The photometric system of the One-meter Telescope at Weihai Observatory of Shandong University

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Received 2013 November 4; accepted 2014 March 27

Abstract The one-meter telescope at Weihai Observatory (WHO) of Shandong University is an f/8 Cassegrain telescope. Three sets of filters are installed in a dual layer filterwheel that use Johnson–Cousins \textit{UBVRI}, Sloan Digital Sky Survey \textit{ugriz} and Strömgren \textit{uvby}. The photometric system and the CCD camera are introduced, followed by detailed analysis of their performances, and determination of the relevant parameters, including gain, readout noise, dark current and linearity of the CCD camera. In addition, the parameters describing the site’s astro-climate, including typical seeing, statistics on the number of clear nights and average sky brightness, based on data gathered from Sep. 2007 to Aug. 2013, are systematically studied and reported in this work. Photometric calibrations were done using Landolt standard star observations spanning eight nights, which yielded transformation coefficients, photometric precision and system throughput. The limiting magnitudes are simulated using the derived calibration parameters and classic observation conditions at WHO.

Key words: telescopes — site testing — instrumentation: miscellaneous — techniques: photometric

1 INTRODUCTION

The one-meter telescope at Weihai Observatory (WHO) of Shandong University was installed in June 2007. It is operated by the School of Space Science and Physics, Shandong University, Weihai. This is a Cassegrain telescope made by APM-Telescopes\(^1\) in Germany. This telescope is similar to the Lulin one-meter telescope (LOT) in Taiwan (Kinoshita et al. 2005) and the Tsinghua-NAOC 80-cm telescope (TNT) at Xinglong station (Huang et al. 2012). The main scientific projects conducted on the WHO 1-m telescope (WHOT) include variability of active galactic nuclei (Bhatta et al. 2013; Hu et al. 2014; Chen et al. 2013, 2014; Guo et al. 2014), variable stars (Yang et al. 2010; Dai et al. 2012; Li et al. 2014), exoplanets, afterglow of Gamma-ray bursts (Xu et al. 2013), searching for minor planets and so on. Two instruments were built for and are attached to WHOT. These include one imaging CCD camera equipped with several sets of filters and one fiber-fed high resolution Echelle spectrograph (HRS). It is essential to know the properties and performance, such as detection

\(^{*}\) Supported by the National Natural Science Foundation of China.

\(^{1}\) http://www.apm-telescopes.de
limit, throughput, photometric precision and instrument response of the system, which will help astronomers prepare observation proposals (e.g. Kinoshita et al. 2005; Zhou et al. 2009; Mao et al. 2013; Zhang et al. 2013).

A program to characterize the photometric system has been carried out, and the results are reported in this work. The performance of the HRS will be given in another paper. The instruments and control software are briefly introduced in Section 2. The site conditions are reported in Section 3. Basic characteristics of the CCD camera are shown in Section 4. The photometric calibration results are reported in Section 5. Performance of the system is described in Section 6, and Section 7 gives a summary.

2 THE OBSERVATION SYSTEM AND CONTROL SOFTWARE

The optical system of WHOT has a classical Cassegrain design with a focal ratio of 8, and is made by Lomo Optics. It has a parabolic primary mirror with an effective diameter of 1000 mm (1020 mm mechanical diameter), and a hyperbolic secondary mirror with an effective diameter of 360 mm. Over the entire field of view (FOV), 80% of the energy is concentrated with a 0.65′′ point spread function. Aluminium plus SiO$_2$ is coated on both mirrors. The mount system is an equatorial fork mount with high accuracy fiction servomotors. The maximum slew speed can reach 4° per second in both Right Ascension and Declination directions actuated by 48 Volt DC motors. The pointing accuracy is 5.4′′ (RMS) for altitudes higher than 20°, and the tracking accuracy can reach 0.6′′ (RMS) in 10 min of blind guiding.

A back-illuminated PIXIS 2048B CCD camera from Princeton Instruments Inc.\(^2\) is mounted on the Cassegrain focus of WHOT. The dark current rate is low at a temperature of −55°C, thanks to the thermoelectric cooling system. With a 2048×2048 imaging array (13.5×13.5 µm pixel$^{-1}$), the camera provides an FOV of 12′×12′, with a pixel scale of 0.35′′ per pixel. The specifications of the CCD chip are given in Section 4. A dual layer filter wheel manufactured by American Astronomical Consultants and Equipment Inc. is inserted between the telescope flange and the CCD camera. Each layer consists of eight cells holding filters with size 50×50 mm. Standard Johnson–Cousins UBVRI, SDSS $u'g'r'i'z'$ and Strömgren $u'v'by$ filters (see Bessell 2005 and references therein) are available. The time needed for changing a filter is shorter than 1 s, so the speed is very high.

