunities for astronomical observations. They facilitate integration, reduce costs, and offer a higher degree of scalability, enabling the formation of large arrays and enhancing sensitivity for detecting faint objects. Additionally, CMOS detectors possess higher readout speeds and frame rates, enabling the capture of astronomical transients with rapid variations. These attributes make CMOS technology particularly advantageous for time-domain astronomy, where fast and precise measurements are essential.

In recent years, the field of time-domain astronomy in the optical band has seen rapid development. As technology advances, higher demands are placed on observational capabilities. In parallel, CMOS detector technology has evolved significantly and has been increasingly adopted in various astronomical applications, including both wide-field surveys and individual telescope systems. Several projects have demonstrated the effectiveness of CMOS detectors in astronomical observations. Qiu et al. (2013) conducted comprehensive tests on a scientific CMOS camera (DC-152Q-FI by Andor Technology) to characterize its performance parameters, demonstrating stable bias, gain, readout noise, and photometric precision. Duan et al. (2020) demonstrated excellent linearity (better than 99%) and uniformity (better than 3%) of commercial-grade large-format

CMOS chips with global shutters, highlighting the growing capabilities of CMOS technology in astronomical applications.

Zhang et al. (2020) developed the Time-domain Multi-band Transient Survey (TMTS) system, which employed the QHY4040 CMOS detector. This system has successfully detected a variety of transient phenomena in their observations, showcasing the potential of CMOS technology in time-domain astronomy. Further supporting the viability of CMOS detectors for precision astronomy, Mu et al. (2024) evaluated an observational system with a ZWO ASI6200MM Pro Camera and a 60 cm telescope. Their study assessed the photometric and differential photometric precision through various astronomical observations, achieving promising results with photometric precision reaching 0.02 mag and differential photometry precision of 0.004 mag. This work demonstrates that CMOS-based systems can achieve precision comparable to traditional CCD systems across optical wavelengths.

These studies collectively demonstrate that CMOS detectors are not only suitable for wide-field surveys but are also being successfully integrated into various telescope systems for targeted observations. The adoption of CMOS technology in astronomy is driven by its advantages in high readout speed, low noise, and cost-effectiveness, making it an increasingly attractive option for both large-scale surveys and precision astronomical measurements.

With the enhancement of telescope detection capabilities, an increasing number of transient sources are being discovered. The SiTian project is one of the next-generation time-domain surveys, aiming to monitor large sky areas every 30 minutes with 60 one-meter-class telescopes to detect various types of optical transients (Liu et al. 2021), such as supernovae, flare variables, gamma-ray bursts, tidal disruption events, and optical counterparts of gravitational waves. The early detection of these transients provides valuable information for exploring their nature. However, the luminosity of some transients changes rapidly, making it crucial to use CMOS detectors to capture these early light variations.

The Mini-SiTian (MST) project (Huang et al. 2025; He et al. 2025) serves as a pilot initiative for the SiTian project, accumulating valuable experience in operation, observation, and data processing for its successor. The Mini-SiTian project comprises three telescopes equipped with g, r, and i filters, located at the Xinglong Observatory, National Astronomical Observatories, Chinese Academy of Sciences (NAOC). ZWO ASI6200MM Pro cameras are utilized as the detector for three telescopes. Its sensor is SONY IMX455 CMOS, which is a back-illuminated CMOS image sensor with a resolution of  $9576 \times 6388$  and pixel size of  $3.76 \mu\text{m}$ , yielding a field of view of  $2.^\circ29 \times 1.^\circ53$  (pixel scale 0.86). Detailed technical specifications of the camera are shown in Table 1.

In this study, we performed detailed laboratory evaluations of three cameras by examining several critical parameters, including bias stability, dark current, pixel anomalies, linearity, gain, and read noise. Laboratory testing of the ZWO ASI6200MM Pro cameras plays a crucial role in evaluating the performance

of CMOS cameras, serving as the initial step to ensure device reliability and optimize astronomical observations. These tests provide essential baseline information on the fundamental characteristics of the cameras, laying the groundwork for subsequent on-sky testing. We specifically reference the on-sky tests conducted by Xiao et al. (2025), which demonstrate that the same three ZWO ASI6200MM Pro CMOS camera systems, mounted on the Mini-SiTian telescopes, achieve high-precision photometric performance under actual astronomical observing conditions. These field results further validate the performance characteristics of the camera observed in our laboratory tests. The study of Xiao et al. (2025) highlights the potential of these CMOS detectors for wide-field optical time-domain surveys, showing that the detectors can achieve photometric accuracy comparable to CCDs, with impressive astrometric precision of approximately 70–80 mas and photometric accuracy of about 4 mmag for bright stars. The MST project underscores the feasibility of using CMOS detectors for large-scale time-domain surveys, offering a cost-effective alternative to CCDs.

