Research in Astron. Astrophys. **2012** Vol. **12** No. **10**, 1451–1456
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in Astronomy and Astrophysics

Preliminary results of solving the problem of geometric distortion for the 2.4 m telescope at Yunnan Observatory *

Qing-Feng Zhang[1,2,3], Qing-Yu Peng[1,2,3] and Zi Zhu[2,3]

[1] Department of Computer Science, Jinan University, Guangzhou 510632, China
[2] Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210032, China
[3] Sino-French Joint Laboratory for Astrometry, Dynamics and Space Science, Jinan University, Guangzhou 510632, China; *tpengqy@jnu.edu.cn*

Received 2012 March 5; accepted 2012 April 26

Abstract We observed the open clusters NGC 1664 (43 exposures) and M35 (42 exposures) by the Yunnan Faint Object Spectrograph and Camera in the 2.4 m telescope at Yunnan Astronomical Observatory on 2011 January 3, and processed them by a method recently proposed by us. The result shows that there is a geometric distortion effect in the field of view and the maximum distortion is $\sim 0.25''$ (i.e. 1 pixel). After correcting the geometric distortion, the precision of stellar positional measurement is significantly improved. The best precision in each direction is 6 mas for well-exposed stars.

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

1 INTRODUCTION

In high-precision astrometry, the associated geometric distortion (hereafter called GD) should not be ignored. According to the research by Gilmozzi et al. (1995), the HST WFPC1 and WFPC2 are both subject to a GD effect, and the distortion ranges from a few tenths of a pixel in the center of each chip to 2∼3 pixels at the edge of each chip. Furthermore, the distortion effect can cause positional errors anywhere from 20 mas to 300 mas. In fact, for the latest camera on HST, WFC3, the GD can be corrected better than 0.008 pixel (∼0.3 mas) in each direction (Bellini et al. 2011). So the GD solution for a CCD chip is very important for high-precision astrometry.

Anderson & King (2003) proposed a novel method using the superimposed residuals from dithered frames to solve the GD for HST WFPC2. The GD solution is accurate to ∼0.01 pixel in the WF chips and to ∼0.02 pixel in the PC chip. Thereafter, many scholars used this method to systematically study the GD effect for various cameras in HST (Platais et al. 2003, 2009; Bellini & Bedin 2009; McLean et al. 2010), so it has become a classical method for solving the GD problem.

Because the HST is weightless in space, its GD solution is nearly constant in time. Although ground-based telescopes are under the influence of gravity, is it still possible to apply the classical method to correct their GD effects? Anderson et al. (2006) adapted the classical method to correct the GD for the ground-based ESO 2.2 m telescope, and they found that the final GD solution can

* Supported by the National Natural Science Foundation of China.

achieve a precision of ∼7 mas. Bellini & Bedin (2010) applied it to study the GD correction for the blue prime-focus camera on the Large Binocular Telescope, and they achieved a precision of 0.09 pixel (∼20 mas). These research achievements demonstrated that the classical method can be implemented for ground-based telescopes.

In 2009, we started research about the GD solution for a ground-based telescope (Peng & Fan 2010; Peng & Tu 2011). We proposed an alternative approach for the GD solution which is somewhat different from the classical method. Our studies have shown that the GD for the 1 m telescope at Yunnan Astronomical Observatory (YNAO) can accurately be measured. The precision of stellar positional measurement is significantly improved after correcting with the GD, and the best precision is 4 mas in each direction.

Since the end of 2009, a new terminal (i.e. the Yunnan Faint Object Spectrograph and Camera, YFOSC) has been installed on the 2.4 m telescope at Gaomeigu Station in YNAO. Due to using a focal reducer, its field of view ($10' \times 10'$) is much wider than the original one ($5' \times 5'$). In order that the terminal could be used for high-precision astrometry, we have studied its GD effect. We observed two open clusters and took many CCD frames.

In this paper, we present our research on the GD for the 2.4 m telescope. The paper includes five sections: the principle of the GD solution is introduced in Section 2; specifications for the telescope, the CCD chip and observed data are described in Section 3; the result and analysis are given in Section 4; the conclusions are drawn in Section 5.