To examine the overall image quality of WHOT, one exposure centered on the field of NGC 7790 in the $V$ band was taken on 2010 October 9 and used to do the full width at half maximum (FWHM) measurement.

The image is shown in the left panel of Figure 1. The FWHM of all point sources with signal to noise ratio (SNR) higher than 5 were determined, and its contour is shown in the right panel of Figure 1. This diagram shows that the image quality at the focal plane is good and uniform, in the sense that variation in FWHM is less than 0.2′′. We note that the lower-right corner has a slightly larger FWHM than the other areas, which is possibly caused by a misalignment of the CCD camera with respect to the optical axis.

In order to improve efficiency during observations, software called PCF was developed in cooperation with Xinglong station of National Astronomical Observatories. A file that has the observation plan, including, for example, the target coordinates, filter name, exposure time and the number of repeat observations, should be provided to PCF. PCF will control the telescope to move to the position where the object is located. It will move the dome window and filter wheel to the correct position, and control the camera to record the data automatically. This process is very efficient and convenient for astronomers who use the facility.

\(^2\) http://www.princetoninstruments.com/
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3 SITE CONDITIONS

WHOT is located on the top of Majia Mountain in Weihai (122°02′58.6″ E, 37°32′09.3″ N), with an elevation of about 110 m. Parameters like seeing, number of clear/photometric nights and sky brightness are important when evaluating an astronomical site (Zou et al. 2010; Yao et al. 2012; Zhang et al. 2013). To evaluate the seeing conditions for the site where WHOT is located, we have done a statistical analysis using data recorded during the past six years from September 2007 to August 2013. The left panel of Figure 2 shows values for the long term seeing. Because we have no differential image motion monitor (DIMM) to measure the seeing, these values were measured by the FWHM of sources in an image taken at about 14:00 (Universal Time) during most nights when observations were taken in the past six years. These values include all related effects, such as dome seeing, the telescope being out of optimal focus, optical effects and so on (Liu et al. 2010; Yao et al. 2012; Zhang et al. 2013).
The yearly average and standard deviation of seeing in the past six years were calculated and are shown as red dots in the left panel of Figure 2 (the standard deviation is represented by error bars). The seeing condition has been stable in the past six years. The small variation is probably due to a sampling bias, because the criteria for using the telescope for observations has changed from year to year. To analyze the seasonal variation of seeing, we plot all the seeing data versus the date in a year in the right panel of Figure 2, and the monthly average is given by red solid squares (the standard deviation is represented by error bars). It increases slowly from January to April, then it experiences some variations from May to August, and finally it almost stabilizes for the rest of a year. The histogram and cumulative statistics related to seeing are shown in Figure 3. The median of seeing is 1.70″. The best seeing can reach 0.8″, and seeing is less than 2.0″ on more than 85% of nights.

Figure 4 illustrates the real observational time, when useful data were obtained according to the observation log in each month during the past six years. The left panel of Figure 4 gives the number of nights when observations were taken in each month and the right panel of Figure 4 gives the number of hours when the telescope was being operated during each month. We can see that summer is the time when a minimum of observations was acquired because of rain and high humidity. As shown in the plots, the other three seasons are almost the same. Actually there are more clear nights during winter, but sometimes we have to close the dome because of strong wind or frozen precipitation on the dome. The observational nights varied from 134 to 168 in one year during the past six years, and the average is 155 nights. The number of hours when observations were taken ranges from 1115 to 1427 h in a year, and the average is 1226 h. The total clear nights, which means useful data were taken during the whole night, was 113 from September 2011 to August 2013, so the yearly average total clear nights is 56.5 nights.

The night sky brightness can be measured using the observations of Landolt standard stars. The night sky count (Sky_{count}) can be obtained from observations during the photometric calibration. Then the sky instrumental brightness can be calculated by Equation (1)

\[
\text{Sky}\_{\text{inst}} = 25 - 2.5 \times \log_{10}\left(\frac{\text{Sky}\_{\text{count}}}{\text{scale}^2}\right),
\]

where Sky\_{inst} is the instrumental night sky brightness and ‘scale’ is the angular size of a CCD pixel projected on the sky, i.e. 0.35″ per pixel for our configuration. Then, the night sky brightness Sky\_x, in units of mag arcsec^{-2}, can be given by Equation (2)

\[
\text{Sky}\_x = \text{Sky}\_{\text{inst}} - Z P_x ,
\]
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Fig. 4 Monthly observational time in each month during the past six years. Numbers of monthly observational nights and monthly observational hours are given in the left and right panels, respectively.

