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Digitizer of astronomical plates of Shanghai Astronomical Observatory and its performance test *

Yong Yu[1], Jian-Hai Zhao[1], Zheng-Hong Tang[1], Zheng-Jun Shang[1]

Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
yuy@shao.ac.cn

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Abstract Before CCD detectors were widely employed in observational astronomy, the main method of detection was the use of glass astrophotographic plates. Astronomical plates has recorded the information of the position and the activity of celestial bodies for more than 100 years. There are about 30,000 astronomical plates in China, and the digitization of astronomical plates is of great significance for permanent preservation and the full use of these valuable observation data. A digitizer with high precision and high measuring speed is the key equipment to carry out the digitization task of these astronomical plates. A digitizer for glass astrophotographic plates was developed jointly by Shanghai Astronomical Observatory and Nishimura Co. Ltd of Japan. The manufacturing of the digitizer hardware was undertaken by Nishimura Co. Ltd, and the performance test, error corrections as well as image processing of the digitizer was carried out by Shanghai Astronomical Observatory. The main structure and working mode of the digitizer are introduced in this paper. Performance test shows that the brightness uniformity of illumination within the measuring area is better than 0.15%,the repeatability of digitizing positions is better than 0.2 μm and the repeatability of digitizing brightness is better than 0.01 instrumental magnitude. The systematic factors affecting digitizing positions, such as the lens distortion, the actual optical resolution, the non-linearity of guide rails and the non-uniformity of the linear motors of mobile platform, the deviation of image mosaic, and the non-orthogonality between the direction of scanning and camera linear array, are calibrated and evaluated. Based on an astronomical plate with the size of 300 mm $\times$ 300 mm, which was digitized at different angles, the conversion residuals of the positions of the common stars on different images were investigated. The results show that the standard deviations of the residuals are better than 0.9 μm and the residual distribution is almost random, which proves the digitizer has a higher digitization precision.

Key words: astrometry — instrumentation: detectors — methods: data analysis — techniques: image processing

1 INTRODUCTION

Before CCD detectors were widely employed in observational astronomy, the main method of detection was the use of glass astrophotographic plates. Astronomical plates hold the information of the position

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and the activity of celestial bodies for more than 100 years, and they were non-reproducible record of observations. The information on astronomical plates can be used not only as a basis of the modern CCD observations, but also in some astronomical research, such as solar dynamics (Kavelaars (2004)), stellar kinematics (Hog et al. (2000)), long-period binary stars, multiple-star system dynamics (Torres & Stefanik (2000)) and the light variability of the celestial bodies with long time scales (Fresneau et al. (2001)), and so on. According to statistics, there are about 30,000 astronomical plates in China. At present, most of these plates have been centrally preserved in Sheshan Astronomical Plate Library of Shanghai Astronomical Observatory.

Due to its special physical and chemical properties, the astronomical plate are very hard to preserve. Once the preservation conditions are not ideal, the astronomical plate is prone to mildewing, falling film off, or even scrapping the entire. In addition, the vast majority of astronomical plates have not been digitized yet, which restricts the value of the observation data to exert. Therefore, the digitization of astronomical plates is extremely significant for permanent preservation and the full use of these valuable observations. Thus the International Astronomical Union (IAU), since 2000, has had a working group dedicated to the Preservation and Digitization of Photographic Plates (PDPP). This working group asked all observatories around the world to digitize their plates as soon as possible. As a result, a project was launched in China in 2012 to digitize the 30,000 plates available in all Chinese Observatories in the next five years. The digitizer of glass astrophotographic plates with high precision and high measuring speed is the key equipment to carry out this project.

In the past, domestic scholars have ever adopted Photometric Data Acquisition System (PDS) to collect the information of some astronomical plates (Yan et al. (1986), Mao et al. (1993), Wang et al. (1996)). However, the measuring speed of PDS is very slow and it would take several hours (depending on size) to measure a plate, which limits the application of PDS in the digitization of astronomical plates. Using a commercial scanner to digitize astronomical plates seems a simple way, but the measuring accuracy of commercial scanners is difficult to guarantee. Especially in the scanning direction of a commercial scanner, there are random error of several microns and systematic error of tens of microns (Yan et al. (2016)). In order to improve the efficiency and accuracy of the digitization, in recent ten years, Harvard College Observatory and Belgian Royal Observatory have developed the digitizers of astronomical plates respectively (Simcoe et al. (2006), De Cuyper & Winter (2006)). Both digitizers use the method of block scanning to take a series of frames of the plate which are then stitched together in a mosaic to create an image of the whole plate. They are equipped with an air bearing and linear motor XY-table with micron accuracy, a doublesided telecentric lens and a stable light system of LED arrays, so as to ensure the digitization quality of astronomical plates.

