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New solution for the geometric distortion in astronomical images: Application to Phoebe observations

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ABSTRACT

A new approach for the correction of the geometric distortion is proposed. This approach is applied to observations of three open clusters taken at the Yunnan Observatory. It is shown that the correction depends on the filter used. The technique is then used to correct the positions of Phoebe (ninth satellite of Saturn). The precision on the positions is significantly improved.

Subject headings: Geometric Distortion, Astrometry, Phoebe, Image Analysis

1. Introduction

In order to check the astrometric property of the new CCD camera (a resolution of 2048 × 2048 with 13.5 μm for each pixel) of the 1-m telescope at Yunnan Observatory, we try to solve its geometric distortion. For the astrometry for the Hubble Space Telescope (HST), Anderson & King (2003) solved the geometric distortion (called GD hereafter) of HST by designing a novel routine. It is just after solving the GD that the HST opens its tap of astrometric potential. For example, the observations of Saturnian satellites have much better precision than ever before (Poulet & Sicardy 2001) mainly because of the correction of GD according to French et al. (2006). Furthermore, this novel technique of solving GD for HST is popularized toward a ground-based telescope. Here, we propose an alternative technique but take advantage of an astrometric catalogue to derive our GD for a ground-based telescope. A series of CCD frames of Phoebe, the ninth satellite of Saturn, are used to test the solved GD.

2. Principle

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 displacement, a rotation, and a scale factor. In other words, the star positions in one frame can be accurately associated with those of the same stars only by a 4-constant plate model. Furthermore, a set of overlapping exposures are chosen to derive the GD of HST according to Anderson & King (2003).

Similar to the practice by Anderson & King (2003), we take multiple dithered exposures of the same sky field at different offsets in a pattern. In our experimental observations, the offsets between any two neighboring CCD frames are about 1 *arcmin* in right ascension or in declination.

After all stellar images are automatically searched and extracted for their pixel positions by a 2-D Gaussian fit technique, as many stellar images as possible are matched by our developed technique (Ren & Peng 2010) to their corresponding stars in some dense astrometric catalogue so that each matched star image has unique identification (strict requirement is not needed for its positional precision). We then adopt a 4-constant plate model to solve the plate constants and to derive the pseudo positional residuals, i.e., the Observed minus Computed (O-C) residuals

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$(\Delta\alpha(x,y;\alpha,\delta)$,$\Delta\delta(x,y;\alpha,\delta))$ for all stars in the frame. Here, each computed position of a star image should include all astrometric effects so that any observed position can be directly comparable to its corresponding computed one except for GD effects. Theoretically, each positional residual of a star should contain three components: its catalogue error $(\Delta\alpha_C(\alpha,\delta),\ \Delta\delta_C(\alpha,\delta))$ — depending on only its equatorial coordinates in its catalogue, the Geometric Distortion $(\Delta\alpha_{GD}(x,y)$, $\Delta\delta_{GD}(x,y))$ —depending on its pixel position of the star in its imaging CCD frame and measuring error (v_x, v_y) —depending on mainly the signal to noise ratio of the stellar image. Specifically, we have the following notation,

$$\Delta\alpha(x,y;\alpha,\delta) = \Delta\alpha_C(\alpha,\delta) + \Delta\alpha_{GD}(x,y) + v_x,$$

$$\Delta\delta(x,y;\alpha,\delta) = \Delta\delta_C(\alpha,\delta) + \Delta\delta_{GD}(x,y) + v_y.$$

Because each component originates differently, each one can be separated from the other and be solved. For example, a star has the same catalogue error at different pixel positions (within several nights or even a longer period of time, depending on its error in proper motion). However, the same star will suffer from different GDs because the GD is the function of pixel positions, i.e., $GD = GD(x,y)$. Moreover, stars imaging in the same neighboring field (centering at (x_i, y_i), for example) of every CCD frame will have similar GDs (gradual variation is supposed for the GD pattern) but may suffer from completely different catalogue errors. In addition, measuring errors can be viewed as random, and can be compressed by averaging as many measurements as possible.

