Spatial dependent systematic error correction and colour coefficients for the 2-m telescope of the Rozhen National Astronomical Observatory

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Abstract. Spatial dependent systematic error of the instrumental magnitudes on the CCD frames taken at the 2-m telescope of the Rozhen National Astronomical Observatory due to scattered light was present till mid-June 2009. We derive and discuss $(U)BVRI$ spatial dependent systematic error correction, together with colour coefficients, on the basis of archival data. The simultaneous estimation of the two types of coefficients – spatial and colour, ensures the detachment of the two effects, and, accordingly, the higher accuracy in the coefficient estimates. The application of the spatial dependent systematic error correction to the data in the period discussed would increase photometry accuracy.

Key words: techniques: photometric

Introduction

The Rozhen National Astronomical Observatory (NAO), Bulgaria, was officially put into operation in 1981. The main scientific instrument of NAO is a 2-m telescope. It allows observations in Ritchey-Chrétien (RC) and Coudé foci. For about a decade the light detection in the RC focus was performed onto photographic emulsion (e.g., Markov et al. 1985, Petrov et al. 2007) and occasionally onto a photodiode array (e.g., Tsvetkov & Markov 1984). The first CCD detector in the RC focus was the Peltier cooled 375×272 SBIG ST-6 CCD camera (1993, Georgiev et al. 1994). It was replaced by the generation of the liquid nitrogen cooled CCD cameras – 1024×1024 Photometrics AT200 (since 1997), followed by 1340×1300 Princeton Instruments VersArray:1300B[1] (hereafter VersArray; since 2005). The usage of the CCD cameras significantly increased the efficiency and accuracy of the observations obtained with the 2-m telescope.

During the first years of imaging with the AT200 CCD camera there were indications for problems concerning the photometry. For instance, the brightness of the quasar HS 1946+7658 derived by us showed dependence on the choice of the reference stars (none of them were found variable) across the field of view. Dr. H. Markov (2003, private communication) was the first one who drew the attention of the Bulgarian astronomical community to the presence of a spatial dependent systematic error (SDSE) of the

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instrumental magnitudes measured on the frames: the closer to the frame centre, the weaker the magnitudes. In a series of papers he gave a qualitative and quantitative description of this error (Markov 2005a,b,c, 2008); the author suggested quadratic spatial dependence. Practically unaffected is the central field of view with a radius of about $1'$ (Markov 2005b).

The SDSE was accounted for in Mihov & Slavcheva-Mihova (2008), Ovcharov et al. (2008), and Maciejewski et al. (2009). The two-channel focal reducer FoReRo-2 (Jockers et al. 2000) showed no SDSE (Ovcharov et al. 2008).

If scattered light is present on both the object and flat field frames, SDSE is introduced in photometry (fainter magnitudes closer to the frame centre) after flat fielding although the resulting sky background is flat (e.g., Manfroid et al. 2001). This happens because additive signal (scattered light) is involved in a multiplicative correction (flat fielding; see, e.g., Boyle et al. 2003, Andersen et al. 1995). Scattered light could be identified using a pinhole camera (Grundahl & Sørensen 1996). Generally, the main reason for scattered light presence is imperfect baffling (e.g., Grundahl & Sørensen 1996, Boyle et al. 2003).

The pinhole camera images taken at the 2-m telescope (Markov 2003, 2005, private communication, Ovcharov et al. 2010) revealed the presence of scattered light. It was significantly reduced after the primary mirror baffle was modified and a special diaphragm in front of the filter wheel was mounted in mid-2009 (Ovcharov et al. 2010); as a result SDSE decreased.

The aim of this work is to present SDSE correction, that is to be applied to the photometry on frames taken before the modifications (mid-June 2009), as well as colour coefficients for the AT200 and VersArray CCD cameras in Johnson-Cousins $(U)BVRI$ band.

The paper is structured as follows. In Sect. 1 we describe the method of determination of the SDSE correction and colour coefficients. In Sect. 2 we present the results obtained. They are discussed in Sect. 3. The conclusions are outlined in Sect. 4.