Since 2013, Shanghai Astronomical Observatory and Nishimura Co. Ltd of Japan has jointly developed a brand-new digitizer for glass astrophotographic plates. The manufacturing of the digitizer hardware was undertaken by Nishimura Co. Ltd, and the performance test, error corrections as well as image processing of the digitizer was carried out by Shanghai Astronomical Observatory. After 2 years of development, the machine achieves the precision of better than 1 μm in digitization position, and 10 minutes is needed to digitize a plate of 300 mm $\times$ 300 mm, which meets the requirement of the digitization of astronomical plates. In section 2, we present the main structure and working mode of the digitizer. The tests of the digitizer performance are described in Section 3. Section 4 presents some conclusions.

2 MAIN STRUCTURE AND WORKING MODE OF THE DIGITIZER

The digitizer is settled in the inner laboratory of Sheshan Astronomical Plate Library and it is composed of a linear array camera, a doublesided telecentric lens, a mobile platform and a LED light system, etc., which are integrated and mounted on a marble platform that weighs 900kg, as shown in Figure 1. In order to avoid the influence of the vibration caused by operators movement during measuring process, the marble platform is placed on an independent cement base and kept in isolation with the outer layer. The cement base is embedded in the rock layer of Sheshan Mountain. Sheshan Astronomical Plate Library always maintains a constant temperature (25°C) and a constant humidity (50%) environment.

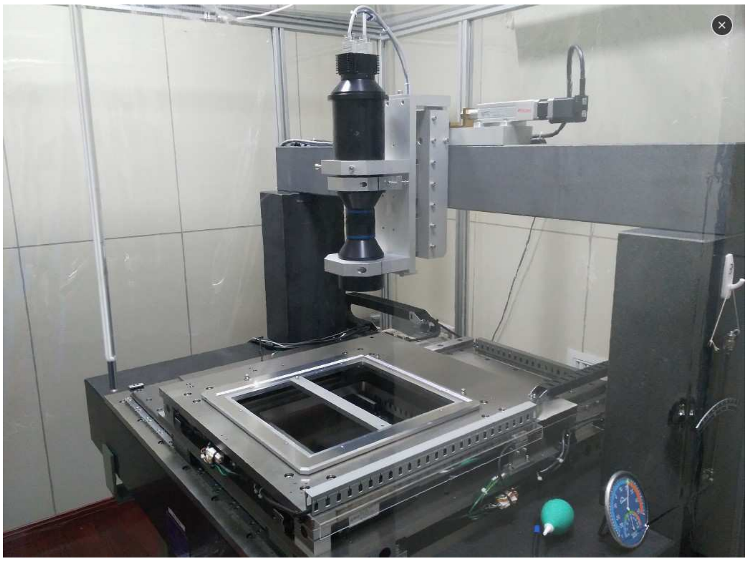

Fig. 1 Photo of the digitizer of astronomical plates of Shanghai Astronomical Observatory.

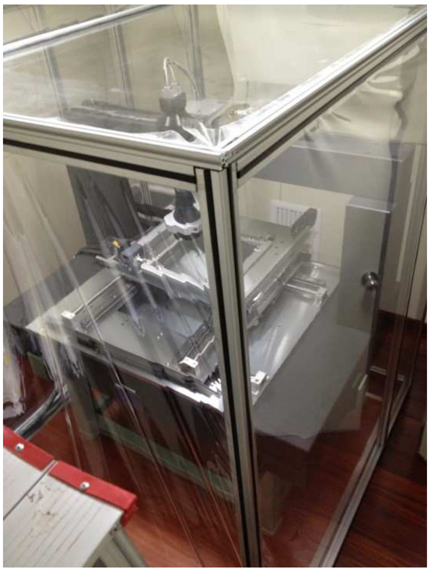

Fig. 2 Digitizer is covered with a customized plastic sheeting room to reduce the impact of the airflow from indoor air conditioning.

The digitizer is covered with a customized plastic sheeting room, as shown in Figure 2, so as to reduce the impact of the airflow from indoor air conditioning on the movement of the mobile platform further.

Different from the working mode adopted by the digitizers of Harvard College Observatory and Belgian Royal Observatory, the digitizer of Shanghai Astronomical Observatory uses the method of line scanning. During measuring process, the camera and the LED light system remain stable, and the mobile platform drives one astronomical plate to perform uniform linear motion along the scanning direction (Y). At the same time, the linear array camera exposes continuously to collect the information of the plate. The camera array is 2880 pixel, the pixel size is 10 μm, which makes the width of single data acquisition 28.8 mm. The total travel in scanning direction is 350 mm. In order to complete information collection of the whole astronomical plate, the mobile platform need to drive plate to do multiple step motions of 28.8 mm in the stitching direction (X). The continuous measuring is done for each step motion until the whole plate is covered. For example, the largest plates in Sheshan Astronomical Plate Library is about 300 mm $\times$ 300 mm in size, and it will take 9 step at least motions to cover the whole plates. Finally, the image mosaic technology is used to stitch all the strip images to a whole image. The entire process takes about 10 minutes.