According to the analysis above, let the pseudo positional residual of a star imaging in the i^{th} CCD frame minus the mean pseudo positional residuals for the same star but imaging in the other N CCD frames so that the catalogue error of this star can be cancelled out as noted in the following equations,

$$\Delta\alpha_{GD}(x_i,y_i) \approx \Delta\alpha(x_i,y_i;\alpha,\delta) - \frac{1}{N}\sum_{j\neq i}\Delta\alpha(x_j,y_j;\alpha,\delta),$$

$$\Delta\delta_{GD}(x_i,y_i) \approx \Delta\delta(x_i,y_i;\alpha,\delta) - \frac{1}{N}\sum_{j\neq i}\Delta\delta(x_j,y_j;\alpha,\delta).$$

As for each equation in the above notations, in comparison with the first term in the right hand, the second term (mean (O-C)s for all imaging positions of the same star except for its pixel position (x_i, y_i) in the i^{th} CCD frame) includes all other GDs (as well as the catalogue error of this star and residual measured errors) in which some GDs are positive and some negative, and some bigger and some smaller. On the whole, the GDs in summation will be cancelled out in some degree and the catalogue error will be highlighted. Therefore, the difference between the first term and the second one in the right hand of each equation will highlight the GD in the neighbor imaging area centering at (x_i, y_i) (if we neglect the measurement errors) and have no relation with the catalogue error of the concerned star. On the other hand, the measurement errors will be compressed greatly after the operation of averaging all pseudo positional residuals. Furthermore, any other star close to the concerned star will have its contribution to the GD solution if at least two images appear in their dithered CCD frames. Because of many frames obtained when a dense star field is observed with our dithered scheme, a great number of contributions can be produced.

In order to derive the initiate GD in a neighbor of (x_i, y_i), we adopted a σ-clipped mean of all $(\Delta\alpha_{GD}(x_i,y_i), \Delta\delta_{GD}(x_i,y_i))$ locating in the neighbor. Specifically, the whole field of view might be divided into rectangles or squares with same areas (such as 8×8 or 16×16) beforehand. These solved $(\Delta\alpha_{GD}(x_i,y_i), \Delta\delta_{GD}(x_i,y_i))$ by the σ-clipped mean show the initiate GDs because all GDs existing in pixel positions will enter to the solved parameters by a 4-constant plate model and only approximate GDs can be obtained after this step. A precise solution of GDs can be achieved simply by an iteration routine. The pixel position of every stellar image can be corrected from its initial GD by a bi-linear interpolation to its nearby initiate GDs in grids. The iterative resolution can be done again and again until the absolute value of each new differentiate GD is less than some preset-threshold (0.01 *pixel* for example). We find from our computation that only 5-8 iterations are usually enough to have a converged GD solution.

3. Observations

Two observational campaigns were made during the first half year of 2011. In each campaign 4-night observations were allocated to the 1-m telescope at the Yunnan Observation (longitude E102° 47′ 18″, latitude N25° 1′ 30″ and height 2000 m above sea level). The focal lengh is 1300cm. The size of the CCD array is 2048×2048 and the size of pixel is $13.5\mu\times13.5\mu$. So the CCD field is $7'\!.1\times7'\!.1$. 3 open clusters (M35, M67 and NGC 2324) were observed in order to solve the GD of field of view. In total, there were 425 CCD frames captured based on 2 filters (Johnson I and R) and a null filter. In each night, Phoebe, the ninth satellite of Saturn, was observed but in different pointings from the calibrated area. 220 CCD frames in total were taken for Phoebe. For the CCD frames of Phoebe, usually only a few UCAC2 (Zacharias et al. 2004) reference stars appear in the field of view. Obviously, a complete solution of GD for its field of view is impossible. We adopted the solved GD from open clusters with the same filter and in the same night to correct the GD for the pixel positions of Phoebe and its reference stars in UCAC2. There is one exception for the observations on Feb. 25 when the GD without filter is adopted from that on Feb. 26.