1. Method of determination of the SDSE correction and colour coefficients

In the case of an SDSE, a quadratic spatial term is added to the transformation equation after Markov (2005c):

$$m - M = m_0 + k\,X + c\,CI + c_\rho\,\rho^2, \qquad (1)$$

where m and M are the total instrumental and catalogue magnitudes of the stars, respectively, m_0 the zero-point magnitude, k the extinction coefficient, X the airmass, c the colour coefficient, CI the catalogue colour index of the stars, and c_ρ the spatial coefficient. We neglected the second order extinction coefficient k''. The radial distance to the frame centre is defined as:

$$\rho = s\sqrt{\left(x - \frac{N_x}{2}\right)^2 + \left(y - \frac{N_y}{2}\right)^2}, \qquad (2)$$

Table 1. Johnson-Cousins V magnitude and colour indices of M 92 standard stars. Their designations are after Majewski et al. (1994).

ID	V	$U-B$	$B-V$	$V-R$	$R-I$
3	14.7155 ± 0.0062	0.093 ± 0.017	0.7858 ± 0.0121	0.485 ± 0.017	0.454 ± 0.018
4	14.6345 ± 0.0043	0.111 ± 0.018	0.7779 ± 0.0066	0.486 ± 0.014	0.464 ± 0.035
5	16.0741 ± 0.0026	-0.111 ± 0.013	0.5247 ± 0.0069	0.313 ± 0.008	0.277 ± 0.005
6	16.3520 ± 0.0042	-0.442 ± 0.012	-0.1070 ± 0.0058	-0.038 ± 0.010	-0.085 ± 0.005
7	16.4573 ± 0.0037	-0.478 ± 0.004	-0.1113 ± 0.0058	-0.041 ± 0.010	-0.086 ± 0.020
8	15.9460 ± 0.0027	-0.079 ± 0.009	0.5560 ± 0.0043	0.351 ± 0.015	0.302 ± 0.019
9	17.0099 ± 0.0034	1.124 ± 0.044	1.1451 ± 0.0069	0.722 ± 0.008	0.589 ± 0.029
10	14.0558 ± 0.0025	0.325 ± 0.029	0.7696 ± 0.0036	0.516 ± 0.014	0.417 ± 0.014
11	15.1669 ± 0.0010	0.844 ± 0.030	1.0110 ± 0.0049	0.630 ± 0.020	0.522 ± 0.019
12	15.9950 ± 0.0049	-0.026 ± 0.014	0.6792 ± 0.0079	0.433 ± 0.013	0.411 ± 0.013
16	15.2833 ± 0.0047	0.061 ± 0.020	0.0831 ± 0.0125	0.058 ± 0.017	0.049 ± 0.005
17	14.4941 ± 0.0029	-0.015 ± 0.044	0.5683 ± 0.0096	0.403 ± 0.016	0.362 ± 0.030
18	17.9871 ± 0.0066	-0.247 ± 0.061	0.4880 ± 0.0161	0.320 ± 0.005	0.320 ± 0.007
19	18.2340 ± 0.0065	-0.317 ± 0.214	0.4164 ± 0.0104	0.286 ± 0.018	0.273 ± 0.008
21	17.9451 ± 0.0037	-0.188 ± 0.014	0.4920 ± 0.0058	0.340 ± 0.009	0.296 ± 0.014
22	17.5785 ± 0.0053	-0.254 ± 0.039	0.5394 ± 0.0080	0.357 ± 0.017	0.323 ± 0.020
23	16.8162 ± 0.0046	-0.132 ± 0.017	0.6302 ± 0.0064	0.403 ± 0.006	0.368 ± 0.043

where s is the CCD scale factor in arcsec/px, (x, y) the stellar centroid coordinates, and $N_x \times N_y$ the CCD chip size in pixels.

In the case of single-airmass photometry, the zero-point magnitude and the airmass term in Eq. (1) can merge into a modified zero-point, m_0', so, we got:

$$m - M = m_0' + c\,CI + c_\rho\,\rho^2. \tag{3}$$

To obtain the coefficients in Eq. (3), we used the standard field[2] of the globular cluster M 92 presented in Majewski et al. (1994). The magnitudes and colours of the standard stars are listed in Table 1; we have added 0.002 mag to the V magnitudes and to the $B-V$ colour indices of the M 92 standard stars, listed in Majewski et al. (1994), according to the addendum of Stetson & Harris (1988). The standard stars are identified in Fig. 1.

A total of 67 (56) frames of M 92 were taken in 6 (7) observing nights in the period 1997-2003 (2007) for the AT200 (VersArray) camera. Generally, frames at 2-3 airmass values were taken in each night. The photometry of the cluster was performed using DAOPHOT (Stetson 1987) run under IDL.