3 PERFORMANCE TEST OF THE DIGITIZER

After the digitizer was developed in 2016, we carried out its performance test. Test includes illumination non-uniformity within the measuring area, the digitizing repeatability, the systematic factors affecting the digitizing positions, as well as the comprehensive test on the precision of the digitizing positions. Test tools include: (1) A glass calibration plate produced by American Edmund Company. Its effective size is 50 mm $\times$ 50 mm and there are 201 $\times$ 201 standard dots distributed evenly. The dot spacing is 0.25 mm and the position accuracy is 1um. (2) An astronomical plates taken by 40 cm telescope in 1981 at Beijing Astronomical Observatory (plate number is DA2849). Its size is 300 mm $\times$ 300 mm and there are about 3500 stars on the plate.

3.1 Illumination non-uniformity

The astronomical plate is digitized by means of transmission measurement, which requires the illumination within the measuring area to be as uniform as possible. In order to test the quality of illumination, an area of 288 mm $\times$ 288 mm was measured without placing any plate to obtain an image. The image is divided evenly into 20 $\times$ 20 regions and Figure 3 shows the distribution of the average grey value of each region. The maximum, the minimum and the mean value are 3290.7ADU, 3282.1ADU and 3287.0ADU respectively. Here $\frac{|maximum-mean|}{mean}$ and $\frac{|minimum-mean|}{mean}$ is used to evaluate the illumination non-uniformity, and it can be gotten that the illumination non-uniformity within the measuring area is better than 0.15%. From the Figure 3, it also can be seen that the darker regions are concentrated in the upper and lower edges of the image, which might due to the shading of the plate holder to the LED light.

3.2 Digitizing repeatability

Digitizing repeatability is the consistency among the successive digitization of the same object under the same condition, which reflects the internal accuracy of the equipment. The direct test of digitizing repeatability is to measure a plate repeatedly and calculate the standard deviation of the measured coordinates and brightness of the stars in multiple images. The standard deviation can reflect the digitizing repeatability. In order to reduce the influence of centering and photometric errors, the ideal scheme is using the digitization image of the calibration plate, since the image of the standard dot on the calibration plate is symmetrical with higher signal-to-noise ratio, as shown in Figure 4, which can ensure higher centering and photometric accuracy. However, the calibration plate is only 50 mm $\times$ 50 mm and cannot cover the entire measuring range, so we also use an astronomical plate with the size of 300 mm $\times$ 300 mm to test digitizing repeatability.

Both the 50 mm $\times$ 50 mm calibration plate and the 300 mm $\times$ 300 mm astronomical plate were digitized and measured repeatedly for 5 times. The standard deviations of the residuals of the measured coordinates and the brightness for all standard dots and stars on the plates were calculated. Figure 5 and Figure 6 displays the histograms of the standard deviations of the residuals of the measured coordinates in X and Y expressed in μm, and of the brightness expressed in instrumental magnitude, for all standard

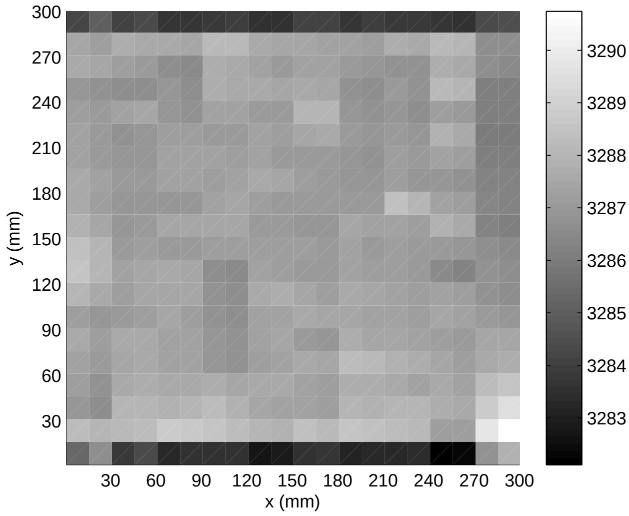

Fig. 3 Distribution of the average grey value of each region within the measuring area of 288 mm × 288 mm.