Fig. 5 The night sky brightness versus UT. The purple squares, blue solid circles, yellow solid squares, red circles and black solid triangles illustrate the night sky brightness in the $U$, $B$, $V$, $R$ and $I$ bands, respectively.

where $ZP_x$ is the instrument’s zero point, which can be calculated by transformation equations (see Sect. 5). $x$ denotes the different filter names. Here we did not analyze the effects caused by the difference in airmass and direction of the sky area. The $UBVRI$ band night sky brightness on eight nights is plotted against Universal Time (UT) in Figure 5. An obvious tendency can be seen that the night sky brightness is turning dark before 16:00 (UT, Beijing time is 24:00), then it is stable, and finally it brightens just before dawn. Most city lights are gradually turned off before midnight because people go to sleep. The variation in the night sky brightness can reach about 2 magnitudes before and after midnight. This tendency strongly supports the idea that the main source of night sky brightness is artificial light pollution from the city of Weihai. The median night sky brightness in the
Fig. 6 Means bias level and standard deviation (filled circles), along with ambient temperature (triangles) of the camera at the time a bias exposure was taken. Data shown in the left panel were taken in the slow readout mode, but those in the right panel were taken in the fast readout mode.

The darkest night sky brightness at WHO in the $U$, $B$, $V$, $R$ and $I$ bands is 20.12, 19.14, 18.00, 17.52 and 17.71 mag arcsec$^{-2}$, respectively. The darkest night sky brightness at WHO in the $U$, $B$, $V$, $R$ and $I$ bands is 20.99, 20.17, 18.90, 18.95 and 19.11 mag arcsec$^{-2}$, respectively. This is much brighter than at good astronomical sites around the world (see table 6 in Kinoshita et al. 2005). It is not surprising that the night sky brightness in the $V$ band is more than 2 mag arcsec$^{-2}$ brighter than that of Xinglong and Xuyi stations (Yao et al. 2012; Zhang et al. 2013) because WHO is very close to an urban area. Appropriate research projects undertaken at WHO should be chosen that are compatible with these site conditions.

4 CCD CHARACTERISTICS

A PI PIXIS 2048B CCD is used for photometry taken at WHOT. The peak efficiency of this CCD can reach 95%. A new back-illuminated Andor iKon-L DZ936-N CCD camera was ordered for WHOT. It has the same E2V 42-40 chip as the PIXIS 2048B, and this camera can be cooled down to $-80^\circ$C with air cooling, but it is still being produced by the manufacturer. Here, we only describe the PIXIS 2048B CCD.

The stability of the CCD bias level is a non-negligible effect for high precision photometry. To better understand the variation in bias, we continuously monitored the bias level from 2011 October 12 to 13 for more than 6 and 13 h for slow and fast readout modes, respectively. One bias image was taken every 2 to 5 min, and the average as well as the standard deviation for the central 400×400 pixels were calculated for every image. The ambient temperature was recorded by a temperature sensor installed in the weather station. The mean bias level and the temperature versus UT are shown in Figure 6. The result for the slow readout mode is shown in the left panel, while the right panel shows the bias level for the fast readout mode. The triangles illustrate the variation in ambient temperature. The error bars in the plot represent the standard deviation of the bias. At the beginning of monitoring, the bias showed a large change, because it was not long enough after the CCD dewar was cooled down. This is the reason why we need to cool the CCD for at least 2 h before scientific images are taken. Usually the CCD camera is kept cool and stabilized at $-55^\circ$C all day except during the thunderstorm season for the safety of the CCD camera. The bias is stable for the slow readout mode, but it is variable when we set the camera in the fast readout mode, and it changed about 25 analog-to-digital unit (ADU) counts during 13 h. Its variation seems to be related to variation in the ambient temperature. So, we need to be careful when acquiring high precision photometry in the fast readout mode.
We did the dark current measurement on 2010 July 24. Dark images were taken with exposure times from 150 to 1800 s, then the average value and the standard deviation for the central 400×400 pixels were calculated for each image. As shown in Figure 7, the average value and exposure time maintain a well-defined linear relationship, whose slope represents the dark current rate. The measured dark current is $0.0022 \pm 0.0001 \text{ e}^{-\text{pixel}^{-1} \text{s}^{-1} (@-55^\circ \text{C})}$, which is very close to the value given by PI. The dark current is very low, so dark correction is unnecessary for normal short exposure observations.