In practice, we proceeded as follows. Firstly, a least-square fit of Eq. (3) to the individual frames of the M 92 standard field was done; the fit was weighted by:

$$w = \frac{1}{\sigma_m^2 + \sigma_M^2}, \tag{4}$$

[2] Kitt Peak Video Camera/CCD Standards Consortium field (Christian et al. 1985).

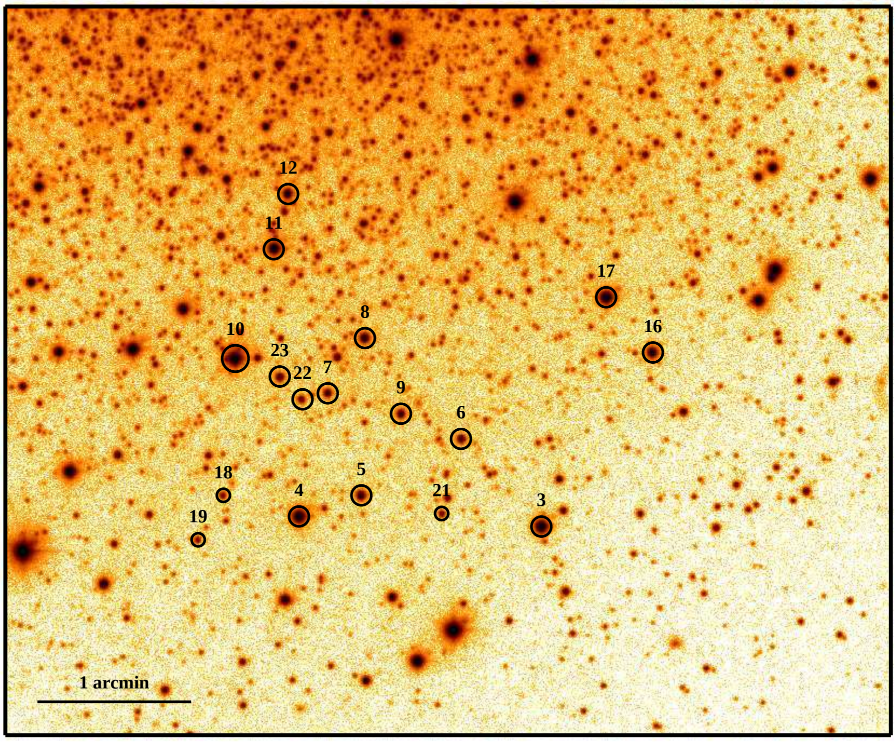

Fig. 1. The standard field of M 92. North is at the top, east to the left.

where σ_m and σ_M are the errors of the instrumental and catalogue magnitudes of the stars, respectively. Next, the estimated zero-point m'_0 was subtracted from the corresponding instrumental magnitude, $m' = m - m'_0$. Finally, the equation:

$$m' - M = c\,CI + c_\rho\,\rho^2 \tag{5}$$

was fitted to the corrected instrumental magnitudes of the stars, merged for each band and camera; the total numbers, n, of entries[3] are given in Table 2. To eliminate the outliers, $3\,\sigma$ clipping was performed. The error of m'_0 was added quadratically to Eq. (4) to weight the fit of Eq. (5) to the data.

2. Results

The results for the individual bands and cameras (the U band is not included for VersArray due to the lack of good quality data) are presented in Table 2. The characteristics of the individual fits: the chi-square per degree

[3] n = (number of frames) $\times$ (number of stars); some stars were omitted.

Table 2. SDSE correction and colour coefficients for the CCD cameras. We also listed the colour index, *CI*, used in Eqs. (1), (3), (5) for the corresponding band.