4. Results

4.1. GD and filter used

When the same filter is used in different nights to derive the pattern of GD, it is found similar. Figure 1 shows all GD distributions when a Johnson R filter is used and an open clusters M67 (NGC 6286) are observed in 4 different nights. The maximum GD changes from 0.752 *pixel* on Apr. 4 to 0.995 *pixel* on Feb. 25. While a Johnson -I filter is replaced in other night observations, similar distributions of GD also appeared . However, the distribution derived from the Johnson I filter is significantly different from the distribution from the Johnson -R filter. We speculate that the difference may be caused by the inhomogeneity in thickness of the filter used.

It is surprised that even no filter is used, the GD distribution is obvious enough and reveals a swirl-like structure (see Figure 5). It might be also caused by the inhomogeneity in thickness of the front glass of CCD window. Perhaps, because the distance between the front glass of CCD window and the CCD chip is less than that between a filter and the chip, or/and better flatness for the front glass, the magnitude of GD becomes less. Anyway, further investigation is interesting and needed in future.

4.2. (O-C) residuals for open clusters

Some main results for open clusters are given here. As an example, Figure 3 shows the positional (O-C) residuals of M35 observed in night of Feb.24 and Feb.27 respectively for the common stars. A good agreement can be found.

The standard deviations (SD) of the same stars in the open cluster M35 become much better after GD correction for most brighter stars. For fainter stars, there is only a little improvement as their low signal noise ratios. It needs to be noted that the solution of observed positions for each star in M35 is made by a 4-constant plate model.

4.3. Positional measurement of Phoebe

Usually, a CCD frame for Phoebe has only a few stars appearing in. So, it is impossible to find enough reference stars in some astrometric catalogue. Figure 4 is a typical CCD frame for Phoebe in which only three stars (with circles) can be found in UCAC2. Therefore, we cannot deliver the GD pattern based only on these CCD frames. A simple practice is to adopt the GD solution delivered from some open cluster in the same night and by the same filter to remove the effect of GD for the pixel positions of reference stars and Phoebe. Then, we compare the pixel positions for these reference stars with the theoretical positions of the same reference stars to derive calibration parameters for the Phoebe field of view. Specifically, all astrometric effects are included in the computation of these theoretical positions and a 4-constant plate model is then adopted to compute the calibration parameters. In practice, atmospheric refraction and central projection are incorporated into the topocentric positions so as to transform all theoretical positions into the corresponding standard coordinates in each CCD frame. In order to compare the effect of GD on positional measurement of Phoebe, we adopt a modern ephemeris developed by the

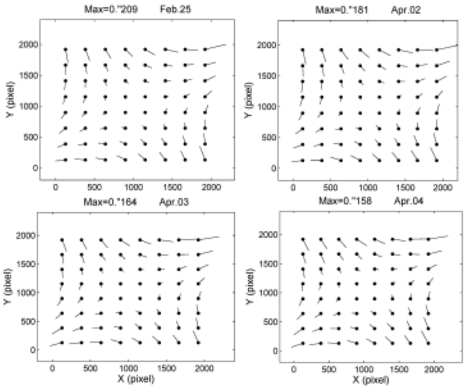

Fig. 1.— GDs derived from a Johnson -R filter from observations of M67 in 4 nights