2 THE METHOD OF THE GD SOLUTION

Anderson & King (2003) gave a detailed discussion on the essence of a distortion-free optical system. When we observe a field with a detector, all we can obtain is a set of positions of stars as measured in the coordinate system, or frame, of that detector. The question of whether a particular frame is free of distortion then becomes how to tell if the set of positions that define it is free of distortion. The answer is a purely operational one: a frame is distortion-free if the star positions that define it have been corrected in such a way that the positions of the same stars, measured in any image with a different pointing, but corrected in the same way can be transformed into those of this frame with nothing more than a combination of displacement, rotation and scale factor. In fact, every optical instrument suffers from some amount of GD. We suppose, when observing at a certain epoch, the GD in one camera's field of view is only a function of position on a CCD chip. That is, GD=GD(x, y), where (x, y) is the pixel position on a CCD chip which is only related to the reference coordinates. The main task of the GD solution is to find the numerical expression of the GD function. The solution is derived with the following steps.

Step 1. Dithered observations are implemented by observing a region with a crowded field of stars, and a series of CCD frames is obtained in which every two neighboring frames are overlapped and have a slight positional offset (e.g. $1'$ between two neighboring frames).

Step 2. The stars in each frame are matched with stars in some reference catalog, so that each star in the catalog may have many star images from various frames that have the same ID as that in the catalog. It should be mentioned that the most accurate cataloged positions of these stars are not necessary computed during the matching process. As a result, some matching lists are generated, in which one master list records all the matched stars in the catalog, and the other lists record them in the other frames respectively.

Step 3. All matched stars in each original frame are compared in terms of their measured and cataloged positions by a four-constant plate model, and their residuals are evaluated. Theoretically, the positional residual is composed of three parts: positional error in the catalog ($\Delta\alpha_c(\alpha, \delta)$, $\Delta\delta_c(\alpha, \delta)$), the GD in the field of view ($\Delta\alpha_{\rm GD}(x, y)$, $\Delta\delta_{\rm GD}(x, y)$) and the measurement error in a frame (ν_x, ν_y). That is, the positional residual can be written in terms of the following

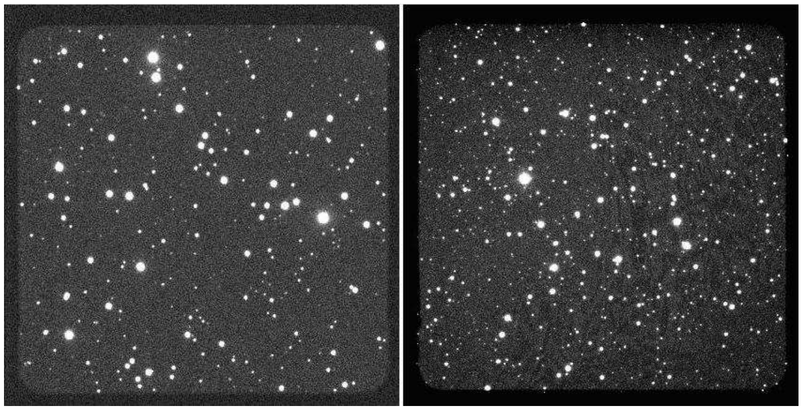

Fig. 1 Two typical CCD frames. The left one is M35 and the right one is NGC 1664.

formulas

$$\Delta\alpha = \Delta\alpha_c(\alpha,\delta) + \Delta\alpha_{\rm GD}(x,y) + \nu_x,$$
$$\Delta\delta = \Delta\delta_c(\alpha,\delta) + \Delta\delta_{\rm GD}(x,y) + \nu_y.$$

For the positional errors from the catalog, each cataloged star has a different value and all star images with the same ID have the same value. For the GD, only the position in the field of view is related to it. It can be assumed that all stars in one small region in the field have roughly the same error (meaning that the error changes slightly in a small region). The measurement error in a frame is generally considered as a random error, and can be reduced by the average of many data values. In practice, we divided the CCD field of view into several regions (for example, 8×8). For every small region, we averaged the differences between each star's positional residual in it and the ones in any other region, so the star's GD was highlighted and the other errors were reduced. Finally, the small region's GD was obtained. We took all the regions' GDs as the initial GD solution in the field of view.