Band	CI	n	c	c_ρ	$\sigma_{\rm fit}$	$\chi^2_{\rm df}$	$c_{\rho,\rm n}$
				$\left[10^{-6}\,\frac{\rm mag}{\rm arcsec^2}\right]$	[mag]		[mag]
				AT200			
U	$U-B$	137	-0.091 ± 0.017	-5.223 ± 0.658	0.042	0.3	-0.131 ± 0.017
B	$B-V$	231	-0.056 ± 0.003	-5.111 ± 0.243	0.030	1.0	-0.128 ± 0.006
V	$V-R$	230	-0.078 ± 0.004	-5.325 ± 0.186	0.022	0.9	-0.134 ± 0.005
R	$V-R$	215	$+0.002\pm0.005$	-5.777 ± 0.308	0.037	1.7	-0.145 ± 0.008
I	$R-I$	215	-0.019 ± 0.009	-6.687 ± 0.379	0.033	0.5	-0.168 ± 0.010
				VersArray			
B	$B-V$	192	-0.101 ± 0.003	-4.810 ± 0.216	0.016	0.5	...
V	$V-R$	256	-0.128 ± 0.003	-3.812 ± 0.112	0.015	0.9	...
R	$V-R$	223	-0.103 ± 0.004	-4.194 ± 0.161	0.016	0.5	...
I	$R-I$	224	-0.014 ± 0.007	-4.518 ± 0.216	0.019	0.3	...

of freedom, $\chi^2_{\rm df}$, and the standard deviation about the fitted function, $\sigma_{\rm fit}$, are also given.

No systematic study of the SDSE for the individual bands and cameras has been done up to our knowledge. Initially, normalized radial distance was introduced (Markov 2005a,c) and used in the further attempts to account for the SDSE (e.g., Ovcharov et al. 2008). However, its usage does not allow comparison among cameras of different size and is not proper for cameras with $N_x \neq N_y$ (like VersArray).

For the sake of comparison with literature data, we re-estimated the coefficients for AT200 using normalized distance:

$$\rho_{\rm n} = \sqrt{\left(\frac{x}{512}-1\right)^2+\left(\frac{y}{512}-1\right)^2}. \tag{6}$$

The spatial coefficients are listed in Table 2, last column. They are in good agreement with Markov (2005c) in BV and Ovcharov et al. (2008) in R. The former author, however, had slightly different approach – he used single-epoch observations of a standard field with many stars, whereas we performed multi-epoch observations of a relatively poor standard field. In addition, Markov (2005c) did not fit colour coefficients.

In Figs. 2 and 3 we present the relation between $m' - M - c\,CI$ and ρ^2 for the V band for both cameras.

3. Discussion

The spatial coefficients are similar for both cameras and across the bands. Their absolute values are systematically lower for VersArray, accompanied

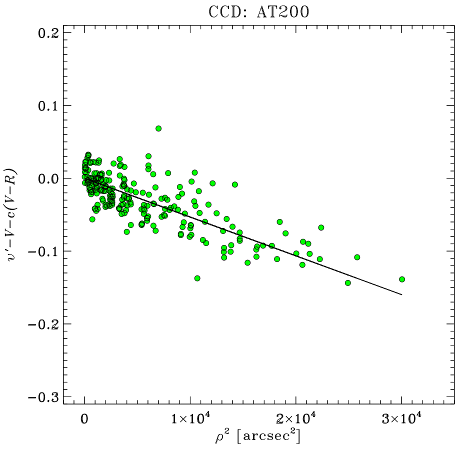

Fig. 2. Relation between $v' - V - c(V - R)$ and ρ^2, with the corresponding linear fit overplotted, for the AT200 CCD camera.

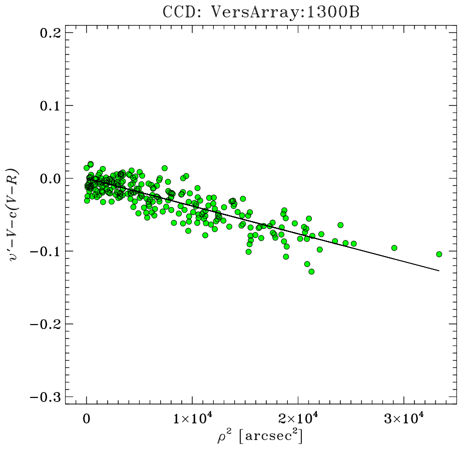

Fig. 3. The same as in Fig. 2, but for the VersArray CCD camera.

by smaller uncertainties, which is illustrated for V in Fig. 2. This might mean that the scattered light distribution may also be related to the CCD mounting, apart from the other factors already discussed. The colour coefficients are generally larger in absolute values for VersArray compared to AT200 for the individual bands, except I. The colour coefficients estimated above are in good agreement with the ones determined on the basis of M 92 data (VersArray) acquired after the modifications, using multi-airmass photometry with no SDSE correction (unpublished results). This should mean that no interplay is present between the spatial and colour coefficient sets.