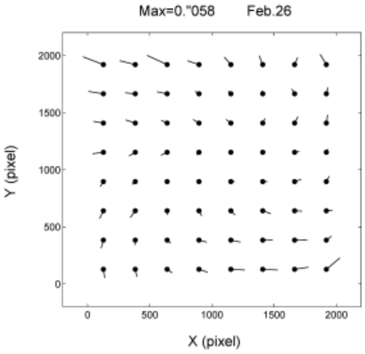

Fig. 2.— A small but visible swirl-like GD is also found while no filter is used

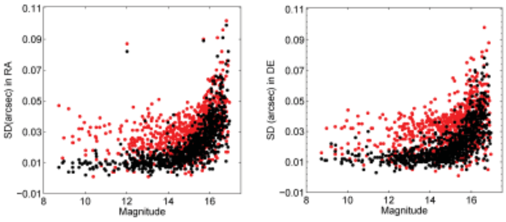

Fig. 3.— (O-C) residuals in two nights

IMCCE via the website of http://www.imcce.fr/. And DE405 developed by the JPL (Standish 1998) is adopted for the primary planet Saturn.

In order to illustrate the effect of GD correction, no GD correction is also made under the condition that all other computations are completely the same. On the whole, the dispersion after GD correction becomes smaller.

A statistics is listed in Table 1 for the observations of Phoebe, and all results before and after GD corrections are shown. It is clear that the significant improvement of the positional residuals of Phoebe appears.

5. Discussions

A 4-constant plate model is advantageous since only 2 reference stars are able to calibrate the CCD field of view. It is preferable for a faint movable objective (such as Phoebe). Careful attentions must be paid to the positional computation of the working stars (those to be used to derive the GD). According to our findings mentioned before, GD's patterns depend on the filter used. This may be explained since a filter can distort the direction of light passing through it. As for this, better quality filter should be manufactured. In view of application, more observations are needed to study the law of variation of the pattern of GD, especially when the telescope is operated in different pointings and under the different environments, such as temperatures and pressures. Perhaps, no filter has more advantageous than other filters when GD is taken into account. Our proposal approach may be convenient to apply to solve the GD pattern for other telescopes with a great field of view, such as Schmidt telescopes or other short focal length ones, when a high precision in position is required.

6. Conclusions

A convenient but effective approach is proposed to solve the geometric distortion of a CCD field of view in present paper. After many CCD frames of some open clusters observed by a 1-m telescope at the Yunnan Observatory are used to test the approach, its effectiveness was verified, especially its application to the observations for Phoebe, the ninth satellite of Saturn. Positional precisions for both stars from clusters and the satellite Phoebe

Table 1: Statistics of (O-C) residuals of Phoebe observed in two campaigns. All units are arcsec. GDC means the correction of GD. The columns of $\langle O-C\rangle$ in RA and in DE list the mean (O-C) residuals of Phoebe.

	Obs in Feb			
	$\langle O-C\rangle$ in RA	SD	$\langle O-C\rangle$ in DE	SD
Before GDC	0.023	0.069	-0.035	0.086
After GDC	0.025	0.061	-0.029	0.072
	Obs in Apr.			
Before GDC	0.165	0.083	-0.013	0.072
After GDC	0.165	0.043	-0.049	0.049

are found to be improved greatly after correcting the geometric distortion. Besides, it is also found that the geometric distortions depends strongly on the filter used. In addition, even no filter is used, a small but obvious enough distortion appears too. The approach can be also applied to other telescopes for high precision astrometry.

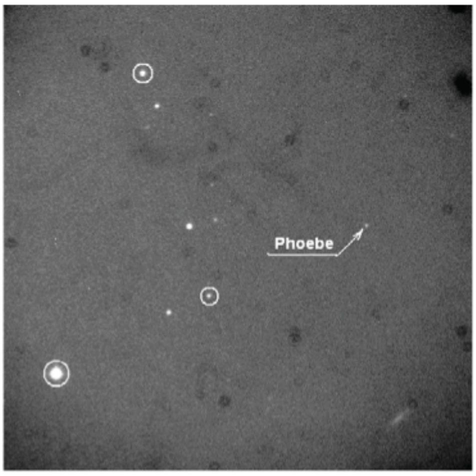

Fig. 4.— A typical CCD frame for the satellite Phoebe taken on February. Only three reference stars (with circles) can be found in UCAC2

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