Linearity is quite important for high precision photometry, so the linearity in the CCD response was measured using a series of unfiltered flat-field images with median ADU values from $\sim 2000$ to $\sim 60,000$. The test was done in a room without light entering it. A fluorescent light was used to generate uniform illumination on the ceiling of the room, and the camera was covered by several pieces of plain white paper, then the camera was placed upright to take flat field images. Tests were only done with settings of low noise output and median gain, which is the most commonly used setting in observations. The exposure time varied from 2 to 70 s for the slow readout mode and from 2 to 85 s for the fast readout mode. Four images were taken for each exposure time. The average ADU count was calculated for the central 400×400 pixels for each image. The relationship between the exposure time and the average ADU count for slow readout and fast readout mode is shown in the left and right panels of Figure 8, respectively. The solid line in Figure 8 is the linear least squares fitting of the measured data points. The nonlinearity can be calculated by the following equation

$$\text{Nonlinearity(\%)} = \frac{\text{MaxPositiveDev} + \text{MaxNegativeDev}}{\text{MaxSignal}} \times 100,$$

where ‘MaxPositiveDev’ and ‘MaxNegativeDev’ is the measured maximum positive and negative deviation from the linear fitting, respectively. ‘MaxSignal’ is the measured maximum of the ADU counts. From measurement and calculation, the nonlinearity is 0.67% and 1.18% at 42,700 and 58,950 ADU, respectively for slow readout speed, while it is 0.49% and 0.82% at 40,530 and 60,200 ADU, respectively for fast readout speed. Other specifications of the detector, such as gain, readout noise and readout time, are listed in Table 1.
Table 1 Specifications of the PIXIS 2048B CCD Camera Reported by the Manufacturer and Our Measurements

| Attribute                      | Specifications                                                                 |
|--------------------------------|-------------------------------------------------------------------------------|
| Chip                           | E2V 42−40                                                                     |
| CCD format                     | 2048 × 2048 pixels, pixel size is 13.5 µm 100% fill factor.                  |
| Image area                     | 27.6 × 27.6 mm²                                                               |
| Cooling                        | Air cooling, down to −55°C                                                    |
| Single pixel full well         | 110,000 e−                                                                  |
| Dark current (e− pixel−1 s−1)  | 0.0024 (by manufacturer) @ −55°C                                        0.0022 (this work) @ −55°C |
| Non-linearity                  | Readout speed                                                                 |
|                                | 100 kHz 0.67% (2310–42700 ADU)                                               |
|                                | 2 MHz 0.49% (2160–40530 ADU)                                                  |
|                                | 1.18% (2310–58950 ADU)                                                       0.82% (2160–60200 ADU) |
| Readout noise (e−)             | Low noise output                                                             |
|                                | 100 kHz 3.67                                                                  |
|                                | 2 MHz 15.35                                                                  |
|                                | High capacity output                                                         |
|                                | 2 MHz 7.02                                                                   |
|                                | 36.23                                                                        |
| Gain (e− ADU−1)                | Low (1) 1.65                                                                  |
|                                | Median (2) 0.81                                                               |
|                                | High (3) 3.33                                                                |
|                                | 100 kHz 14.14                                                                |
|                                | 2 MHz 15.58                                                                  |
|                                | 7.41                                                                        |
|                                | 3.88                                                                        |
| Readout time (s) per frame     | Bin mode                                                                     |
|                                | 100 kHz 36.45                                                                |
|                                | 2 MHz 2.265                                                                  |
|                                | 9.521                                                                       |
|                                | 2.595                                                                       |
|                                | 0.738                                                                       |
|                                | 0.288                                                                       |
|                                | 16 × 16                                                                      |
|                                | 100 kHz 9.452                                                                |
|                                | 2 MHz 0.956                                                                  |
|                                | 0.458                                                                       |
|                                | 0.249                                                                       |
|                                | 0.154                                                                       |

Fig. 8 Linearity of the CCD. The left and right panels illustrate linearity in the CCD for slow readout and fast readout modes, respectively. The solid lines show the linear least squares fitting.

5 PHOTOMETRIC CALIBRATION

In order to compare data acquired with different telescopes and instruments, photometric calibration must be done, i.e., to convert instrumental magnitudes into standard systems. The transformation coefficients for the Johnson-Cousins UBVRI system are measured and reported in the current work.
Fig. 9 Standard magnitude (Landolt) versus calibrated magnitude from derived transformation equations for $UBVRI$ bands. The observations were done on 2008 October 24. The $U$, $B$, $R$ and $I$ calibrated magnitudes were shifted by $2$, $1$, $-1$ and $-2$ magnitudes, respectively for clarity. Solid lines are the best linear fit for the data points.