Step 4. The original pixel positions of every matched star in various frames are corrected with the GD solution, so we obtain a set of updated pixel positions. We take them as new measurement positions, and repeat Steps 3 and 4 until we can attain the final and converged GD solution. For more details, see Peng & Tu (2011).

3 TELESCOPE'S SPECIFICATIONS AND OBSERVED DATA

On the night of 2011 January 3, we observed the open clusters M35 and NGC 1664 using the overlapping scheme of CCD frames by the 2.4 m telescope at YNAO. During observations, we used a Johnson I-type filter. The exposure time was about 10∼20 s, depending on weather conditions. The dither pattern proposed by Anderson et al. (2006) was adopted in the overlapping image scheme. We obtained 42 CCD frames of M35 and 43 ones of NGC 1664. Figure 1 shows two typical cases.

As Figure 1 shows, there are no visible stars in the border region of the frames. This is due to the small difference between the CCD's chip size and the field size of the focal reducer. Therefore, we only analyzed the imaging area during data processing. Specifications of the 2.4 m telescope at YNAO and its CCD chip are listed in Table 1.

4 RESULTS AND ANALYSIS

We have processed every frame's data set by the above method for computing the GD solution. For registering images, we used a scheme of auto searching and identifying stars developed by Ren &

Table 1 Specifications of the Telescope and Its CCD Chip

Focal length	1920 cm
Aperture	240 cm
CCD resolution	2200×2048
Size of pixel	$13.5 \times 13.5\mu^2$
Size of field of view	$\sim 10' \times 10'$
Approximate scale factor	0.285 arcsec pixel^{-1}

Peng (2010). For measuring stars' pixel position in any frame, we applied a 2D Gaussian fitting. In addition, it should be noticed that it is the stars in the UCAC3 catalog that are not in the UCAC2 which are used to match the stars in every frame. This is because the UCAC3 has more faint stars than the UCAC2. In this way, we acquired every matched star and its astrometric parameters. For the 2.4 m telescope, each CCD field of view (corresponding to each frame) usually has 200–300 cataloged stars. After that, we worked out the theoretical positions of those matched stars in every frame, and solved their residual values of observed minus calculated $(O - C)$ based on a four-constant plate model. Here, the calculation of theoretical position was strict and thorough, in which a variety of factors were taken into account (i.e. atmospheric refraction and central projection based on topocentric position). During data processing, the field of view was uniformly divided into 8×8 cells. It was assumed that the GD at the center point in one cell is equal to the average GD in it. We averaged a large number of residuals in one cell, removed some residuals by the 3σ criterion, and solved the initial GD of each cell. Based on the GD solution, we corrected the original position measurement for each matched star in the frames (bilinear interpolation was applied to calculate the GD at any point). We repeatedly solved the GD several times until the GD correction was less than a given threshold (1–2 mas). Figure 2 shows the final GD distribution in the CCD field of view for the 2.4 m telescope.

It can be seen from Figure 2 that the GD distributions derived from each cluster are very similar. The maximum distortion is about 250 mas (i.e. 1 pixel). Note that the area shown in Figure 2 is not the whole area in the CCD field of view because of its "pyramid" effect (Anderson & King 2003). It is clearly necessary to further study the "pyramid" effect in the future. In addition, there is greater distortion in the left border region of the CCD field, and the GD distribution is asymmetric on the whole. This phenomenon could be caused by the off-center and/or the tilting of the CCD chip relative to the optical axis because of the focal reducer. A similar situation can be found in Bustos Fierro & Calderón (2002). They used a different method to calculate the distortion; their GD solution was

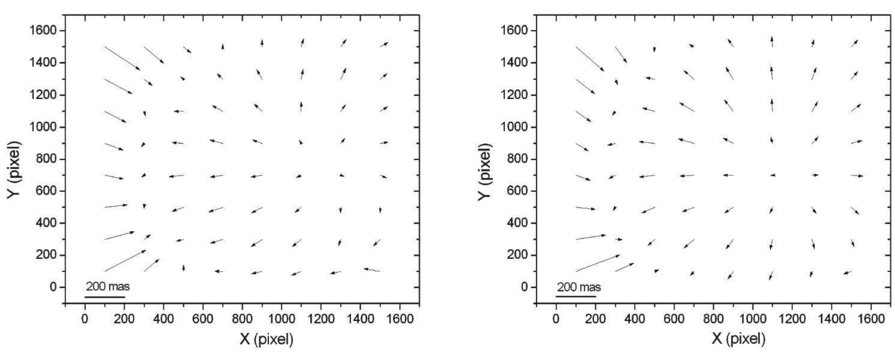

Fig. 2 GD distribution. The graph on the left shows the GD distribution for M35 and the one on the right for NGC 1664.