## 2. Methods

To evaluate the performance of the ZWO ASI6200MM Pro camera and verify its technical specifications provided by manufacturers, we conducted a series of laboratory tests on bias stability, dark current, abnormal response pixels, linearity, gain, and read noise for three cameras equipped with Mini-SiTian telescopes.

The laboratory is designed as a dark room, equipped with an experimental platform for various experimental equipment, including integrating spheres and light sources. The room is maintained in complete darkness to facilitate the acquisition of dark images without interference from external light sources, ensuring optimal conditions for testing the performance of imaging sensors under true dark-field conditions. The light source is installed inside the integrating sphere, and the light is diffusely reflected by the interior walls of the sphere. This results in a uniform and stable illumination emerging from a circular aperture on the sphere. The light exiting near the circular aperture can be considered to exhibit uniform intensity and stability. The camera was positioned outside the integrating sphere, on the central axis of the circular aperture, approximately 10 cm away from the aperture. The primary requirement was for a stable light source, and uniformity was not a critical factor. Consequently, the precise positioning of the camera relative to the integrating sphere was not of vital importance.

In our tests, the ZWO ASI6200MM Pro camera offers a range of configurable acquisition parameters. Unless otherwise stated, the following parameters were utilized for all three cameras during the experimental procedure: the gain was set to 100, which corresponds to a gain value of around  $0.25 \text{ e}^- \text{ ADU}^{-1}$  as indicated by the gain value in the FITS file header. The offset and USB bandwidth parameters were set to 50 and 40, respectively. The sensor cooling temperature was set to  $0^\circ\text{C}$ .

A series of images were taken in the sequence of bias, flat, and dark frames after the temperature was stable. The detailed exposure plan is outlined in Table 2. For bias images, the light source was turned off, and the camera was covered with black cloth to ensure a completely dark environment. One hundred bias images were captured for each of the three cameras. For flat image acquisition, the CMOS sensor was illuminated by a stable light source emanating from the aperture of the integrating sphere. The brightness of the light source was adjusted such that the average counts of the central region of the flat image for 2 s exposure fell within the range of 20,000–40,000 ADU. Flat images were captured with varying exposure times, with several exposure time intervals (as detailed in the Exposure Time Interval column of Table 2). Within each interval, different exposure times were selected based on a specific step length (as detailed in the Exposure Time Step column of Table 2), and a flat image was exposed for each selected exposure time. The conditions for dark image acquisition were identical to those for bias images, and the exposure times of bias images were consistent with those for flat images.

### 3.1. Bias Stability Analysis and Frame Characteristics

Bias, also known as the bias frame, represents the inherent electronic noise and offset in the CMOS detector, captured with zero exposure time and closed shutter. It reflects the base level output of the sensor in the absence of any light or dark current. In astronomical observations, all images require subtraction of the bias to isolate the photon signal and eliminate this systematic electronic offset. The stability of the bias is crucial, as it directly impacts the quality and accuracy of subsequent image processing steps, such as dark current subtraction and flat-field correction. In the context of this paper, bias stability refers to the consistency of the bias signal over a time period under constant environmental conditions. To evaluate the stability of the bias, we captured 100 bias frames over a period of approximately 20 minutes under controlled laboratory conditions. For each bias image captured by the three cameras, we calculated the mean of the counts within a  $2000 \times 2000$  pixel area at the center of the image. This approach allows us to assess short-term variations between consecutive frames. A stable bias ensures a consistent noise floor, leading to more reliable and repeatable scientific measurements. In our analysis, we consider the bias to be stable when the variation in mean counts remains within  $\pm 0.03$  ADU of the overall average throughout the short observation period.