The transformation equations are defined as follows:

$$U_{\text{inst}} = U_{\text{std}} + Z_U + K'_U X + C_U(U - B)_{\text{std}}, \quad (4)$$

$$B_{\text{inst}} = B_{\text{std}} + Z_B + K'_B X + C_B(B - V)_{\text{std}}, \quad (5)$$

$$V_{\text{inst}} = V_{\text{std}} + Z_V + K'_V X + C_V(B - V)_{\text{std}}, \quad (6)$$

$$R_{\text{inst}} = R_{\text{std}} + Z_R + K'_R X + C_R(V - R)_{\text{std}}, \quad (7)$$

$$I_{\text{inst}} = I_{\text{std}} + Z_I + K'_I X + C_I(V - I)_{\text{std}}, \quad (8)$$

where $U_{\text{inst}}, B_{\text{inst}}, V_{\text{inst}}, R_{\text{inst}}$ and $I_{\text{inst}}$ are the instrumental magnitudes, $U_{\text{std}}, B_{\text{std}}, V_{\text{std}}, R_{\text{std}}$ and $I_{\text{std}}$ are the standard magnitudes, $Z_U, Z_B, Z_V, Z_R$ and $Z_I$ are the zero points of the transformation equations, $K'_U, K'_B, K'_V, K'_R$ and $K'_I$ are the first-order extinction coefficients, $C_U, C_B, C_V, C_R$ and $C_I$ are the color terms in the transformation equations, and $X$ denotes the airmass.

To derive the above parameters, we observed many Landolt standards (Landolt 1992) with a wide range of color on photometric nights covering a large range of airmass. Many standards were observed on eight nights from 2008 to 2013. All the images were reduced by standard photometry steps, and the same aperture radius of $7''$ as Landolt (1992) was used for photometry, then the instrumental magnitudes and the airmass were obtained. The standard magnitudes and colors are taken from Landolt (1992), so all the parameters could be solved by linear regression. The second-order extinction coefficients were found to be small, so we ignored them in this paper.

Figure 9 shows the relationship between the Landolt standard magnitude and the shifted calibrated magnitude using transformation coefficients derived from observations taken on 2008 October 24. It is shown that the slopes of all the fitted lines are quite close to 1.0, so the calibration is quite good and no systematic errors are recognized.

All the calculated transformation coefficients for these eight photometric nights are listed in Table 2. The observation dates are listed in the first column in Table 2. The filter names, zero points ($Z$), first order extinction coefficients ($K'$), color terms ($C$), the numbers of standards observed on that night ($N_{\text{std}}$), the numbers of observations per night ($N_o$), median night sky brightness on that night ($B_{\text{Sky}}$), average system throughput on that night, range of airmass (minimum~maximum) and color (minimum~maximum) are listed in the following.
| Date       | Filter | $Z$   | $K'$ | $C$  | $N_p$ | $N_{sky}$ | $B_{sky}$ | Throughput | Airmass | Color |
|------------|--------|-------|------|------|-------|-----------|-----------|------------|---------|-------|
| 2008–10–24 | $U$    | 4.826 &pm; 0.096 | 0.645 &pm; 0.005 | −0.019 &pm; 0.002 | 20 | 21 | 19.00 | 5.9 | 1.2−2.3 | −1.13−1.19 |
| 2008–11–29 | $U$    | 4.476 &pm; 0.035 | 0.844 &pm; 0.001 | −0.175 &pm; 0.001 | 5 | 22 | 19.96 | 6.8 | 1.2−2.0 | −0.98−0.14 |
| 2010–03–10 | $I$    | 3.688 &pm; 0.058 | 1.039 &pm; 0.002 | −0.163 &pm; 0.001 | 17 | 16 | 20.29 | 4.35 | 1.1−1.8 | −1.11−1.31 |
| 2010–10–09 | $U$    | 4.956 &pm; 0.097 | 0.650 &pm; 0.003 | −0.090 &pm; 0.002 | 9 | 16 | 18.90 | 5.1 | 1.1−2.2 | −1.19−2.23 |
| 2011–03–04 | $I$    | 5.180 &pm; 0.167 | 0.810 &pm; 0.003 | −0.209 &pm; 0.001 | 21 | 28 | 19.29 | 4.2 | 1.1−1.8 | −1.11−1.31 |
| 2012–02–18 | $U$    | 3.728 &pm; 0.051 | 0.881 &pm; 0.005 | −0.232 &pm; 0.001 | 17 | 9 | 20.44 | 9.95 | 1.1−1.9 | −1.11−1.21 |
| 2013–04–11 | $U$    | 4.180 &pm; 0.125 | 0.814 &pm; 0.002 | −0.194 &pm; 0.001 | 12 | 24 | 19.77 | 10.9 | 1.3−2.5 | −1.12−1.32 |
| 2013–08–31 | $I$    | 4.385 &pm; 0.515 | 0.538 &pm; 0.003 | −0.379 &pm; 0.001 | 8 | 26 | 19.63 | 7.1 | 1.1−2.5 | −1.19−2.31 |

