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Abstract

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Full Text

Preamble

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ChinaXiv Astronomical Test with CMOS on the 60 cm Telescope at the Xinglong Observatory, NAOC

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Abstract

This work presents a detailed evaluation of an observational system comprising a complementary metal-oxide-semiconductor (CMOS) detector, a 60 cm telescope, and a filter set. The system's photometric precision, differential photometric precision, and extinction coefficients were assessed through observations of supersky flat fields, open clusters, standard stars, and exoplanets. Photometric precision was achieved at the 0.02 mag level, with differential photometry reaching 0.004 mag precision. The measured extinction coefficients were found to agree with previous studies conducted at Xinglong Observatory. Ultimately, the results demonstrate that this observing system is capable of precision scientific observations comparable to those achieved with charge-coupled devices across optical wavelengths.

Key words: atmospheric effects – instrumentation: detectors – techniques: polarimetric – stars: atmospheres – eclipses

1. Introduction

Since the application of charge-coupled devices (CCDs; [?]) to astronomical observation, there has been a significant expansion in observational capabilities. With subsequent developments in modern semiconductor technology, complementary metal-oxide-semiconductor (CMOS) sensors emerged. However, early CMOS technology was not suitable for scientific astronomical observation due to high readout noise and lower dynamic range compared to CCD technology ([?]). Furthermore, the independent readout of each pixel could potentially lead to non-uniformity in readout levels between pixels. Consequently, early CMOS technology was primarily used for non-scientific astronomical imaging.

The advent of scientific CMOS image sensors enabled the initial application of CMOS cameras in amateur astronomical observation ([?]; [?]). Advancements in CMOS manufacturing processes have become increasingly significant, and currently only a small difference exists between the readout noise of CMOS devices and CCDs. Moreover, the dynamic range of CMOS sensors has expanded considerably. The emergence of back-illuminated CMOS chips has substantially increased quantum efficiency ([?]; [?]), and the readout noise of CMOS devices now approaches that of CCDs. As a result, the performance gap between CCD and CMOS image sensors continues to diminish.

Although CMOS applications are popular among amateur astronomers, CCDs remain widely used in professional astronomical observations. However, CMOS has been employed in some sky survey projects, such as the Argus Optical Array ([?]), the Large Array Survey Telescope ([?]), and the next-generation telescope of the ATLAS project ([?]), which will be installed at the ATLAS-

Teide observatory on Teide mountain ([?]). Some of these projects use CMOS because of its low cost and ability to achieve wide field-of-view and high signal-to-noise ratio (SNR) measurements. Nevertheless, performance differences exist between different brands of CMOS sensors.

Considerable testing has been performed on CMOS devices ([?]; [?]; [?]), revealing unique problems such as salt-and-pepper noise that are not seen with CCDs. However, these tests focus solely on performance characteristics, while astronomical tests of CMOS, such as photometric accuracy and extinction coefficient measurements, remain rare.

In this article, we test the SONY IMX455 CMOS chip, which features back-illuminated architecture. Section 2 introduces the observation system. Section 3 describes the data reduction procedures. Section 4 presents the results and analysis of astronomical observations. Section 5 provides a summary and conclusions.

2.1. Observation System

The observation system used in this work includes a telescope, CMOS camera, and filters. The telescope is the 60 cm telescope at the Xinglong Observatory of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). According to the official observatory website, the telescope has the following parameters: a corrected focal ratio of F/4.23 at the primary focus.

The 60 cm telescope achieved first light in 1964 as a technical test telescope for the 2.16 m telescope at Xinglong Observatory. It was fully commissioned in 1968 after a series of upgrades. Since 1974, the telescope has been used for photometric observations of variable stars such as eclipsing binaries and pulsating stars. From 1995 to 2000, it was primarily used for a supernova search survey, and since 2000 it has focused on variable star observations.

The IMX455 ([?]) is a back-illuminated CMOS sensor installed in the ZWO ASI6200MM PRO camera for this observation system. Table 1 shows some parameters of the camera, with detailed information available on the official website. The dark current noise is only 0.003 e^{-} s^{-1} pix^{-1} at 0°C, which means that a 5-minute exposure would result in only 0.9 e^{-} dark current noise, which is negligible. The pixel size is 3.76 m, yielding a pixel scale of 0.306 arcsec pixel^{-1} for our system.