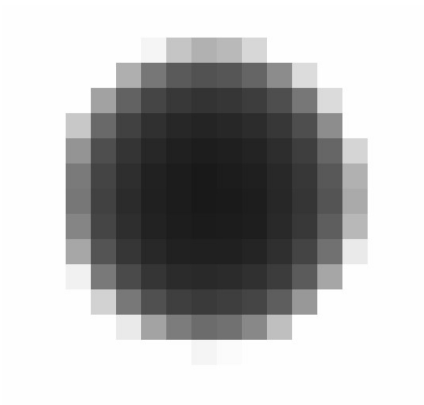

Fig. 4 Example of the standard dot on Edmund calibration plate.

dots and stars respectively. Table 1 lists the average values of the corresponding standard deviations. It can be seen that the digitizing repeatability in X and Y are almost the same. For the calibration plate, the position repeatability of the standard dots is about 0.03 μm, the brightness repeatability is about 0.001 instrumental magnitude. For the astronomical plate, the position repeatability of stars is about 0.2 μm, the brightness repeatability is about 0.01 instrumental magnitude. Considering the calculation error existed in centering and photometry for the stars on the astronomical plate, the digitizing repeatability of the machine itself should be better than the above values in the measuring range.

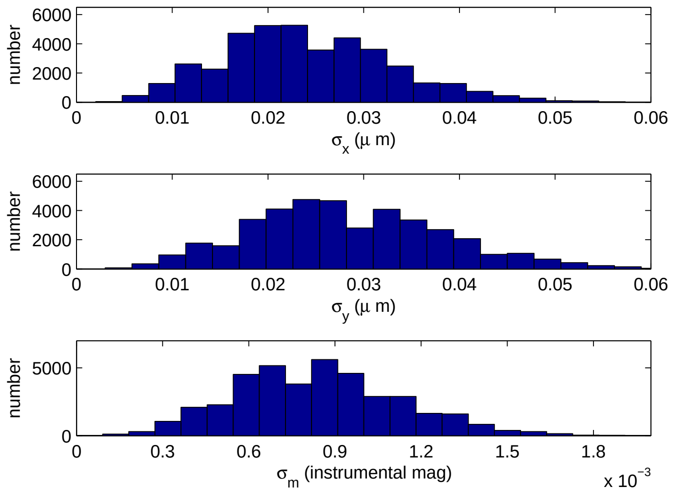

Fig. 5 Histogram of the standard deviations of the residuals of the measured coordinates and brightness for all standard dots on the standard plate with the size of 50 mm $\times$ 50 mm .

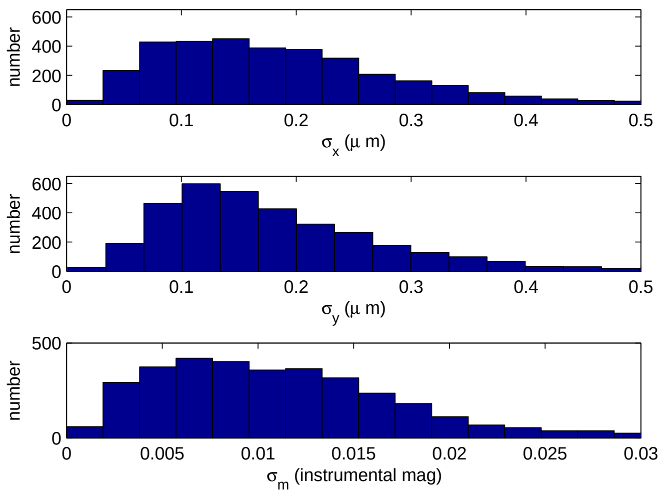

Fig. 6 Histogram of the standard deviations of the residuals of the measured coordinates and brightness for all stars on the astronomical plate with the size of 300 mm $\times$ 300 mm .

3.3 Systematic factors affecting digitizing positions

The optical and mechanical components of the digitizer contain manufacturing errors, and there are also installation errors inevitably in the integration process of all components, which may introduce systematic influence to digitization results. These factors include: the lens distortion, the actual optical

Table 1 Test results of digitizing repeatability

Object	Measuring range (mm)	$\overline{\sigma_x}$ (μm)	$\overline{\sigma_y}$ (μm)	$\overline{\sigma_m}$ (Mag.)	Number of stars
Calibration plate	50×50	0.024	0.028	0.0001	40359
Astronomical plate	288×288	0.175	0.169	0.01	3501

resolution, the non-linearity of the guide rails and the non-uniformity of the linear motors of the mobile platform, the deviation of image mosaic (starting deviation in Y and overlapping deviation in X) and the non-orthogonality between scanning direction and camera line array direction. According to their various representations, these factors were evaluated and calibrated respectively.