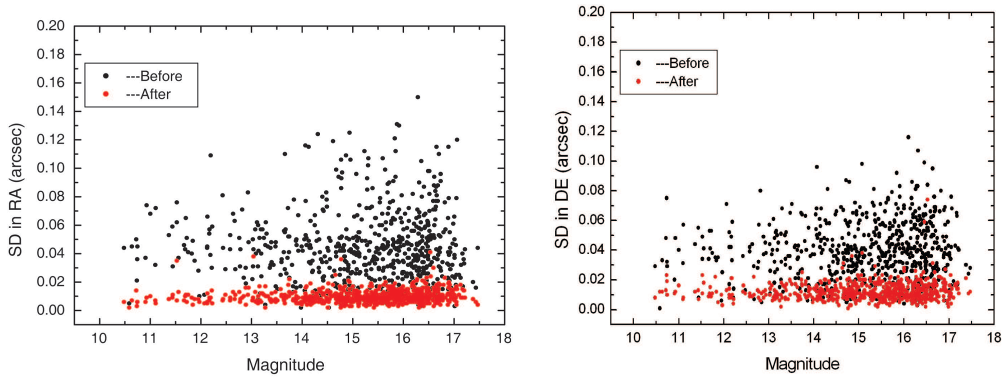

Fig. 3 Before and after the GD correction, the SD of the star's position $(O-C)$ is calculated by the four-constant model. The left is the SD of right ascension and the right is the SD of declination.

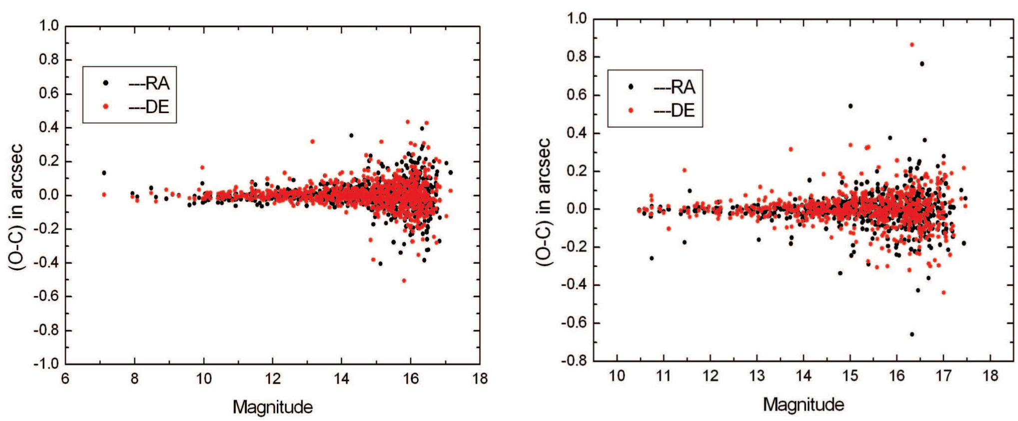

Fig. 4 $(O-C)$ of positional measurement results from two open clusters. The left is from M35 and the right is from NGC 1664.

neither symmetric nor smooth. In addition, to eliminate the pyramid effect, the original CCD frames were cropped off more on the right side than the left side during image preprocessing. This also increased the asymmetry.

In order to show the effect of the GD correction, we illustrated it with the results of processing the data of the cluster NGC 1664.

Figure 3 shows the change of the standard deviation (SD) with the star magnitude before and after the GD correction. Here, the SD is derived based on the difference $(O-C)$ between the theoretical position and the star's position transformed from the measured position in one frame by the four-constant model. Obviously, the effect of the GD correction is significant. After the GD correction, the SD in each direction is $\sim$10 mas. For some stars with suitable brightness, their measured positions have a precision of 6 mas.