The results of our bias stability analysis for each camera are shown in Figure 1 [Figure 1: see original paper]. This figure illustrates the temporal evolution of the mean bias counts for each camera over approximately 20 minutes. The red dotted line in each panel represents the average of these 100 mean values, calculated using a sigma-clipping method. We employed a  $3\sigma$  clipping algorithm to mitigate the impact of potential outliers. Regarding long-term stability of bias, Mu et al. (2024) found that the deviation of mean counts of bias on one night was less than 0.08 ADU. These results are crucial for understanding the

consistency of the bias level across multiple acquisitions, which is fundamental for accurate image processing and scientific data reduction in astronomical observations.

To investigate the characteristics of bias frames in depth, we performed mean stacking of 100 individual bias frames for each ZWO ASI6200MM Pro CMOS camera in our Mini-SiTian telescope array. The abbreviations MST1, MST2, and MST3 refer to telescopes 1, 2, and 3 of the Mini-SiTian Array, respectively. Figure 2 [Figure 2: see original paper] presents the resulting combined bias frames for these three cameras. Analysis of these combined frames reveals several notable patterns, which can be largely attributed to the Fixed Pattern Noise (FPN; Gamal et al. 1998) characteristic of CMOS sensors. FPN is a type of noise that remains constant across different exposures and is especially prominent in CMOS sensors due to their architecture. In the context of bias frames, we are primarily observing the effects of Dark Signal Non-Uniformity (DSNU; Jiménez-Garrido et al. 2012), a component of FPN. It is important to note that while the numerical differences these patterns represent are quite small, they are consistent and detectable.

In MST1 and MST3, all three cameras exhibit a subtle gradient in their bias levels, with count values generally decreasing from the bottom to the top of the frame, while MST2 shows an even less pronounced gradient. Additionally, MST1 and MST3 display corner effects where the two corners along the bottom edge of the frames show slightly higher count values compared to other areas, though this effect is less noticeable in MST2. All three cameras also show faint horizontal structures parallel to the short edge of the frame, appearing as subtle horizontal striations or banding patterns. This is a common form of FPN in CMOS sensors, often associated with the row-by-row readout process. The presence of these subtle gradients, corner effects, and horizontal structures—all manifestations of FPN—underscores the importance of proper bias correction in the data reduction process.

Furthermore, the distribution of mean count values for each pixel in these bias frames deviates from a Gaussian (normal) distribution, as shown in Figure 3 [Figure 3: see original paper]. This non-Gaussian nature can be attributed to the DSNU component of FPN. The distributions for all three cameras exhibit asymmetry, with a long tail extending toward higher ADU values, and appear broader than a standard Gaussian distribution. These characteristics likely stem from the unique architecture of CMOS sensors, particularly their independent pixel readout system. In CMOS sensors, each pixel is equipped with its own readout circuitry, which offers advantages in terms of speed and flexibility but can also exacerbate the effects of DSNU. The independent readout structure leads to inherent variations in response and noise characteristics across the sensor, significantly contributing to the observed non-Gaussian distribution of pixel values in the bias frames. Furthermore, the specific readout mechanisms and electronics of the ZWO ASI6200MM Pro camera modulate these characteristics, likely influencing both the asymmetry in pixel value distributions and the

distinct patterns observed in combined bias frames.

### 3.2. Anomalous Response Pixels

In CMOS sensors, there exist pixels with abnormal responses, which can manifest as significant deviations in pixel count values, appearing either excessively high or low compared to their surroundings, or exhibiting unusually large standard deviations. These anomalies can be attributed to various factors, including manufacturing defects, structural inconsistencies within the pixel, variations in dark current, non-ideal behavior of the readout circuitry, or degradation over time. The “Salt and Pepper” effect, known as Random Telegraph Noise (RTN), is a common manifestation of this issue, referring to pixels that exhibit either very high (salt) or very low (pepper) values, appearing as random speckles in the image. This phenomenon has been found in QHY411M (Alarcon et al. 2023) and is evident in some pixels where the distribution of their counts exhibits either a bimodal or trimodal pattern. The presence of such anomalous response pixels could potentially affect photometric accuracy to the extent that they require precise identification and annotation.

