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UBVRI photometric system of the meniscus telescope MTM-500

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ABSTRACT

We present the method and results of defining coefficients while passing on from the instrument brightness values in u, b, v, r, i bands to U, B, V, R, I bands of the Johnson – Cousins system at the telescope MTM-500.

Key words: photometric system, extinction coefficients

1 Introduction

The optics of the MTM-500 meniscus telescope (D = 50 cm, F = 1/13), manufactured by the Leningrad Optical Mechanical Association (LOMO) in 1950, are a mirror-lens system developed by D.D. Maksutov (Maksutov, 1944). The telescope was one of the first installed in the Cimean Astrophysical Observatory. Since 1963, observations with MTM-500 have been carried out using a high-sensitivity television tube LIZ-804 superisocon. In 2014 this detector has been replaced by an Apogee Alta U6 camera with a 1024×1024 chip and an Apogee FW50-9R filter wheel containing the u, b, v, r , i filters. The telescope with the Apogee Alta camera has a field of view of $14' \times 14'$, limiting magnitude in the r filter is $\approx$ 15 mag at the exposure of 60 s. In connection with the replacement of the photodetector of the telescope, it became necessary to obtain the coefficients of transformation from the u, b, v, r, i instrumental system of magnitude to the Johnson – Cousins UBVRI system.

2 Methods of binding of the photometric systems and reduction ratios

There are several methods for determining the relationship of instrumental photometric systems with widely used standard photometric systems (Zhang et al., 2013; Hardie, 1962). Following by Hardie, one can write the expressions relating the outside atmosphere magnitudes and colors V, U – B, B – V, V – R and V – I of stars in the standard photometric system with the observed magnitudes and colors v, u – b, b – v, v – r and v – i of stars in the instrumental system at the air mass X:

$$V = v - k'_v X + \alpha(B - V) + C1 \tag{1}$$

$$B - V = \beta(b - v)(1 - k''_{bv} X) - \beta k'_{bv} X + C2 \tag{2}$$

$$U - B = \gamma(u - b)(1 - k''_{ub} X) - \gamma k'_{ub} X + C3 \tag{3}$$

$$V - R = \delta(v - r) - \delta k'_{vr} X + C4 \tag{4}$$

$$V - I = \eta(v - i) - \eta k'_{vi} X + C5 \tag{5}$$

$$X = sec(z) - 0.0018167(sec(z) - 1) - 0.002875(sec(z) - 1)^2 - 0.0008083(sec(z) - 1)^3, \tag{6}$$

where $\alpha, \beta, \gamma, \delta, \eta$ are the reduction coefficients, k'_v, k'_{bv}, k'_{vr}, k'_{vi} are the main extinction coefficients of the atmosphere, k''_{ub}, k''_{bv} are the secondary extinction coefficients (Forbes coefficients), z is the zenith distance of the star, and constants C1, C2, C3, C4, C5 are related to the sensitivity of the receiving equipment. Due to the small number of stable photometric nights at the Crimean Astrophysical Observatory, we used the differential method to determine the reduction coefficients in order to exclude extinction of the Earth's atmosphere. The essence of the method is to obtain the difference in stellar magnitudes and colors of n stars of a compact cluster of different colors and magnitudes with respect to the star selected as the standard one (st). The standard star should be bright, and its color indices approximately average with the respect to the stars in the selected area, n should be of the order of 10 ÷ 20. If the selected area is compact, and observations are carried out near the meridian, where variations of the air mass are minimal, the differential atmospheric extinction and its possible instability can be neglected. Using the system of equations (1–6), we can write the differences in the magnitudes and colors of the selected stars with respect to the selected standard star (st):