We used the Johnson-Bessell filter system ([?]), applying only the BVRI bands. Their corresponding central wavelengths are shown in Table 2.

2.2. Observation

2.2.1. Observation Plan for Tests

The tests in this article primarily include: supersky flat field, photometric accuracy, differential photometric accuracy, and calculation of extinction coefficients during CMOS observations.

Supersky Flat Field. The primary goal of capturing a supersky flat field is to compare it with dusk and dawn flat fields, allowing assessment of differences between dusk and dawn sky illumination patterns. A supersky flat field is obtained by observing low stellar density fields. A fixed exposure time was adopted, with the telescope being offset slightly between individual exposures, yielding approximately 300 images acquired across three bands.

Open Clusters. To measure photometric accuracy, we observed four open clusters—NGC 6913, NGC 7243, NGC 6811, and NGC 744—considering time constraints on individual exposures. Open clusters were selected based on having an optimal density of stars within the field-of-view to balance sufficient numbers with avoiding excessive crowding. Additionally, open clusters contain large populations of variable stars and binary systems ([**?**]), which informed our choice to utilize them in our calculations. Table 3 lists the specific open cluster targets in our observing program. Open clusters serve as ideal targets for testing photometric accuracy through calibration to literature values.

Standard Stars. Extinction coefficients were computed from observations of standard stars, which involves monitoring standard stars throughout the entire night from rise to set. Photometric standard stars have precisely determined flux measurements across various photometric systems ([**?**]; [**?**], 2013). Through measurements using a CCD camera or photometer, the brightness or flux of another object can be determined by comparison to these standards. By tracking standard star magnitudes versus airmass, the extinction coefficient can be derived. In this work, standard stars were selected from Landolt's catalog ([**?**], 2013), as listed in Table 3.

Exoplanets. To measure differential photometric precision, we observed two exoplanets: HAT-P-32 b and WASP-33 b (Table 3). The approach involved capturing single-band V exposure frames during transit, monitoring both targets continuously from one hour before until one hour after the transit event.

2.2.2. Observation Details

Due to mechanical tracking limitations of the 60 cm telescope, the maximum observation time for a single target is 30 s. For camera settings, the GAIN parameter was set to 100, corresponding to a gain value of 0.25 e^-/ADU, with a readout noise value of 1.5 e^-. The camera was cooled to -10°C.

Our observation log is listed in Table 4, including primary observation targets, observational time, band, exposure, and frame count. The main observation period was from 2022 September 23 through September 30. Prior to each night, imaging quality was assessed and the optical focus adjusted to optimize image quality. Each open cluster was observed sequentially in four filters, with 80 images per band. Standard stars were monitored throughout entire nights in all four filters. Exoplanet targets were observed in V band alone for the whole night. The observation strategy differed between targets: HAT-P-32 b was observed in normal focus, while WASP-33 b was observed defocused.

3. Data Reduction

3.1. Image Trimming

As described in Section 2, the approximate field-of-view of the 60 cm telescope is 18 × 18 . However, during observations, the full field captured by the camera subtended roughly 32 × 48 . Therefore, image trimming was required to extract the relevant field-of-view for analysis. To obtain the best results, only a subsection of the full CMOS frame corresponding to the area illuminated by the telescope optics was retained for photometry.

After trimming, the image data size changed to 3354 × 3354 pixels^2, and its field of view became 17.05 × 17.05 . The pre-trimmed and post-trimmed planar fields are shown in Figure 1, where the left panel shows the pre-trimmed planar field and the box indicates the trimmed range. The right panel shows the trimmed flat field. All bias frames, flat fields, and science target images were trimmed for further processing and analysis.

3.2. Bias

This section evaluates the stability of CMOS bias frames and investigates temporal variations before and after observation. Bias images were taken at dusk and dawn on different nights. Examination of the biases indicates the background stabilizes at approximately 510 ADU. First, we combined bias frames using the median to mitigate the effects of salt-and-pepper noise ([**?**]). Differences between biases were analyzed to highlight temporal variations. Table 5(a) shows the differences between the mean of the combined dusk bias and the combined dawn bias each day. Table 5(b) shows the differences between the mean of the September 24 combined dusk bias and the other days' combined dusk biases.

These comparisons demonstrate bias stability throughout the observation nights, leading us to conclude that the CMOS detector operation was stable throughout the observation period. During pre-processing, the dusk bias frame was subtracted from both the raw science images and flat fields each night. Overall, the characterized bias stability supports reuse of a single master bias constructed from dusk frames only, without requiring time-variable corrections over the observation run.