Table 2 All the Calculated Transformation Coefficients and Related Parameters

| Date       | Filter | $Z$   | $K'$ | $C$  | $N_p$ | $N_{sky}$ | $B_{sky}$ | Throughput | Airmass | Color |
|------------|--------|-------|------|------|-------|-----------|-----------|------------|---------|-------|
| 2008–10–24 | $I$    | 3.017 &pm; 0.037 | 0.121 &pm; 0.001 | −0.037 &pm; 0.001 | 24 | 19 | 17.07 | 26.9 | 1.2−2.5 | −0.12−0.93 |
| 2008–11–29 | $I$    | 3.239 &pm; 0.038 | 0.128 &pm; 0.001 | −0.044 &pm; 0.001 | 3 | 10 | 18.06 | 14.3 | 1.2−2.1 | −0.26−0.63 |
| 2010–03–10 | $I$    | 3.512 &pm; 0.025 | 0.203 &pm; 0.001 | −0.054 &pm; 0.001 | 19 | 18 | 17.67 | 29.0 | 1.1−1.9 | −0.30−2.79 |
| 2010–10–09 | $I$    | 2.935 &pm; 0.039 | 0.190 &pm; 0.002 | −0.016 &pm; 0.001 | 11 | 16 | 17.23 | 19.0 | 1.1−2.6 | −0.33−2.27 |
| 2011–03–04 | $I$    | 3.031 &pm; 0.114 | 0.287 &pm; 0.005 | −0.058 &pm; 0.001 | 16 | 11 | 14.63 | 17.6 | 1.1−1.8 | −0.30−2.79 |
| 2012–02–18 | $I$    | 2.563 &pm; 0.032 | 0.165 &pm; 0.001 | −0.058 &pm; 0.001 | 23 | 35 | 17.76 | 31.8 | 1.1−2.0 | −0.30−3.48 |
| 2013–04–11 | $I$    | 2.957 &pm; 0.055 | 0.136 &pm; 0.001 | −0.085 &pm; 0.001 | 13 | 24 | 17.30 | 20.0 | 1.3−2.6 | −0.29−2.97 |
| 2013–08–31 | $I$    | 2.867 &pm; 0.083 | 0.246 &pm; 0.001 | −0.050 &pm; 0.001 | 13 | 51 | 17.88 | 21.9 | 1.1−2.7 | −0.33−2.40 |

mean 4.427 &pm; 0.548 | 0.778 &pm; 0.159 | −0.183 &pm; 0.105

mean 2.644 &pm; 0.378 | 0.537 &pm; 0.101 | −0.138 &pm; 0.036

mean 2.670 &pm; 0.296 | 0.331 &pm; 0.054 | 0.064 &pm; 0.033

mean 2.392 &pm; 0.271 | 0.241 &pm; 0.039 | 0.115 &pm; 0.049

mean 2.890 &pm; 0.243 | 0.185 &pm; 0.059 | −0.050 &pm; 0.020
The average of the first-order extinction coefficient is 0.778, 0.537, 0.331, 0.241 and 0.158 mag/airmass for bands $U$, $B$, $V$, $R$ and $I$, respectively. We are not surprised that they are larger than those of Xinglong station (Huang et al. 2012), Lulin and other places that are the best sites in the world (see table 4 and references in Kinoshita et al. 2005) because of the low elevation of WHO. They are similar to those at Xuyi station (Zhang et al. 2013). The color term of each band is close to the results from TNT and LOT. The mean values of each band are listed in Table 2 as well. The byproducts of photometry calibration are night sky brightness and system throughput. The night sky brightness was given in Section 3, and the system throughput will be illustrated in Section 6.