3.3.1 Lens distortion

The digitization of the astronomical plate is equivalent to re-imaging of the original plate. In order to reduce imaging distortion, the digitizer is equipped with a doublesided telecentric lens. The lens has a very low distortion that is better than 0.05$\%$ for the specified working size of 70.0 mm. The more close to the center of field of view, the smaller the lens distortion effect is. It can be estimated that even 0.01$\%$ distortion can amount to micron level in the case of the length of 28.8 mm for the linear array camera. So the lens distortion should not be ignored and need to be calibrated. The effect of the lens distortion on digitizing positions is reflected in the direction of the linear array camera, expressed in X. Therefore, for the digitization image of the calibration plate, we can fit the relationship between the theoretical and the measured position of all standard dots, and then investigate the distribution of the residuals in X along X, as shown in the upper of Figure 7. It can be shown obviously that, the influence of the lens distortion is symmetrically distributed on both sides of the center of field of view. With the distance from the center of field of view, the lens distortion is getting bigger and bigger, and the maximum is about 0.7 μm. In data processing, the digitizing positions can be corrected according to the calibration data of the lens distortion. The below of Figure 7 shows the distribution of the residuals after the correction, here the distribution has no systematic characteristic and the effect of the lens distortion has been eliminated.

3.3.2 Optical resolution

The nominal magnification of the doublesided telecentric lens is 1:1, and the nominal physical size of the pixel of the linear array camera is 10 μm, so the theoretical optical resolution of the digitizer is 2540DPI. In practice, the lenses are not perfect and there may be bias for physical size of the camera pixel. The actual optical resolution of the digitizer should be calculated based on the digitization image of the calibration plate. Assume ξ, η and x, y as the theoretical and measured coordinates of the standard dots on the calibration plate, and their relationship can be described as

$$\begin{cases} x = fcos\theta\xi + fsin\theta\eta + c \\ y = -fsin\theta\xi + fcos\theta\eta + d \end{cases} \tag{1}$$

where c, d and θ represent the translation and rotation between the theoretical and measured coordinate system, f represents magnification. According to the calculation of standard dots, the digitizer has a magnification of 0.999844, and then the actual optical resolution is 2539.6DPI.

3.3.3 Non-linearity of the guide rails and Non-uniformity of the linear motors of the mobile platform

Ideally, the mobile platform should drive the astronomical plate to do a strict uniform linear motion along the scanning direction. However, the bending of the guide rails and the installation error affect the linearity of the scanning motion, which will introduce the errors to digitizing positions in X. On the other hand, the accuracy of linear motor affects the uniformity of the speed of the scanning motion, which will introduce the errors to digitizing positions in Y. In order to estimate the non-linearity and

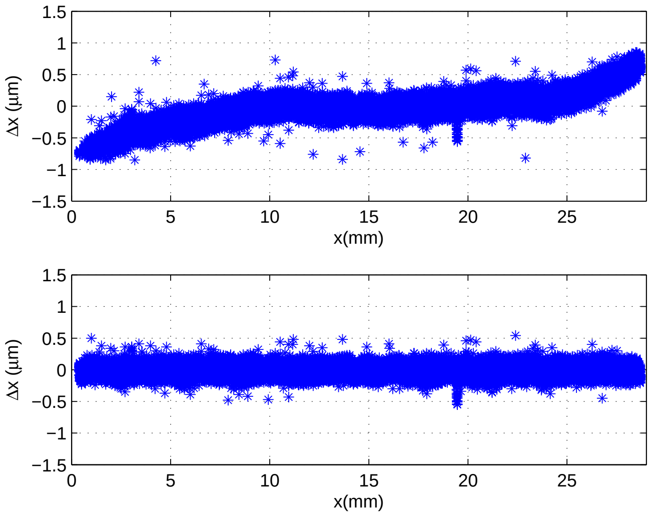

Fig. 7 Distribution of the residuals in X along the direction of the linear array camera before and after the correction of the lens distortion.

non-uniformity quantitatively, we placed the calibration plate along the direction of scanning for 6 times according to the step size of 50 mm, as shown in Figure 8. The digitization images of the calibration plate in different locations are utilized to calculate the relationship between the theoretical and measured positions, and then investigate the systematic distribution of the residuals in X and Y along Y, which reflects the influence of the non-linearity of the guide rails and non-uniformity of the linear motors in each covering range, as shown in Figure 9 and Figure 10, respectively. It can be shown that the effect of the non-linearity of the guide rails is mainly in the range of 0.4 μm, and the non-uniformity of the linear motors is in the range of 0.6 μm.

3.3.4 Deviation of image mosaic

Limited by the optical lens and the linear array camera, the width of single data acquisition is 28.8 mm. Since the side length of most astronomical plates exceeds 100 mm, each plate needs to be scanned for many times to obtain multi strip frames. Once all the strip frames from one plate have been recorded, they must be stitched into a mosaic image of the whole plate. Stitching process will introduce errors including starting deviation in Y and overlapping deviation in X, as shown in Figure 11.