3.3. Flat Field

Flat field correction is essential for processing observational data, not only to correct for uneven sky illumination but also to correct differences between the amplifiers for each pixel. Table 6 presents the results of calculating the ratio of the median combined flat field captured during dusk versus that obtained during dawn for each day. This ratio represents the variation between the maximum and minimum of the images of the two flat fields after normalizing and smoothing via a median filter. This metric provides a measurement of the illumination uniformity achieved across each band.

Comparing values among different dusk and dawn flats indicates any variation introduced by changing illumination conditions at dusk versus dawn. Table 6 shows that within each band, the median difference is within 1% in the B, V, and R bands, and within 2% in the I band. Table 7 presents results from dividing the median value of the dusk flat field for each night during September 24–29 by the September 24 dusk flat. These values indicate the level of consistency between daily flats during the observation period. As expected, flat fields agree to within 1% in all bands. This consistency validates the temporal stability of the flats throughout the observation window, supporting their use for corrections without introducing spurious variations. Therefore, we applied bias correction and dusk flat field correction to obtain the scientific images.

3.4. Photometry

We used Source-Extractor (SExtractor) tools for photometric measurements. SExtractor's automatic aperture photometry routine is derived from Kron's "first moment" algorithm ([**?**]); for details, see the SExtractor manual ([**?**]). Table 8 presents some parameters of SExtractor. DETECT_{THRESH} represents the threshold for star detection, for which we opted for the default value. PHOT_{AUTOPARAMS} denotes the parameters for automatic aperture photometry, for which we also chose default settings. BACKPHOTO_{TYPE} specifies the background calculation method, with our selection being LOCAL to compute the flux error using local background estimation.

The formula used by SExtractor to calculate the flux error is as follows:

$$\text{Fluxerr} = \sqrt{\sum_{i \in A} \sigma_i^2 + \frac{p_i}{g_i}}$$

where A is the set of pixels defining the photometric aperture, σ_i is the standard deviation of noise (in ADU) estimated from the local background, p_i is the measurement image pixel value subtracted from the background, and g_i is the effective detector gain in e^-/ADU at pixel i. Note that this error estimate provides a lower limit of the true uncertainty, as it only accounts for photon and detector noise. With aperture photometry and target extraction, we can obtain the light curve of the target ([**?**]). However, before doing this, we need to correct the exposure time. We correct the exposure time t and magnitude m_{phot} obtained from photometry to determine the ultimate instrumental magnitude:

$$m_{\text{inst}} = m_{\text{phot}} - 2.5 \log_{10}(t)$$

3.5. System Conversion

After exposure time correction, we perform calibration and filter system correction. We introduce the reference catalog—Gaia's synthetic photometry (Gaia-SP; [?]) and Gaia Data Release 3 (DR3) ([?]). Here we applied Equation (3) to make corrections and, according to different situations, transformed the formula to simplify the process:

$$m_{\text{inst}} - m_{\text{Gaia-sp}} = k_1 \times X + k_2 \times (m_{B,\text{Gaia-sp}} - m_{V,\text{Gaia-sp}}) + C$$

where m_{inst} is the instrumental magnitude, $m_{\text{Gaia-sp}}$ is the magnitude from the Gaia-SP catalog, X is airmass, k_1 is the extinction coefficient corresponding to a certain band, k_2 is the color coefficient corresponding to the two systems, and C is the zero-point between the two systems.

Flux calibrations are typically performed using field star maps that are photographed and processed. The magnitude calibrations used here convert instrumental magnitude to true magnitude, and we use the Vega system. Because of the high accuracy of Gaia DR3 data, we have selected Gaia DR3 as the reference magnitude.

4. Results and Analysis

4.1. Supersky Flat Field

This comparison evaluates illumination differences between the supersky flat field and flat fields from dusk and dawn, revealing discrepancies in the sky background. Figure 2 displays the image after dividing the supersky flat field by the dusk and dawn flat field, followed by smoothing with a box size of 100 pixels. Table 9(a) presents results comparing the supersky flat to dawn flats, showing the peak-to-valley difference. As flat fields were only obtained in three bands, comparisons are shown for those bands. The differences between dawn flats on each night are within one percent, matching expectations.

