Postprint of the Study on Photometric Precision Evaluation of the Jilin 280mm Rotatable All-Sky Photoelectric Array

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Abstract

The 280mm all-sky rotatable photoelectric array at the Jilin Astronomical Observation Base is a facility designed for space debris survey observations. To investigate its photometric performance and evaluate its photometric accuracy, photometric standard stars within the M67 open cluster—a designated photometric calibration field—were selected for observation. The observed images were first preprocessed in IRAF, followed by differential photometry. Photometric data were then extracted and subjected to least-squares linear fitting across the entire night' s dataset. The fitting results yielded the primary extinction coefficient and corresponding system transformation coefficients, establishing the conversion formula from instrumental magnitudes to standard magnitudes. Finally, the photometric accuracy of the equipment was assessed using the calculated root mean square error. The results indicate that on a standard photometric night, the array achieves a photometric accuracy of 0.13 magnitudes for stars brighter than magnitude 13.8. Simultaneously, the observed images were cross-matched and identified with the UCAC2 catalog, and UCAC2 standard stars among the background stars were utilized for external accuracy verification, yielding results essentially consistent with the former. The photometric accuracy of this equipment basically meets the requirements for space debris survey observations.

Full Text

Study on Photometric Accuracy Evaluation of the 280 mm Rotatable Photoelectric Array in Jilin Astronomical Observation Base

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Abstract: The 280 mm all-sky rotatable photoelectric array located at the Jilin Astronomical Observation Base is a facility dedicated to space debris survey observations. To investigate its photometric performance and evaluate its measurement accuracy, we observed photometric standard stars in the M67 open cluster, a recognized photometric calibration field. After preprocessing the images using IRAF, differential photometry was performed. Photometric data were extracted and subjected to least-squares linear fitting across the entire night, yielding the primary extinction coefficient and corresponding system transformation coefficients, from which the conversion formula from instrumental to standard magnitudes was derived. Finally, the root-mean-square error was calculated to assess the photometric precision of the instrument. Results indicate that under standard photometric conditions, the 280 mm all-sky rotatable photoelectric array achieves a photometric accuracy of 0.13 magnitudes for stars brighter than 13.8 mag. Additionally, by matching observed images with the UCAC2 catalog and using UCAC2 standard stars among background stars for external verification, we obtained essentially identical results. The photometric accuracy of this instrument essentially meets the requirements for space debris survey observations.

Keywords: photometric accuracy; survey observation; standard stars; transformation formula; UCAC2 catalog

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The 280 mm all-sky rotatable photoelectric array belongs to the Changchun Artificial Satellite Observation Station of the National Astronomical Observatories, Chinese Academy of Sciences, and is situated at the Jilin Astronomical Observation Base in Jilin Province. Conventional observation modes where a single instrument can only track one target at a time severely limit the cataloging capability for space objects, prompting the emergence of wide-field, multi-target photoelectric telescope array observation modes. Currently, large-area survey observation facilities are increasingly common internationally, and optical survey observations not only improve observation efficiency but also yield more spatial target parameters, making such instruments extremely valuable. This photoelectric array consists of four 280 mm refracting optical telescopes and two T-shaped mount equatorial systems. Actual measurements demonstrate that the pointing accuracy of this equipment is better than 9 arcseconds in both right ascension and declination, while the tracking measurement accuracy shows average errors of 0.9 arcseconds in right ascension and 1 arcsecond in declination. Each telescope has an effective aperture of 280 mm $\pm$ 2 mm and is equipped with a scientific-grade CMOS camera featuring 4096\$$\times$\$4096 pixels with a pixel size of 9 m $\times$ 9 m and quantum efficiency no less than 70%. All four telescopes share identical design parameters and exhibit essentially consistent photometric performance compared to a single telescope, with the primary difference being a substantially expanded sky coverage area. Although unavoidable mechanical errors exist in alignment, unified terminal control ensures coordination among the telescopes. The observation field of view covers 160 square degrees, and under 19-magnitude sky conditions, the system can detect targets brighter than 16.5 magnitudes.