Previous determinations of the SDSE correction were based on equations similar to Eq. (3) but with no colour term included (Markov 2005a,c, Mihov & Slavcheva-Mihova 2008, Ovcharov et al. 2008, Maciejewski et al. 2009). Our approach allows differentiation of the magnitude differences due to the different colour indices of stars and due to the SDSE. As a result, the systematic error of the spatial coefficient should decrease. Moreover, the colour coefficients can also be determined.

The presented SDSE correction could be considered as a first order one. To be more precise, at least a couple of factors, already mentioned in Sect. 1, have to be taken into account.

Firstly, the second order extinction coefficient has been omitted.

Secondly, we assumed alignment between the telescope optical axis and the CCD camera. Otherwise, $N_x/2$ and $N_y/2$ should be replaced by the coordinates of the optical axis (see, e.g., Markov 2008). We replaced the camera centre by the optical axis centre suggested in Markov (2008) and the scatter got larger. Similar was the effect of replacing the centre by the apexes of a square with a side length of about 50 px. That is why we left the camera centre and the optical axis to coincide.

The outermost camera regions have not been studied, either. However, the effects of these factors on the coefficients derived are beyond the scope of our study.

4. Conclusion

Using archival data in the period 1997 – 2007, we acquired spatial, as well as colour, coefficients for the two CCD cameras used in that period. Our approach presumes differentiation of the influence of the two effects – the SDSE and different colour index – on magnitude difference of stars. Thus, not only do we have spatial and colour coefficients estimated in a uniform manner for the individual bands and cameras, but both coefficient sets are free from each other's influence. The location of the targets close to the field-of-view centre minimizes the SDSE effect; in this case the SDSE correction can even be skipped. The small but systematic difference between the special coefficients of the two cameras may mean that the CCD mounting is also related to the SDSE.

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References

Andersen M. I., Freyhammer L., Storm J., 1995, in Proc. ESO/ST-ECF Workshop "Calibrating and Understanding HST and ESO Instruments", ed. P. Benvenuti (Garching near Munich: ESO), 87
Boyle R. P., Janusz R., Philip A. G. D., Kazlauskas A., Laugalys V., 2003, *Balt. Astron.* 12, 476
Christian C. A., Adams M., Barnes J. V., et al., 1985, *PASP* 97, 363
Georgiev Ts., Getov R., Semkov E., Mutafov A., Todorova H., 1994, IAU Commission 9, Working Group on "Wide-Field Imaging", *The Newsletter* 6, 21
Grundahl F., Sørensen A. N., 1996, *A&AS* 116, 367
Jockers K., Credner T., Bonev T., et al., 2000, *Kin. i Fiz. Neb. Tel Suppl.*, 3, 13
Maciejewski G., Mihov B., Georgiev Ts., 2009, *AN* 330, 851
Majewski S. R., Kron R. G., Koo D. C., Bershady M. A., 1994, *PASP* 106, 1258
Manfroid J., Selman F., Jones H., 2001, *The Messenger* 104, 16
Markov H., Golev V., Tsvetanov Z., Petrov G., 1985, *Astrophys. Invest.* 4, 110
Markov H., 2005a, *Aerosp. Res. Bulg.* 20, 171
Markov H. S., 2005b, *Bulg. J. Phys.* 32, 51
Markov H. S., 2005c, *Bulg. J. Phys.* 32, 59
Markov H., 2008, *Bulg. Astron. J.* 10, 85
Mihov B. M., Slavcheva-Mihova L. S., 2008, *AN* 329, 418
Ovcharov E. P., Nedialkov P. L., Valcheva A. T., et al., 2008, *MNRAS* 386, 819
Ovcharov E. P., Petrov N., Markov H., Bonev T., Donchev Z., 2010, *Publ. Astron. Obs. Belgrade* 90, 217
Petrov G. T., Slavcheva-Mihova L., Kopchev V., 2007, in Proc. 5th Bulg.-Serb. Conf. "Astronomy and Space Science", eds. M. K. Tsvetkov, L. G. Filipov, M. S. Dimitrijević, L. Č. Popović (Heron Press Ltd, Sofia), 385
Slavcheva-Mihova L., Mihov B., 2011, *A&A* 526, A43
Stetson P. B., 1987, *PASP* 99, 191
Stetson P. B., Harris W. E., 1988, *AJ* 96, 909
Tsvetkov M. K., Markov H. S., 1984, *Dokl. Bolg. Akad. Nauk* 37, 11