In order to test the stitching error, we placed the calibration plate along X according to the step size of 28.8 mm, as shown in Figure 12. Every time the calibration plate was placed, it would cover two adjacent data acquisition regions. According to the standard dots on the previous data acquisition region, the relationship between the measured and theoretical positions can be fitted. Then, the theoretical positions of the standard dots on the latter region was converted through the relationship and compared with their corresponding measured positions, so as to get starting and overlapping deviation of the two adjacent regions. Here, the starting deviation between the two adjacent regions is reflected in the relative shift in Y, and the overlapping deviation is reflected in the relative shift in X. We carried out 5 rounds of measurement and the results are presented in Table 2 and Table 3. It can be seen that, each of the two adjacent regions has starting and overlapping deviation of micron level, which would be accumulated to a few microns from the first strip to the last. From multiple rounds of measurement, the starting and overlapping deviation is stable relatively and the repeatability is better than 0.15 μm. Therefore,

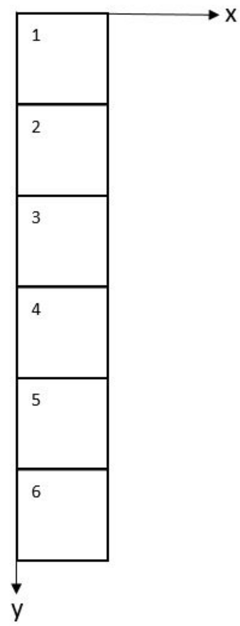

Fig. 8 Calibration plate was placed for 6 times along Y according to the step size of 50 mm.

Table 2 Measurement results of the starting deviation of two adjacent data acquisition regions

	the latter region relative to the previous one (μm)								
No.	2-1	3-2	4-3	5-4	6-5	7-6	8-7	9-8	10-9
1	-0.69	-0.34	-0.72	-0.22	-0.50	-0.49	-0.06	-0.66	-0.48
2	-0.58	-0.51	-0.52	-0.18	-0.42	-0.39	-0.16	-0.51	-0.57
3	-0.81	-0.27	-0.60	-0.22	-0.41	-0.59	0.09	-0.77	-0.53
4	-0.89	-0.22	-0.51	-0.26	-0.36	-0.65	0.02	-0.74	-0.57
5	-0.76	-0.35	-0.66	-0.33	-0.55	-0.51	-0.05	-0.71	-0.51
Mean	-0.75	-0.34	-0.60	-0.24	-0.45	-0.53	-0.03	-0.68	-0.53
σ	0.12	0.11	0.09	0.06	0.08	0.10	0.09	0.10	0.04

the mean value of deviation measurement can be taken as the compensation for the step motion of the mobile platform to reduce the influence of stitching error.

3.3.5 Non-orthogonality between scanning direction and camera line array direction

Line scanning requires that the scanning direction should be perpendicular to the direction of the linear array camera. However, there are some non-orthogonality between the two directions because of the installation error. The effect of the non-orthogonality on digitizing positions in Y will reach the maximum at the edge of the field of view, which can be expressed formally as

$$\Delta y_{max} = 0.5 \cdot l \cdot tan\theta \tag{2}$$

where l represents the length of linear array camera, θ represents the non-orthogonal angle. The following approach is adopted to evaluate the non-orthogonality. For the digitization image of the calibration plate, two straight lines are obtained respectively by fitting the standard dots on each row and each column. The difference between the angle of the two lines and the $90°$ can reflect the non-orthogonality

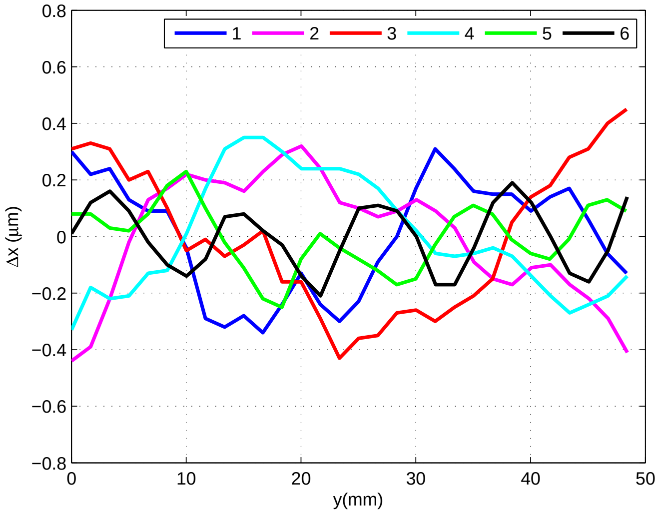

Fig. 9 Systematic distribution of the residuals in X along Y in the case of the calibration plate in different locations.