Similarly, Table 9(b) compares the supersky flat to dusk flats, also showing percent-level agreement with the dusk reference each night. All flat fields show sub-percent level consistency. The supersky flat field serves as an independent check of the dusk and dawn flat fields' ability to represent the illumination. Table 9 demonstrates that the flat field is stable at slightly under 0.01 during nights. Furthermore, each band flat field and the supersky flat field remain within 1% over the entire observation period.

4.2. Limiting Magnitude

The limiting magnitude is an important indicator of an observing system's capability. In this system, due to mechanical limitations of the telescope, we can only use single exposures up to 30 s. Below are the limiting magnitudes calculated from the open clusters, after calibrating and computing the limiting magnitudes in the BVRI bands at 3σ and 5σ. Figure 3 displays the magnitude-error plots and magnitude statistics after calibration, where m_{err} is obtained from Equation (1).

From Table 10 we see that limiting magnitude variation in different bands corresponds to the quantum efficiency of the CMOS, with the limiting magnitude at 5σ in the V band being 19.205 mag, as expected.

4.3. Open Clusters

Table 3 shows the four open star clusters we observed: NGC 6913, NGC 7243, NGC 6811, and NGC 744. Figure 4 displays their R-band trimmed images. In this section, we introduce the imaging and processing results for each open cluster separately.

After completing photometry, we used Gaia-SP as the reference magnitude. Based on the characteristics of open clusters, since stars in the same field experience nearly equal extinction, we regard $k_1 \times X$ as a constant. Thus, Equation (3) becomes:

$$m_{\text{inst}} - m_{\text{Gaia-sp}} = \text{constant} + k_2 \times (m_{R,\text{Gaia-sp}} - m_{I,\text{Gaia-sp}})$$

We can see that Equation (4) has only two variables, $C + \text{constant}$ and k_2, from which we can obtain their respective parameters through simple straight-line fitting. The color corrections are combined using Equation (4) ([**?**]; [**?**]).

4.3.1. NGC 6913 We performed photometry on 80 frames in the same band and calculated the standard deviation of the magnitude distribution for each star across these 80 frames, as depicted in Figure 5(a). This figure displays the error of stars before selection, with instrumental magnitude on the x-axis and the standard deviation of the magnitude distribution for each source across the 80 frames on the y-axis. Based on Figure 5(a), we obtained an internal precision of magnitude measurement. We then used Figure 5(a) for target selection, removing variable stars, saturated stars, and non-Zero Age Main-Sequence cases. Finally, we selected member stars and matched them to the Gaia-SP star catalog.

Figure 5(b) compares the color–magnitude plot of instrumental magnitude with that of Gaia-SP. The horizontal axis is the R–I color, and the vertical axis is the R-band magnitude. Figure 5(c) derives from Equation (4). The vertical axis in Figure 5(d) shows the difference between the corrected magnitude $m_{R,\text{fit}}$ and Gaia-SP magnitude $m_{\text{Gaia-sp}}$. After the final fit, we calculate the difference between the magnitude and Gaia-SP color by multiplying the color coefficient with the color value. The R-band instrumental magnitude is on the horizontal axis, and the accuracy obtained from the final photometry is reflected in the standard deviation shown in Figure 5(d).

Table 11 displays the coefficients $k_{2,R}$, zero-points $C_{R,0}$ + constant, and photometric accuracy computed for each open cluster. From this table, we see that the photometric accuracy is 0.016 mag.

4.3.2. NGC 7243

The processing procedure for NGC 7243 is similar to that of NGC 6913. Figure 6(a) shows the magnitude and standard deviation plot obtained with the same processing procedure. Figure 6 represents the same calculation process as Figure 5 for NGC 6913. Finally, by calculating the standard deviation of the data in the scatter plot of Figure 6(c), we obtained a photometric accuracy of 0.022 mag.

4.3.3. NGC 6811

The processing procedure for NGC 6811 is similar to that of NGC 6913. Figure 7(a) shows the magnitude and standard deviation plot obtained with the same processing procedure as NGC 6913. Figure 7 represents the same calculation process as Figure 5 for NGC 6913. Finally, by calculating the standard deviation of the data in the scatter plot of Figure 7(c), we obtained a photometric accuracy of 0.011 mag.