6 PERFORMANCE OF THE SYSTEM

6.1 System Throughput

The total throughput of the entire optical system can be estimated by observing a series of standard stars. The throughput involves the telescope optics, filter response, quantum efficiency of the detector and atmospheric transmission. Following Kinoshita et al. (2005), measurements of the system throughput for WHOT in each band were done on photometric nights. As shown in Col. 9 of Table 2, the throughput is not constant, which may be due to a change in hardware, dust, variations in atmospheric extinction and so on. The total throughput on 2011 March 4 was quite low, because the optical instruments were not cleaned for almost two years. The median throughput of WHOT is 6.4%, 15.6%, 24.2%, 27.2% and 19.5% in the $U$, $B$, $V$, $R$ and $I$ bands, respectively, and the peak throughput is 10.9%, 27.0%, 38.8%, 38.8% and 31.8% in the $U$, $B$, $V$, $R$ and $I$ bands, respectively.

6.2 Limiting Magnitude and Photometric Precision

Equation (9) can be used to calculate the SNR of one object observed by the CCD camera (Howell 2000)

$$\text{SNR} = \frac{N_s}{\sqrt{N_s + n_{\text{pix}}(N_S + N_D + N_R^2)}}$$

(9)

where $N_s$ is the total number of photons collected by the CCD from the object. It can be calculated by the flux density corresponding to zero magnitude of a specific filter (Bessell 1979), if we know the throughput of our telescope and the atmospheric extinction. $N_S$ is the total number of photons in each pixel from the sky background, which can be obtained when the night sky brightness is known. $N_D$ is the ADU dark current per pixel per second and $N_R$ is the readout noise from the CCD camera, which are both specifications of the CCD camera. $n_{\text{pix}}$ is the pixel area considered for the SNR calculation, which is related to the seeing of the observation. The photometric error can be given from the SNR by Equation (10) (Howell 2000)

$$\delta = \frac{1.0857}{\text{SNR}}$$

(10)

where $\delta$ is the photometric error for the object. So, the photometry error can be simulated according to Equations (9)–(10). To check the reliability of the simulation, we reduced 60 s exposure observations of M67 in the $U$, $B$ and $V$ bands that were taken on 2012 February 18 and in the $R$ and $I$ bands on 2013 April 11. All the sources with SNR higher than 2 were extracted, then their brightness and photometry error were obtained by standard procedures used in photometry, and the calibration was done using M67 standards given by Dr. Arne Henden3.

The relationship between the brightness and the photometry error is shown in Figure 10. The curves that show photometry error versus brightness in five bands, which were simulated using the same night sky brightness, atmospheric extinction coefficients, throughput, exposure time and

3 http://binaries.boulder.swri.edu/binaries/fields/m67.ids.txt
Fig. 10 Photometry error versus the brightness of sources. Purple solid diamonds, blue squares, yellow solid circles, red triangles and green stars illustrate the measurement from fields with M67 using $U$, $B$, $V$, $R$ and $I$ bands, respectively. Solid lines show the simulation result.

Fig. 11 Left panel: The actual photometry accuracy of WHOT for the $V$ band with a 60 s exposure. Right panel: Differential magnitude light curves for comparison stars in exoplanet transit in the fields with HAT-P-33 (blue line) and blazar BL Lac (black, red and green lines are for the $V$, $R$ and $I$ bands, respectively).

airmass as the observations, are also plotted by solid lines in Figure 10. We can see that the simulation fits the observations very well, so the simulation is reliable.

To evaluate the observation ability of WHOT, the simulation was done with a 300 s exposure at zenith, using the average extinction coefficients, the median night sky brightness, the median seeing value (using the radius of 2.5 times that of the seeing area in the SNR calculation) and the peak efficiency of WHOT. Under the same observation conditions as the simulation was done, the limiting magnitude with respect to SNR of 100 and 300 s exposures is 15.7, 16.7, 16.2, 16.1 and 15.9 mag for the $U$, $B$, $V$, $R$ and $I$ bands, respectively. The limiting magnitude is much brighter than that of TNT (Huang et al. 2012) and the 85-cm (Zhou et al. 2009) telescope at Xinglong station because of the brighter night sky brightness and larger atmospheric extinction at WHO. We have to focus on some projects with bright targets for WHOT, but we should point out that we did not
use the smallest extinction coefficients and the darkest night sky brightness at WHO to simulate the
limiting magnitude, so the limiting magnitude will be at least half a magnitude deeper than what we
reported here if we use them.
To estimate the internal photometric accuracy of WHOT, two 60-s exposures were done centered
on NGC 7790 in $V$ on 2010 October 9. The airmass of the two observations was 1.24 and 1.09, and
the time interval was about two and half hours. Photometry of all sources with SNR higher than 2
was obtained and calibrated. The differences in magnitude for the same source in two images were
calculated, and plotted against the mean of the two measurements, as shown in the left panel of
Figure 11. The accuracy in this case was underestimated, especially for the fainter objects because
the set of optics was dusty. According to the operations log, they had not been cleaned for two years.