Figure 4 shows that the $(O-C)$s of the measured star positions in two clusters change with the stars' magnitudes. It is found that the brighter stars usually have smaller $(O-C)$s. The fainter the star, the greater the dispersion of the $(O-C)$ of the measured star position.

It is well known that there exist obvious proper motion errors in the UCAC3 catalog, especially those representing faint stars. Some research in this area has recently been done (Röser et al. 2008; Bobylev & Khovritchev 2011; Liu et al. 2011). In order to avoid the impact of the errors from proper motion in the catalog, we assume that the proper motions of the cataloged stars are zero. The final results show that this assumption is appropriate. If we do not adopt it, larger $(O - C)$s will be generated (See Lin et al. 2011 for more details).

5 DISCUSSION AND CONCLUSIONS

In general, the positional measurements of a star may be affected by the filter type because of different stellar spectral types. The measurement errors caused by this effect should be taken into account in high-precision astrometry. At this point, we can say the GD effect may vary with filter type. So it is necessary to study the GD effects in different types of filters. Now, we have studied the GD effect in a Johnson I-type filter, but this is not enough. As a follow-up, we plan to take more frames with the other types of filters to study the problem further.

We used the newly installed YFOSC in the 2.4 m telescope at YNAO to observe two open clusters: M35 and NGC 1664. During observations, the Johnson I-type filter was used. The observed data were processed by following the latest procedure. The final result shows that there exists a significant GD in the CCD field of view, and that the maximum distortion is about 1 pixel. After the GD correction, the precision of stellar positional measurements is significantly improved. For well-exposed stars, the best precision of positional measurement is 6 mas in each direction. However, we also find the "pyramid" effect in the field of view. It is worthy of further study.

Acknowledgements This work is supported by the National Natural Science Foundation of China (Grant Nos. 10973007, 11273014) and the open fund of the Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, China. We wish to thank the 2.4 m telescope research team at Yunnan Astronomical Observatory for their great help during observations. We are grateful to Dr. Bai Jinming, the chief scientist of the 2.4 m telescope research team, for his valuable suggestions and discussions. Finally, we also thank the anonymous referee very much for some valuable comments.

References

Anderson, J., Bedin, L. R., Piotto, G., Yadav, R. S., & Bellini, A. 2006, A&A, 454, 1029
Anderson, J., & King, I. R. 2003, PASP, 115, 113
Bellini, A., Anderson, J., & Bedin, L. R. 2011, PASP, 123, 622
Bellini, A., & Bedin, L. R. 2009, PASP, 121, 1419
Bellini, A., & Bedin, L. R. 2010, A&A, 517, A34
Bobylev, V. V., & Khovritchev, M. Y. 2011, MNRAS, 417, 1952
Bustos Fierro, I. H., & Calderón, J. H. 2002, Revista Mexicana de Astronomía y Astrofísica, 38, 215
Gilmozzi, R., Ewald, S., & Kinney, E. 1995, WFPC2 Instrument Science Report, 95
Liu, J.-C., Zhu, Z., & Hu, B. 2011, RAA (Research in Astronomy and Astrophysics), 11, 1074
Lin, Z., Peng, Q. Y., & Zhang, Q. F. 2011, Chin. J. Space Sci., 31, 344 (in Chinese)
McLean, B., Cox, C., Platais, V. K., et al., 2010, Instrument Science Report WFC3 2009-41
Peng, Q., & Tu, B. 2011, Scientia Sinica Physica, Mechanica & Astronomica, 41, 1126 (in Chinese)
Peng, Q., & Fan, L. 2010, Chinese Science Bulletin, 55, 791
Platais, V. K., Anderson, J. & Koekemoer, A. M. 2003, Instrument Science Report WFPC2 2003-002
Platais, V. K., Cox, C., McLean, B., et al. 2009, Instrument Science Report WFC3 2009-33
Ren, J. J., & Peng, Q. Y., 2010, Astron. Res. Tech., 2010, 7, 115 (in Chinese)
Röser, S., Schilbach, E., Schwan, H., et al. 2008, A&A, 488, 401