4.3.4. NGC 744

The processing procedure for NGC 744 is similar to that of NGC 6913. Figure 8(a) shows the magnitude and standard deviation plot obtained through the same processing procedure as NGC 6913. Figure 8 represents the same calculation process as Figure 5 for NGC 6913. Finally, by calculating the standard deviation of the data in the scatter plot of Figure 8(d), we obtained a photometric accuracy of 0.019 mag.

Table 11 summarizes the results for these four open star clusters, where the standard deviation listed represents the photometric accuracy. The color coefficient k_2 is not the true system conversion coefficient and incorporates the main-order contribution of the cluster. Therefore, the photometric accuracy is approximately 0.02 mag ([**?**]; [**?**]; [**?**]).

4.4. Standard Stars

Table 3 shows that we observed two standard stars, SA 20–43 and BD+39 3312, in four different bands. After completing pre-processing and photometric processing, we extracted the light curves of the targets in each band, matched them with the catalog, and calculated the extinction coefficients using the system transformation, Equation (2). At this point, the system transformation formula needs to be modified. Because there is only one target with uniform color, for this standard star, the color term $k_2 \times (m_{B,\text{Gaia}} - m_{V,\text{Gaia}})$ can be regarded as a constant, and the formula can be rewritten as:

$$m_{\text{inst}} - m_{\text{Gaia-sp}} = k_1 \times X + \text{constant}$$

We can see that Equation (5) has only two variables, c + constant and k_1, from which we obtain their respective parameters through linear fitting.

4.4.1. BD+39 3312 Figure 9 shows the airmass versus magnitude residuals of the standard star BD+39 3312 in each band. The blue dots represent observed data, while the red line shows the fitted line. The x-axis represents airmass, and the y-axis shows the difference between instrumental magnitude and Gaia-SP reference magnitude (m_{residual}). Because observations were made in summer, the range of airmass values is relatively small. Table 12 summarizes the fitting results in four bands, with k_1 and c_0 corresponding to the coefficients in Equation (5). k_{1s} and c_{0s} represent simulated errors. The values are: $k_{1,B} = 0.335 \pm 0.022$, $k_{1,V} = 0.193 \pm 0.018$, $k_{1,R} = 0.090 \pm 0.013$, and $k_{1,I} = 0.070 \pm 0.017$.

4.4.2. SA 20-43 Figure 10 shows the variation of the standard star's magnitude with respect to observation time. The x-axis represents time in UT (hours), while the y-axis shows the difference between instrumental magnitude and Gaia-SP magnitude (m_{residual}). The variation pattern shows gradual dimming followed by sudden brightening, continuing to increase until reaching maximum brightness at zenith. Subsequently, the target undergoes a descending phase with continuous dimming, followed by slight brightening and eventual fading. This pattern is observed for all targets within the field of view, indicating the absence of variability during the observation period.

Figure 11 displays airmass versus magnitude residuals, with the x-axis representing airmass and the y-axis showing the difference between instrumental magnitude and Gaia-SP reference magnitude (m_{residual}). The blue triangles represent the ascending phase, while the orange dots signify the descending phase.

This problem has been discussed in the literature ([**?**]; [**?**]), with two different correction methods: one corrects for atmospheric extinction by including a band-independent but time-varying zero-point correction term in the calibration, which was later replaced by a time-varying atmospheric extinction coefficient term ([**?**]); the other uses a time-varying atmospheric extinction coefficient term to correct for atmospheric extinction variations ([**?**]). In this work, we used the second method to establish a time-dependent term for the atmospheric extinction coefficient. Since we are using only one target, there is no color term. To better correct atmospheric extinction, we add a time-varying atmospheric extinction coefficient term. For Equation (5), based on the corrected relationship of the individual standard stars, this becomes:

$$m_{\text{inst}} - m_{\text{Gaia-sp}} = k_1 \times X + f(\text{UT}) + \text{constant}$$

In reality, Equation (7) is a polynomial. We start with the simplest case for our analysis. By fitting the data using this approach, we obtain the coefficients. Subsequently, through stepwise iteration, we can transform the monomials into a polynomial, thereby fully correcting the observed data. This yields results shown in Figure 12, where the x-axis represents airmass and the y-axis shows the difference between instrumental magnitude and Gaia-SP reference magnitude

(m_{residual}). The blue dots represent corrected data points, while the red line shows the linear fit to the corrected data. The final results are summarized in Table 13.