With the increasing proliferation of space debris, the safe operation of on-orbit spacecraft faces severe threats, necessitating observations to obtain positional and orbital information of space debris for collision warning, effective spacecraft avoidance, and debris cataloging. Optical observation of medium- and high-altitude space debris holds broad prospects for target detection, tracking, and identification. Continuous photometric observations of space debris using ground-based telescopes can capture characteristics of brightness and positional variations, enabling studies of target shape, size, and operational attitude. This equipment implements a movable blind-scanning observation mode that reduces operator workload, enables batch capture of space targets, and enhances cataloging and orbit determination capabilities. The primary function of the 280 mm all-sky rotatable photoelectric array is space debris survey observation, with a design wavelength of 650 nm and apochromatic correction from 500 nm to 800 nm. To ensure the detection capability for faint space targets, no filter was installed. Therefore, evaluating the photometric accuracy of this instrument in the visible band is highly significant. This study selects the M67 open cluster as the photometric calibration field, observes standard stars within the cluster to determine the primary extinction coefficient, establishes the conversion relationship between the instrumental magnitude system and the standard system, reduces observed instrumental magnitudes to extra-atmospheric standard magnitudes for comparison with standard values, and calculates the root-mean-square error to evaluate the photometric accuracy.

2. Observation and Data Processing

The 280 mm photoelectric array currently employs a short-exposure survey observation mode, where it points to specific sky areas according to predictions for imaging. Observation targets primarily concentrate on medium-high orbit and geosynchronous space objects, so the parameters for space target and stellar observations are essentially identical. Typically, ground-based telescope photometric system performance studies use Landolt standard stars as observation targets. However, for telescopes of several tens of centimeters aperture with large fields of view containing numerous background stars, observing single target stars is impractical. Moreover, space debris positions and attitudes constantly change, with photometric information varying continuously, making them unsuitable as calibration targets. Based on these characteristics, this study selects an open cluster as the observation target. Messier 67 (M67 or NGC 2682, hereafter referred to as M67) is an open cluster in Cancer containing approximately 500 members with a non-dense star field and brightness concentrated around 10–11 magnitudes, making it an ideal photometric calibration field. Our photometric work was conducted in this cluster using the photometric standard star catalog provided by the American Association of Variable Star Observers (AAVSO), selecting 10 standard stars for photometry as shown in . The website also provides queries for variable stars in M67, which will not be elaborated here.

We conducted all-night observations of the selected standard stars on December 6, 7, and 8, 2020, with stable weather conditions on these nights. Imaging began when M67 transited and descended to an altitude of 60°, where moonlight had negligible impact on photometry. Ten images were taken every 0.1 airmass with an exposure time of 2 seconds per image, continuing until the cluster descended to approximately 30° altitude. According to the plane-parallel atmospheric model theory, when zenith distance z < 75°, airmass M(z) sec(z), and the airmass varied significantly from 1.1 to 2.0 throughout the observation sequence.

After obtaining the observational data, we performed bias subtraction, dark current correction, and flat-field correction on the images using IRAF. Differential photometry was then applied to the preprocessed images to obtain instrumental magnitudes of the standard stars under different airmass conditions. Combined with the standard magnitudes in , we determined the primary extinction coefficient and system transformation coefficients.

2.1 Determination of Main Extinction Coefficient

At high altitudes, the atmosphere can be approximated as an ideal plane-parallel layer. Under this assumption, the extinction magnitude of a celestial object is proportional to the extinction path length, leading to the atmospheric extinction formula:

$$\Delta m = k' \cdot M(z)$$

where $\Delta m = m_z - m_0$ represents the magnitude difference between the observed apparent magnitude m_z at zenith distance z and the extra-atmospheric apparent magnitude m_0, k' is the primary extinction coefficient, and $M(z)$ is the airmass at zenith distance z. Atmospheric extinction is related to color index, so the extinction coefficient k typically includes two components: a wavelength-independent primary extinction coefficient k' and a secondary extinction coefficient k'' related to color index C. Since the 280 mm all-sky rotatable photoelectric array telescopes have no filters installed and k'' is much smaller than k' and generally negligible, we consider only the primary extinction coefficient representing direct atmospheric attenuation of stellar brightness. The extinction formula thus simplifies to the linear relationship shown above.

Using magnitude difference $\Delta m = m_z - m_0$ as the vertical axis and airmass $M(z)$ as the horizontal axis, we performed least-squares fitting on the entire night' s photometric data to improve fitting accuracy. [Figure 1: see original paper] presents the data fitting for December 6–8, 2020, simultaneously determining the atmospheric extinction coefficient k', which corresponds to the slope of the fitted line, with results listed in .