To assess the prevalence of anomalous pixels, we analyzed a series of 100 bias images to calculate the mean and standard deviation of the count for each pixel. The resulting distributions of the mean count of each pixel for the three cameras are presented in Figure 3 [Figure 3: see original paper]. Each panel represents a distinct camera. The percentages of pixels exhibiting extreme responses, falling beyond the  $5\sigma$  limit, are highlighted within the figure. The top panel corresponds to the camera attached to MST1, with approximately 0.018% of pixels having mean counts below  $\text{mean}-5\sigma$  and another 0.057% exceeding  $\text{mean}+5\sigma$ . Similarly, the middle panel shows results for the camera of MST2, where about 0.025% of pixels fall below  $\text{mean}-5\sigma$ , while 0.037% surpass  $\text{mean}+5\sigma$ . Lastly, the bottom panel represents the camera of MST3, with 0.016% of pixels exhibiting counts below  $\text{mean}-5\sigma$  and 0.051% above  $\text{mean}+5\sigma$ . These findings indicate that the proportion of pixels displaying unusually high or low responses ranges from 0.06% to 0.08%, demonstrating the presence of noise sources such as RTN.

Additionally, the standard deviation of each pixel was calculated to identify those with significant variations in response. These results are displayed in Figure 4 [Figure 4: see original paper], which consists of three panels representing the three cameras. The mean value and the  $5\sigma$  threshold of these values are depicted by the dashed green and red lines, respectively. The percentage of pixels with standard deviations beyond the  $5\sigma$  threshold is approximately 1.05% across all three cameras. The top panel represents the camera of MST1 with a mean standard deviation of 4.12 ADU and a  $5\sigma$  threshold at 22.11 ADU. The middle panel corresponds to the camera of MST2 with a mean standard deviation of 3.91 ADU and a  $5\sigma$  threshold at 20.64 ADU. Finally, the bottom panel illustrates results for the camera of MST3, featuring a mean standard deviation of 4.04 ADU and a  $5\sigma$  threshold at 22.62 ADU. It should be noted that none

of the cameras exhibit pixels with a constant value, as there are no instances of zero standard deviation observed in any of the three cameras.

Considering the spatial distribution of the identified anomalous pixels, Figure 5 [Figure 5: see original paper] offers insights into their locations in the CMOS sensor. The three panels illustrate the anomalous pixel distribution across the entire sensor area for each of the three cameras in the Mini-SiTian telescope system. A color-coded representation enables visual comparison of count differences among various regions. These anomalous response pixels tend to cluster around the edges and corners of the CMOS sensor, indicating a possible correlation between their abnormal response and proximity to the sensor boundaries. This observation may suggest potential issues related to manufacturing defects or mechanical stress affecting the peripheral regions of the detector array.

In Figure 6 [Figure 6: see original paper], we present the two-dimensional distribution of the mean signal and standard deviation for each pixel, derived by combining information from Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper]. This visualization provides insight into the statistical properties of pixel responses across the entire sensor area. It becomes evident that the majority of pixels exhibit mean values ranging from 495 ADU to 505 ADU with standard deviation between 3 ADU and 5 ADU, representing typical behavior under normal conditions. However, two distinct branches of pixels deviate from this normal distribution, offering clues about potential anomalies in CMOS sensor performance. One branch appears at the upper end of the normal pixel distribution, characterized by widespread dispersion in standard deviation. The other branch is on the upper right of the normal pixel distribution, with both the mean and standard deviation falling far outside the average range for most pixels. Pixels distributed in both branches may exhibit a distinct “Salt and Pepper” effect. We have marked these anomalous response pixels to reduce their impact on photometric accuracy during data processing. Future work should focus on exploring the factors contributing to these anomalies and devising methods to mitigate them effectively.

### 3.3. Dark Current

Dark current primarily stems from thermal excitation. At ambient temperatures, electrons within semiconductor materials gain enough energy through thermal fluctuations to transition from the valence band to the conduction band, generating noise in astronomical imaging. To ensure high-quality observations, especially when capturing faint sources, it is crucial to have low dark current. A series of dark frames were collected over exposure times ranging from 0.01 to 600 s, with subsequent subtraction of the master bias frames to evaluate dark current levels. Analysis revealed a roughly linear relationship between dark current and exposure time (Figure 7 [Figure 7: see original paper]), with an average rate of approximately  $0.002 \text{ e}^- \text{ pixel}^{-1} \text{ s}^{-1}$  at  $0^\circ\text{C}$ . While this rate is relatively low, the complex distribution of dark current across pixels requires careful consideration in data processing.