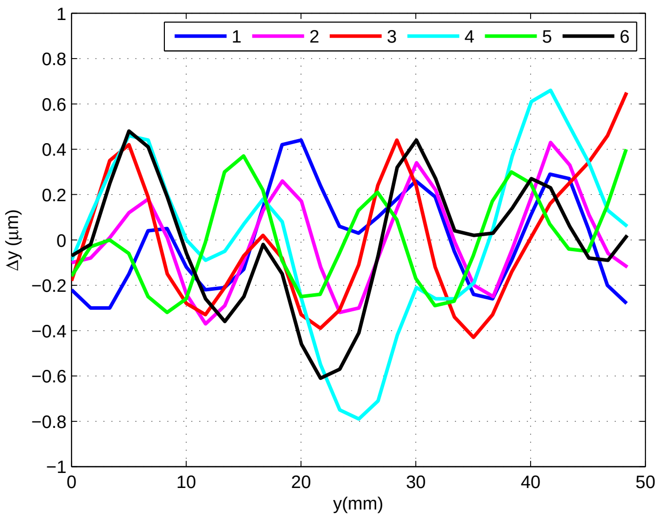

Fig. 10 Systematic distribution of the residuals in X along Y in the case of the calibration plate in different locations.

between the scanning and the linear array camera direction. In the actual test, the digitization image contains 201 rows $\times$ 100 columns of the standard dots, which consists of 20,100 pairs of lines. Figure 13 shows the distribution of the non-orthogonality results from all pairs of lines. It can be seen that, the average value of the non-orthogonality is about 1.25”. In the case of the linear array camera with the length of 28.8 mm, the influence of the non-orthogonality would be less than 0.17 μm.

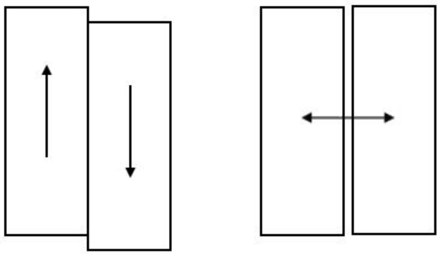

Fig. 11 Sketch map of starting deviation in Y and overlapping deviation in X.

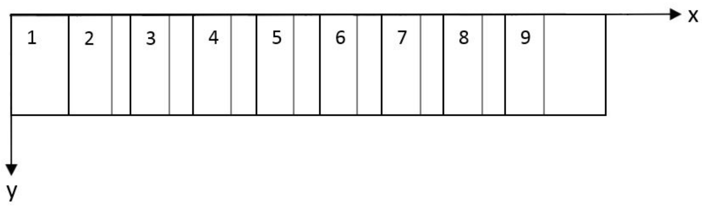

Fig. 12 Calibration plate was placed for 9 times along X according to the step size of 28.8 mm.

Table 3 Measurement results of the overlapping deviation of two adjacent data acquisition regions

	the latter region relative to the previous one (μm)								
No.	2-1	3-2	4-3	5-4	6-5	7-6	8-7	9-8	10-9
1	0.11	-1.59	0.04	-0.38	-1.16	0.17	-0.94	0.32	-1.45
2	0.03	-1.58	-0.04	-0.54	-1.26	0.07	-0.94	0.21	-1.48
3	0.20	-1.69	0.14	-0.42	-1.15	0.26	-1.08	0.48	-1.50
4	0.33	-1.89	0.23	-0.50	-1.05	0.22	-0.94	0.46	-1.48
5	0.28	-1.60	0.16	-0.68	-1.04	0.17	-1.03	0.29	-1.40
Mean	0.19	-1.67	0.11	-0.50	-1.13	0.18	-0.99	0.35	-1.46
σ	0.12	0.13	0.11	0.12	0.09	0.07	0.07	0.12	0.04

3.4 Comprehensive test on the precision of digitizing positions

The calibration plate provides a good reference for testing the systematic factors affecting digitizing positions, but the size of the calibration plate is too small to cover the whole measuring range. So we used a 300 mm $\times$ 300 mm astronomical plate to carry out the comprehensive test on the precision of the digitizing positions.

Though the positions of stars on the astronomical plate is not known exactly, the relative positions of all the stars is fixed. With this advantage, the plate was digitized at different angles and the conversion residuals of the positions of the common stars on different images were investigated. The specific measures are as follows: First, the plate was digitized to get its digitization image of 0°. Second, the plate was rotated 90° and 180°, respectively, and digitized again to get its image of 90° and 180°. Third, the common stars were used to fit the 0° image with the 90° image and the 0° image with the 180° image, to remove the systematic error between the images such as translation and rotation. Forth, the

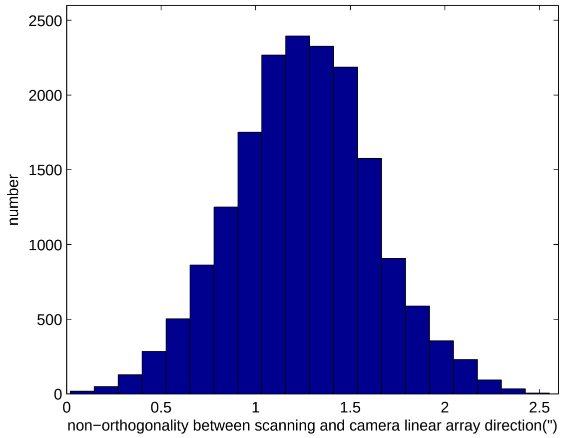

Fig. 13 Test of non-orthogonality between scanning direction and camera line array direction.