Observations of blazars and transiting planets can also be used to estimate precision of differen-
tial CCD photometry. HAT-P-33 was monitored in $V$ for more than 7 h during one of its planetary
transit events on 2013 January 13, with an exposure time of 50 s. The differential light curve between
two quiet reference stars ($V_1 = 10.55$ mag and $V_2 = 10.72$ mag) in the HAT-P-33 FOV is shown in
the right panel of Figure 11 as a blue solid line. The standard deviation of the light curve can be used
to estimate the photometric precision (Zhou et al. 2009; Mao et al. 2013). The photometric precision
is 0.0043 mag for $V \approx 11$ mag with a 50 s exposure from HAT-P-33 observations. Only the $V$
filter was used for the transit observation, so the same analysis was performed for two reference stars close
to BL Lac in the $V$, $R$ and $I$ bands. The reduced differential light curves between B and C (Smith
et al. 1985) are plotted in the right panel of Figure 11. The photometric precision is 0.0097, 0.0073
and 0.0082 mag in the $V$ ($\approx 14.2$ mag), $R$ ($\approx 13.7$ mag) and $I$ ($\approx 13.2$ mag) bands, respectively. There
are no such observations in the $U$ and $B$ bands, so we did not give the photometric precision in these
two bands. The photometric precision depends on the brightness of the target, exposure time and the
observation conditions, but based on our measurements, it is generally smaller than 0.01 mag with
appropriate setup under photometric conditions.

7 SUMMARY

In order to let astronomers understand and make good use of WHOT for their scientific observation
research, we introduce the photometric system of WHOT, and evaluate its performance, and the site
conditions of WHO in this paper. The image quality of the optical system is good and uniform over
the detector. The detector has a very good linearity until a count of $\sim 50 000$, and has low dark current
due to a low working temperature. According to the observation log in the past 6 years, the seeing
has a median value of $\sim 1.7''$, and is smaller than 2.0'' in more than 85% of observation nights. No
obvious seasonal change in seeing is found. The average number of clear nights at WHO is 155 per
year, and the average observational time per year is 1126 h. Summer is the worst season, with only
about 8.7 usable nights per month. The darkest night sky brightness at WHO is 20.99, 20.17, 18.90,
18.95 and 19.11 mag arcsec$^{-2}$ in the $U$, $B$, $V$, $R$ and $I$ bands, respectively, which are much brighter
than those at other astronomical sites. Photometric calibrations were performed using observations
of standard stars taken in eight photometric nights. The average first-order atmospheric extinction
coefficients are larger than those of Xinglong station and LOT, due to the low elevation of WHO, but
the color terms are consistent with those of Xinglong station and LOT. The peak system throughput
is 10.9%, 27.0%, 38.8%, 38.8% and 31.8% in the $U$, $B$, $V$, $R$ and $I$ bands, respectively. The limiting
magnitude with respect to SNR of 100 and 300 s exposures is 15.7, 16.7, 16.2, 16.1 and 15.9 mag
for the $U$, $B$, $V$, $R$ and $I$ bands, respectively. The photometric precision is 4.3 mmag or better for
$V \approx 11$ mag with a 50 s exposure, and the photometric precision is 9.7, 7.3 and 8.2 mmag in the
$V$($\approx 14.2$ mag), $R$ ($\approx 13.7$ mag) and $I$ ($\approx 13.2$ mag) bands, respectively.

Acknowledgements We are very grateful to the referee for insightful comments and valuable sug-
gestions that improved this paper. We owe great thanks to all the staff working at WHO who made
great efforts in operating the telescope and taking observations. We thank Profs. Gang Zhao and
Xiaojun Jiang for their help in building and running WHO. This research is supported by the National Natural Science Foundation of China and the Chinese Academy of Sciences joint fund on astronomy (Nos. 10778701 and 10778619) and by the National Natural Science Foundation of China (Nos. 11203016, 11333002 and 11143012). This work is partly supported by the Natural Science Foundation of Shandong Province (No. ZR2012AQ008).

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