Further investigation into the dark current distribution in our ZWO ASI6200MM Pro CMOS cameras revealed an interesting pattern that deviates from the commonly observed log-normal distribution found in some CMOS sensors (e.g., Konnik & Welsh 2014). Figure 8 [Figure 8: see original paper] shows histograms of pixel count values in 600 s dark frames after bias subtraction for all three cameras of MST1, MST2, and MST3. This distribution exhibits several distinct features: a primary peak below the mean value representing typical dark current levels for most pixels, a long tail extending toward higher ADU values indicating a small number of pixels with higher dark current, and secondary peaks suggesting the potential existence of distinct populations of pixels with elevated dark current levels. This distribution pattern may be attributed to the specific design of the CMOS sensor used in these cameras and the underlying FPN.

Understanding this distinctive dark current distribution is crucial for developing accurate noise reduction algorithms and optimizing the performance of the ZWO ASI6200MM Pro cameras in the Mini-SiTian Array Camera System. The cameras demonstrate good performance with a low average dark current rate of approximately  $0.002 \text{ e}^- \text{ pixel}^{-1} \text{ s}^{-1}$  at  $0^\circ\text{C}$ , which enhances their ability to detect faint celestial objects and improves image quality, particularly during long exposures. However, the complex distribution indicates that some pixels may contribute more significantly to noise than others. This variability needs to be accounted for in data reduction and analysis processes to ensure optimal image quality and scientific accuracy. Future work will focus on characterizing this distribution in detail, potentially modeling it using a mixture of probability distributions or investigating the physical origins of the observed pattern. Additionally, developing advanced pixel-specific correction methods may further improve the overall performance of the camera system.

### 3.4. Linearity

Linearity is a critical parameter for evaluating camera performance, as it determines how well the output signal corresponds to input intensity. To examine the linearity of the ZWO ASI6200MM Pro cameras, a series of flat images were captured with exposure times ranging from 0.01 to 8.1 s. Initially, we found that the actual exposure time did not match the set exposure time, potentially affecting the assessment of linearity. Following communication with the manufacturer, ZWO, the firmware and drivers of the three cameras were updated to rectify this issue. Additionally, the manufacturer provided an Application Programming Interface to access the true exposure time, enabling our master control system (Wang et al. 2025) to record the accurate exposure time in the FITS file headers for linearity assessment and further data processing.

The left panel of Figure 9 [Figure 9: see original paper] indicates the variation of the mean signal (in units of 10,000 ADU) for  $2000 \times 2000$  pixels in the central region of the flat image against exposure time. All three cameras exhibit strong linear trends, with R-squared values exceeding 0.99997, indicating excel-

lent linearity across the tested range. The right panel of Figure 9 [Figure 9: see original paper] presents the nonlinearity percentage against signal level (in units of 10,000 ADU) for each camera, revealing the deviation from perfect linearity. The ZWO ASI6200MM Pro cameras exhibit different levels of nonlinearity across different signal ranges. For signals below 3000 ADU, the minimal signals may result in relatively large nonlinearities due to exposure time error, electronic noise, temperature fluctuations, or intrinsic sensor characteristics. Under most signal levels, the cameras have nonlinearities below  $\pm 0.5\%$ . For signals over 3000 ADU, the cameras exhibit exceptional performance with nonlinearity consistently remaining within a remarkably low threshold of 0.3%. This high degree of linearity is paramount for ensuring precise photometric measurements, a cornerstone of quantitative astronomical research. Such robust performance supports the suitability of the ZWO ASI6200MM Pro cameras for optical astronomical imaging applications and demonstrates their capacity to meet the exact standards required in precise astronomical observations.

### 3.5. Gain and Read Noise

This section employs the conventional gain and read noise calculation method to determine the gain and read noise of ZWO ASI6200MM Pro cameras, while also introducing a novel approach for calculating pixel-level gain and read noise in CMOS sensors, which provides a more detailed characterization of CMOS sensor properties.

Gain and read noise are crucial parameters in evaluating CMOS camera performance. In CCD sensors, gain is typically uniform across the entire sensor and can be calculated using a single value for the entire chip. This uniformity is due to the architecture of CCDs, where charge is transferred through a common output amplifier. The conventional method for calculating CCD gain is based on the photon transfer curve (PTC) technique (Janesick 2007), which uses the following formula:

$$g = \frac{\langle F_1 \rangle - \langle F_2 \rangle}{\sigma_{F_1 - F_2}^2 - \sigma_{B_1 - B_2}^2}$$

where  $\langle F_1 \rangle$  and  $\langle F_2 \rangle$  represent the mean values of two flat-field images, respectively,  $\langle B_1 \rangle$  and  $\langle B_2 \rangle$  represent the mean values of two bias images, respectively, and  $\sigma_{F_1 - F_2}^2$  and  $\sigma_{B_1 - B_2}^2$  are the variances of the difference images (flat-flat and bias-bias, respectively).