2.2 Determination of System Transformation Coefficients

Instrumental magnitudes obtained from observations must be corrected for atmospheric extinction to yield extra-atmospheric instrumental magnitudes. To make these results comparable with standard magnitudes, conversion to the standard magnitude system is required. Since no filter was installed, we consider only the conversion from observed to standard system magnitudes using the following transformation equation:

$$V = v_0 + \varepsilon \cdot (B - V) + \xi$$

where V is the standard magnitude, v_0 is the extra-atmospheric instrumental magnitude, ε is the system transformation coefficient, $(B - V)$ is the standard color index, and ξ is the constant term. Similar to the method for determining the primary extinction coefficient, we used least-squares fitting to determine the transformation coefficients ε and ξ, with results presented in .

After applying atmospheric extinction correction and system transformation to the instrumental magnitudes, we obtained the comprehensive magnitude transformation formula:

$$V = v - k' \cdot M(z) + \varepsilon \cdot (B - V) + \xi$$

3. Photometric Accuracy Analysis

We applied atmospheric extinction correction and system transformation to the instrumental magnitudes of observed targets in M67, then calculated differences with corresponding standard magnitudes V. The root-mean-square error was computed to evaluate photometric precision:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(V_{\mathrm{std},i} - V_{\mathrm{trf},i})^2}{n}}$$

Figure 2: see original paper(b)(c) display comparisons between transformed magnitudes and standard magnitudes for M67 observations on December 6, 7, and 8, 2020, respectively. The diagonal slopes of 1.026, 1.031, and 1.051 indicate that the transformed magnitudes closely match the standard magnitudes. Under standard photometric conditions, the photometric accuracy reaches 0.13 magnitudes for stars brighter than 13.8 mag. Photometric accuracy is influenced by multiple factors, such as urban light pollution. For the 280 mm telescope, the primary limitation is the absence of filters, which causes the instrumental

magnitudes obtained from standard stars to not strictly correspond to the V band, representing the main source of error.

Since the 280 mm telescope is used for space debris survey observations where background stars appear randomly in the field of view, selecting background stars for external accuracy assessment is highly valuable. In this work, we utilized the UCAC2 catalog, which contains 48,330,571 stars covering a wide sky area, reaching up to +52° in some regions. All stars in the catalog provide proper motion and photometric measurements with positions given in the J2000.0 epoch. Users can query the catalog through FORTRAN and C language interfaces provided by UCAC2.

On December 10, 2020, we conducted survey observations of the sky region near M67 using the 280 mm telescope. The observed images were matched with the UCAC2 catalog to identify UCAC2 standard stars in the field, and a batch of UCAC2 standard stars with brightness ranging from 9.76 to 14.79 magnitudes was selected for photometric accuracy evaluation, as shown in . Instrumental magnitudes obtained from observations were transformed using the above equation and compared with standard magnitudes from the catalog. The results are presented in Figure 2: see original paper with a diagonal slope of 1.081, and the RMSE values are listed in .

[Figure 2: see original paper] Relations between transformed magnitudes (V_{trf}) and standard magnitudes (V_{std}). (a)(b)(c) Comparisons for M67 member stars on December 6, 7, and 8, 2020; (d) Comparison for UCAC2 catalog members.

The calculations demonstrate that the linear correlation coefficient between transformed instrumental magnitudes and standard magnitudes approaches 1. Under standard photometric conditions, the photometric accuracy reaches 0.14 magnitudes for stars brighter than 14.8 mag, essentially identical to the accuracy obtained from M67 standard stars.

Conclusion

This study scientifically evaluated the photometric accuracy of the 280 mm all-sky rotatable photoelectric array, demonstrating that under standard photometric conditions, the instrument achieves a photometric accuracy of 0.13 magnitudes for stars brighter than 13.8 mag—an excellent result. The telescope operates without filters because the equipment is primarily used for space debris survey observations, and filter installation would compromise detection of faint space targets. Operating without filters maximizes the detection capability of the photoelectric array. The instrument' s advantage lies in utilizing its wide field of view for space debris monitoring, and the above accuracy assessment results meet the precision requirements for space debris survey observations. Additionally, by matching survey images with the UCAC2 catalog and using UCAC2 member stars for external accuracy verification, we obtained a photometric accuracy of 0.14 magnitudes for stars brighter than 14.8 mag under standard conditions, confirming that the photometric system of the 280 mm all-sky rotatable photoelectric array exhibits good stability and reliability.

While completing the photometric accuracy assessment, we also determined the primary extinction coefficient for the Jilin observation base. However, measuring extinction coefficients for an observatory is a long-term process, so our results represent a preliminary determination. Future work will improve observation methods and utilize other equipment at the Jilin observation base to observe standard stars under better photometric conditions, thereby determining more precise atmospheric extinction coefficients.

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