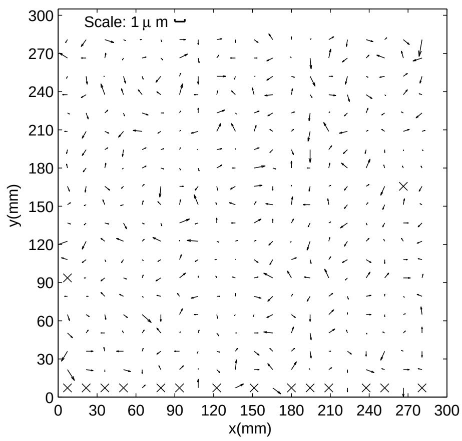

Fig. 14 Residuals distribution between 0° image and 90° image, where x represents no common stars in block.

residuals distribution of the positions and the standard deviations were investigated. Table 4 lists the standard deviations of 6 groups of tests. The conversion residuals of the positions between the 0° image and the 90° image, between the 0° image and the 180° image are shown in Figure 14 and Figure 15, where the plate is divided evenly into 20 × 20 blocks and each arrow represents the average value of the residuals within the block. It can be seen that the residuals distribution does not show a significant systematic tendency; the standard deviations is better than 0.9 μm. According to the principle of error transfer, here the standard deviation (expressed as σ) represents the comprehensive position error of the 2 images, which includes digitizing error (expressed as σ_d) and centroid error (expressed as σ_c), and it can be expressed formally as $\sigma^2 = 2 \cdot (\sigma_d^2 + \sigma_c^2)$, whereby, the overall digitizing error σ_d caused by the machine is deduced to be better than 0.7 μm.

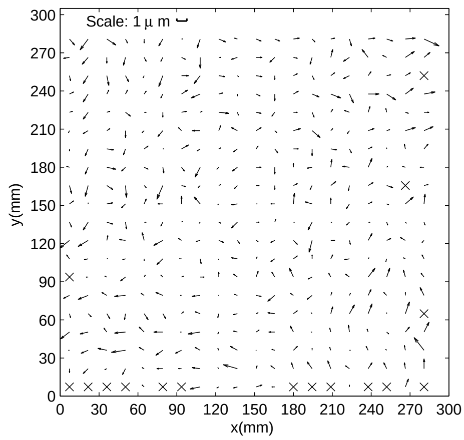

Fig. 15 Residual distribution between 0° image and 180° image, where x represents no common stars in block.

Table 4 Standard deviations of the 0° with the 90° image and the 0° with the 180° image

	σ (μm)	
No.	$0° - 90°$	$0° - 180°$
1	0.79	0.87
2	0.76	0.84
3	0.75	0.86
4	0.75	0.87
5	0.79	0.84
6	0.79	0.88

4 CONCLUDING REMARKS

The vast majority of the astronomical plates in China have not been digitized yet, which restricts the value of the first hand observation data to exert. The main ingredient of the film on the astronomical plate is silver bromide and the change of the environment will make the film become yellow, mouldy or even fall off. Even if kept in the ideal environment of constant temperature and humidity, the film on the plate will gradually deteriorate as time goes on. Therefore, the digitization of the astronomical plates is of great significance for permanent preservation and the full use of these valuable observation data. A digitizer with high precision and high measuring speed is the key equipment to carry out the digitization task of these astronomical plates.

Shanghai Astronomical Observatory and Nishimura Co. Ltd of Japan has jointly developed a brand-new digitizer for glass astrophotographic plates. After 2 years of development, the machine presents the digitization precision of better than 1 μm in position, and 10 minutes is needed to measure a plate with the size of 300 mm $\times$ 300 mm, which meets the requirement of the digitization of astronomical plates. In this paper, we present the main structure and working mode of the digitizer, as well as the results of its performance test. The results show that the brightness uniformity of illumination within the measuring area is better than 0.15%,the repeatability of digitizing positions is better than 0.2 μm and the repeatability of digitizing brightness is better than 0.01 instrumental magnitude. The systematic factors affecting digitizing positions are calibrated and evaluated. Based on an astronomical plate with the size of 300 mm $\times$ 300 mm, the overall measuring error of the digitizer is deduced to be better than 0.7 μm.

At present, the digitization of the astronomical plates is being carried out by the digitizer and it is expected to complete the digitization of all astronomical plates in China in 2017. The digitization data is plan to store in Chinese Virtual Observatory database and gradually release to international astronomical community.

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