In contrast, CMOS sensors have an amplifier for each pixel, resulting in pixel-to-pixel variations in gain. This fundamental difference requires a pixel-level approach to gain and readout noise calculation for CMOS sensors. We propose a method to calculate the gain and read noise for each pixel based on the following assumptions: (1) flat-field images are obtained under stable light source

conditions and with identical exposure times; (2) read noise and dark current noise remain stable over short periods.

For a pixel at row  $i$  and column  $j$ , the gain  $g_{ij}$  is calculated using:

$$g_{ij} = \frac{\langle F_{ij} \rangle - \langle B_{ij} \rangle}{\sigma_{F_{ij}}^2 - \sigma_{B_{ij}}^2}$$

where  $\langle F_{ij} \rangle$  and  $\langle B_{ij} \rangle$  are the mean count values of the pixel in flat-field and bias images, respectively, and  $\sigma_{F_{ij}}^2$  and  $\sigma_{B_{ij}}^2$  are their corresponding variances.

The read noise  $r_{ij}$  is then calculated as:

$$r_{ij} = \frac{\sigma_{B_{ij}}}{g_{ij}}$$

The derivation of these formulas is based on the fundamental principles of the PTC. For an individual pixel, the total noise can be expressed as:

$$\sigma^2 = r_{ij}^2 + g_{ij} \langle S_{ij} \rangle$$

where  $\langle S_{ij} \rangle$  represents the mean signal. For bias images, where the signal is essentially zero, we have:

$$\sigma_{B_{ij}}^2 = r_{ij}^2$$

For flat-field images taken under stable light conditions and identical exposure times, we can write:

$$\sigma_{F_{ij}}^2 = r_{ij}^2 + g_{ij}(\langle F_{ij} \rangle - \langle B_{ij} \rangle)$$

Subtracting Equation (5) from Equation (6) yields:

$$\sigma_{F_{ij}}^2 - \sigma_{B_{ij}}^2 = g_{ij}(\langle F_{ij} \rangle - \langle B_{ij} \rangle)$$

which, when solved for  $g_{ij}$ , gives us Equation (2).

We calculated the gain and read noise for each CMOS sensor using the conventional approach. The results are summarized in Table 3, which shows the gain and read noise values for the three MST cameras. The gain values are notably consistent across all cameras, ranging from 0.252 to 0.255  $e^- \text{ ADU}^{-1}$ , indicating similar sensitivity in converting incoming photons to digital signals. The read noise values show slight variations, with MST2 having the lowest at 1.464  $e^-$ , while MST1 and MST3 have slightly higher values of 1.583  $e^-$  and 1.588  $e^-$ ,

respectively. All cameras demonstrate excellent low-noise performance, with read noise values well below  $1.6 e^-$ . These results demonstrate the high quality and consistency of the CMOS sensors used in the MST cameras.

To verify and compare our novel method, we applied it to the camera of MST3. We had access to 144 flat-field images taken with the same exposure time (2 s), which allowed us to demonstrate the application of our new method. Due to the limited flat images from MST1 and MST2, the resulting errors are large, so they will not be discussed in the paper.

Figure 10 [Figure 10: see original paper] presents a comprehensive analysis of the pixel-level gain and read noise characteristics of the MST3 CMOS sensor. The upper panels show linear-scale histograms, and the lower panels display the same data on a logarithmic scale to enhance visibility of low-frequency occurrences. The left panels illustrate the distribution of gain across pixels of the sensor, measured in electrons per ADU ( $e^- \text{ ADU}^{-1}$ ). As shown in Figure 10 [Figure 10: see original paper], the gain distribution for MST3 exhibits a bimodal characteristic. The primary peak is centered around a median of  $0.255 e^- \text{ ADU}^{-1}$ , indicated by a blue dashed line, while a secondary, smaller peak is observed in the range of  $0.250\text{--}0.252 e^- \text{ ADU}^{-1}$ . The primary distribution is notably narrow and slightly right-skewed, with the majority of pixels clustered tightly around the median. This suggests a high degree of uniformity in the gain characteristics of the sensor, which is crucial for consistent image quality and accurate photometric measurements. The logarithmic plot in the lower left panel reveals a long tail extending toward higher gain values, indicating the presence of a small number of pixels with atypically high gain. The presence of a bimodal distribution suggests two distinct populations of pixels with different gain characteristics, an important feature that may have implications for sensor performance and calibration requirements.