The coefficients k_1 and c_0 in Table 13 correspond to the respective coefficients in Equation (8). k_{1s} and c_{0s} represent simulated errors. The values are: $k_{1,B} = 0.303 \pm 0.013$, $k_{1,V} = 0.192 \pm 0.012$, $k_{1,R} = 0.137 \pm 0.009$, and $k_{1,I} = 0.089 \pm 0.006$.

4.4.3. Comparison Table 14 and Figure 13 compare all our measured extinction coefficients with those calculated for other telescopes at Xinglong Observatory (NAOC). The results are nearly identical to others measured at Xinglong Observatory.

4.5. Exoplanets

For exoplanets, we use differential photometry, which compares the light curves of stars within the field of view of an image, eliminating the influence of instruments and weather. The reference star used to correct the target star must have brightness not too different from the target star, and the distance between the reference and target cannot be too large. Additionally, the standard deviation of the light curve cannot be too large (i.e., >0.01) to ensure it is not a variable star. The number of reference stars should be small so that the image is most appropriate. A comparable star with the same requirements as the reference star is also required at the end for final comparison.

4.5.1. HAT-P-32 b For differential photometry, we can obtain the light curve. Figure 14 shows the light curve extracted after differential correction. The top panel shows the observed eclipse light curve of HAT-P-32 b, while the bottom panel displays the photometric variation of the comparison stars. The x-axis for both panels is deltaTime (hours), representing the time span from the beginning to the end of the observation. The y-axis of both panels represents the relative magnitude, $m_{V,\text{relative}}$. The standard deviation in the bottom panel label represents the differential photometric accuracy, which is 0.0063 mag.

We then combined five frames into one (binned 5) to increase the SNR, as shown in Figure 15(a). Figure 15(a) represents our observation of HAT-P-32 b and its control star, showing obvious eclipse light variation in the target with a scatter of 0.0037 mag. Figure 15(b) compares our light curve with those from other work in the literature, showing complete agreement. The data used in Figure 15(b) are from observations with the OSIRIS instrument of the Gran Telescopio CANARIAS (GTC) in long-slit spectral mode ([**?**]; [**?**]).

4.5.2. WASP-33 b Since WASP-33 is a δ Scuti variable star ([**?**]), the light curve of the exoplanet contains variations from the host star. The relationships in Figures 16 and 17(a) for WASP-33 b are the same as those in Figure 14, where the scatter is 0.0066 mag, and Figure 15(a) for HAT-P-32 b, taken before and after binning 5. Figure 17(a) shows our light curve of WASP-33 b and its host star. We can clearly see its light variation of 0.02 mag, while the precision of the reference star is about 0.004 mag in the best situation. The depth of the eclipse may include the light variations of the host star.

Comparing WASP-33 b with data obtained by other observers using CCD observations, our result also agrees well with [**?**] obtained from the 0.3 m telescope at Monte Carbre Observatory and the 0.8 m telescope at Montserrat Observatory, as shown in Figure 17(b).

We compare the observing performance of the 60 cm telescope using CCDs. From [**?**] and [**?**], we see that they have 60 cm frames set up for exoplanets with differential photometric accuracy around 0.0016–0.0063 mag. The differential photometric accuracy obtained from our measurements is between 0.003 and 0.004 mag, which is comparable or even smaller than the references. Therefore, we conclude that CMOS is suitable for observing exoplanets and can replace CCDs for such programs.

5. Summary and Conclusions

In this work, the tests mainly include: supersky flat field, photometric accuracy, differential photometric accuracy, and extinction coefficients with CMOS observations mounted on the 60 cm telescope at Xinglong Observatory (NAOC). Based on the tests, flat field correction for the CMOS + 60 cm telescope could be better than 1% in the BVRI bands, and the flat field remains stable throughout the observation period. A flat field from one day can be replaced by that of another day during our observations. Therefore, we conclude that the camera's performance is stable.

The open clusters result in a photometric accuracy of 0.02 mag. The calculated extinction coefficient of our work is compared with other coefficients observed at Xinglong Observatory (NAOC) using standard stars, revealing no significant difference. The differential photometric accuracy for exoplanets is 0.004 mag.

Therefore, we can conclude that the observation results of the observing system in this paper are in accordance with our expectations and can be used for scientific observations. This SONY IMX455 CMOS sensor satisfies our requirements and can replace CCDs.

In the future, we will test the pixel stability of this camera. We will also test it on other devices with exposure times of 60, 300, 600, and 1200 s. Additionally, we will study the dark current for each corresponding exposure time.

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