The right panels depict the distribution of read noise across the pixels of the sensor, measured in electrons ( $e^-$ ). The read noise distribution has a median of  $1.028 e^-$ , shown by a blue dashed line. The distribution is characterized by two prominent peaks: a sharp, lower peak between 0 and  $1 e^-$ , and a broader, higher peak centered around  $1 e^-$ . This bimodal structure suggests the presence of two distinct populations of pixels with slightly different noise characteristics. The primary distribution is markedly asymmetric, with a sharp rise on the left side and a gradual decline on the right, forming a positively skewed distribution. This low median read noise demonstrates the capability of the sensor for high-sensitivity imaging, particularly beneficial for faint object astronomical observations. The logarithmic plot in the lower right panel unveils a substantial tail extending toward higher read noise values, suggesting the presence of a subset of pixels with significantly elevated noise levels. This bimodal distribution is similar to the distribution of standard deviation values of each pixel derived from a series of bias images (see Figure 4 [Figure 4: see original paper]).

The gain results from the conventional method are generally consistent with the pixel-level analysis for MST3. However, it is important to note that the conven-

tional method provides only a single value for the entire central region, while our pixel-level approach reveals the distribution of gain across the sensor. The difference in read noise can be attributed primarily to the inherent limitations of the conventional method and the unique characteristics of CMOS sensors. The conventional method provides an average value for the entire sensor, which is significantly influenced by Fixed Pattern Noise (FPN), a characteristic feature of CMOS sensors. FPN is a spatially fixed noise pattern that remains constant from frame to frame and is primarily caused by pixel-to-pixel variations in the sensor. The conventional method, by calculating noise across the entire sensor, inherently includes the noise of FPN in its read noise estimation, which can lead to overestimation. Our pixel-level approach effectively isolates the impact of FPN by calculating gain and read noise for each pixel individually, providing a more accurate representation of the camera's performance.

Overall, our pixel-level analysis method provides several advantages for characterizing CMOS cameras: (1) Enhanced precision—by calculating gain and read noise for each individual pixel, we achieve a substantially higher level of precision compared to conventional methods. Traditional approaches typically provide only average values and inadvertently include the impact of FPN when calculating read noise. Our method circumvents these limitations, offering a more accurate representation of the camera's performance. (2) Comprehensive uniformity assessment—the pixel-level distributions of gain and read noise generated by our method enable a detailed and nuanced assessment of sensor uniformity. This approach reveals the pixel response non-uniformity (PRNU; Jiménez-Garrido et al. 2012) component of FPN and identifies anomalous pixels across the entire sensor array, providing invaluable insights into the sensor's spatial characteristics. (3) Improved calibration capabilities—the pixel-level gain data obtained through our method can be effectively utilized to correct the PRNU component of FPN. Furthermore, the pixel-level read noise measurements allow for a more accurate noise assessment. These refined measurements can significantly enhance the accuracy of photometric analyses, leading to more reliable and precise scientific results.

The proposed method for calculating pixel-level gain and read noise provides a comprehensive characterization of CMOS camera performance. Our results demonstrate that the ZWO ASI6200MM Pro cameras exhibit good uniformity in gain across the sensor, with a narrow distribution centered around a specified value. The read noise distribution reveals a slightly skewed pattern, with a long tail toward higher values. This detailed understanding of camera characteristics is essential for optimizing data reduction processes and achieving high-precision photometry in astronomical observations.

## 4. Conclusion

This study evaluates the performance of the ZWO ASI6200MM Pro camera in a laboratory setting. Our findings demonstrate that the camera exhibits low dark currents, along with good short-term stability and excellent linearity, consistent

with the specifications provided by the manufacturer. The key conclusions are as follows:

Our analysis of the ZWO ASI6200MM Pro CMOS cameras in the Mini-SiTian Array Camera System reveals several key characteristics. The cameras demonstrate good bias stability, with mean bias counts remaining within  $\pm 0.03$  ADU over a 20-minute period, and the deviation of mean counts of bias on one night was less than 0.08 ADU (Mu et al. 2024). Combined bias frames exhibit subtle but consistent FPN, including gradients, corner effects, and horizontal structures. Notably, pixel value distributions in bias frames deviate from Gaussian, showing asymmetry with long tails toward higher ADU values. While all three cameras share these similar characteristics, slight variations exist between them.

Our analysis of the ZWO ASI6200MM Pro CMOS cameras revealed a small but notable proportion of anomalous response pixels, ranging from 0.06% to 0.08%, with approximately 1.05% showing significant variations in response. These pixels, predominantly located near the sensor edges and corners, exhibit characteristics similar to the anomalous response pixels of QHY411M (Alarcon et al. 2023). While the majority of pixels behave consistently and normally in both response and response deviation, the presence of these anomalous pixels underscores the importance of precise identification and annotation to maintain high photometric accuracy in astronomical observations.

The ZWO ASI6200MM Pro CMOS cameras demonstrate good performance with a low average dark current rate of approximately  $0.002 \text{ e}^- \text{ pixel}^{-1} \text{ s}^{-1}$  at  $0^\circ\text{C}$ . This low rate enhances the camera's ability to detect faint celestial objects and improves image quality, particularly during long exposures. Our analysis revealed a non-uniform distribution of dark current across pixels. Future work will focus on characterizing this distribution in detail and developing advanced correction methods to further improve overall system performance.

Our analysis of the ZWO ASI6200MM Pro cameras reveals exceptional linearity across a wide range of exposure times and signal levels. The cameras consistently demonstrate nonlinearity below  $\pm 0.5\%$ , with even higher performance (within 0.3%) for signals above 3000 ADU. This high degree of linearity, coupled with consistent performance across multiple units, makes the ZWO ASI6200MM Pro an excellent choice for precision photometric measurements in various astronomical applications.

We propose a novel method for calculating pixel-level gain and read noise in CMOS sensors, providing a more detailed characterization than conventional methods. Our analysis of the ZWO ASI6200MM Pro cameras reveals consistent gain values across all three MST cameras ( $0.252\text{--}0.255 \text{ e}^- \text{ ADU}^{-1}$ ). The pixel-level analysis for MST3 shows a narrow gain distribution centered around  $0.255 \text{ e}^- \text{ ADU}^{-1}$ , indicating excellent uniformity across the sensor. The read noise distribution exhibits a low median of  $1.028 \text{ e}^-$ . While most pixels perform consistently, the extended tails in both distributions reveal the presence

of outlier pixels, which are important to identify for precise calibration. This detailed characterization enables more accurate calibration and optimized data reduction, crucial for high-precision photometric measurements in time-domain surveys.

In conclusion, our comprehensive analysis of the ZWO ASI6200MM Pro CMOS camera demonstrates its potential for astronomical observations. Laboratory tests reveal characteristics such as low dark current, excellent linearity, good short-term stability, uniform gain, and low read noise, suggesting that the camera has the potential to meet the requirements of time-domain surveys. The positive on-sky results from Xiao et al. (2025) further validate these findings. Their work confirms that the ZWO ASI6200MM Pro systems achieve high-precision photometric performance in real astronomical conditions, consistent with laboratory observations. These results underscore the potential of these CMOS detectors for wide-field optical time-domain surveys, demonstrating photometric accuracy comparable to CCDs and impressive astrometric precision.

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The SiTian project is a next-generation, large-scale time-domain survey designed to build an array of over 60 optical telescopes, primarily located at observatory sites in China. This array will enable single-exposure observations of the entire northern hemisphere night sky with a cadence of only 30 minutes, capturing true color (gri) time-series data down to about 21 mag. This project is proposed and led by the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). As a pathfinder for the SiTian project, the Mini-SiTian project utilizes an array of three 30 cm telescopes to simulate a single node of the full SiTian array. The Mini-SiTian has begun its survey since 2022 November. The SiTian and Mini-SiTian have been supported by the Strategic Pioneer Program of the Astronomy Large-Scale Scientific Facility, Chinese Academy of Sciences, and the Science and Education Integration Funding of the University of Chinese Academy of Sciences.

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**Software:** Matplotlib (Hunter 2007), Numpy (Harris et al. 2020), Astropy (Astropy Collaboration et al. 2013, 2018).

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