$$\Delta V_i = \Delta v_i + \alpha \Delta(B - V)_i \tag{7}$$

$$\Delta(B - V)_i = \beta \Delta(b - v)_i (1 - k''_{bv} X) \tag{8}$$

$$\Delta(U - B)_i = \gamma \Delta(u - b)_i (1 - k''_{ub} X) \tag{9}$$

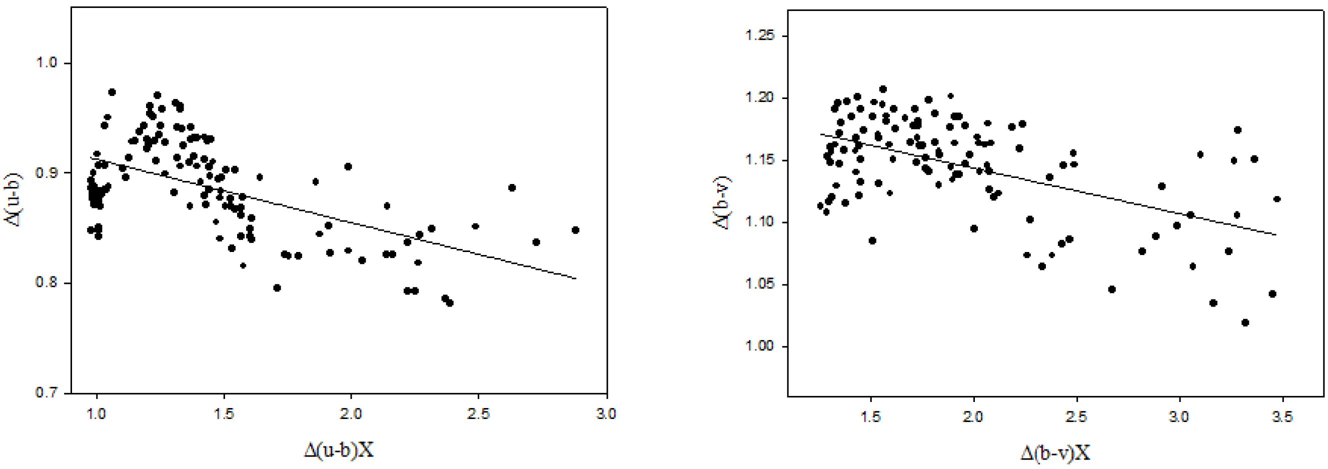

Fig. 1. Variations of the color index differences of two stars with the air mass

$$\Delta(V-R)_i = \delta\Delta(v-r)_i \quad (10)$$

$$\Delta(V-I)_i = \eta\Delta(v-i)_i, \quad (11)$$

Where

$$\Delta v_i = v_i - v_{st}$$

$$\Delta(b-v)_i = (b-v)_i - (b-v)_{st} = (b_i - b_{st}) - (v_i - v_{st})$$

$$\Delta(u-b)_i = (u-b)_i - (u-b)_{st} = (u_i - u_{st}) - (b_i - b_{st})$$

$$\Delta(v-r)_i = (v-r)_i - (v-r)_{st} = (v_i - v_{st}) - (r_i - r_{st})$$

$$\Delta(v-i)_i = (v-i)_i - (v-i)_{st} = (v_i - v_{st}) - (i_i - i_{st},)$$

and $i = 1, 2, 3 \ldots n$ is number of selected stars.

The values of the right-hand sides of these equations can be found from the differential measurements of stars in the corresponding filters.

The secondary extinction coefficients k''_{ub}, k''_{bv} characterized the Forbes effect, which arises due to the dependence of atmospheric extinction on the wavelength and the characteristics of the broadband filters forming the u, b, v photometric system. Their determination requires observations in the u, b, v filters of two stars with very different colors in a wide range of air masses. These coefficients can be found from the next equations:

$$\Delta(b-v)_i k''_{bv} X_i = \Delta(b-v)_i - \Delta(b-v)_0 \quad (12)$$

$$\Delta(u-b)_i k''_{ub} X_i = \Delta(u-b)_i - \Delta(U-B)_0, \quad (13)$$

where i is the number of observations of two stars.

3 Observations and Results

The star HD 194577 and HD 194495 with colors $B-V = 0.93$ mag and $B-V = -0.1$ mag respectively were observed to obtain the secondary extinction coefficients[1]. Observations were carried out on July 11, 2018. The air mass varied in the range 1.1–3, the exposure time increased with increasing air mass and reached 60 s. After removing points that are more than 3σ from the linear trend, we obtained 133 and 121 values of the $\Delta(u-b)_i$ and the $\Delta(b-v)_i$ colors respectively and plotted the dependence $\Delta(u-b)_i$ vs $\Delta(u-b)_i k''_{ub} X_i$ and $\Delta(b-v)_i$ vs $\Delta(b-v)_i k''_{bv} X_i$ (see Fig.1)

As the result, we obtained:

$$k''_{ub} = -0.05 \pm 0.01 \text{ mag}$$

$$k''_{bv} = -0.03 \pm 0.01 \text{ mag.}$$

To calculate the reduction coefficients β and γ, 15 stars of the open cluster NGC 2169 were observed (Fig. 2). For determination of the coefficients α, δ, η 28 stars of the cluster NGC 2168 were observed (Fig. 3). The observations of these clusters were carried out on April 4, 2018 and May 2, 2019 near the meridian within the one hour angle.

When calculating the coefficients δ, η, we used the data from the AAVSO Photometric All Sky Survey (APASS) catalog, which provide the magnitudes in the v', r', i' bands corresponding to the Sloan Digital Sky Survey (SDSS)[2] filters that differ from the magnitudes in Johnson – Cousins system. To match the values of v', r', i' to the values of V_C, R_C, I_C (Johnson – Cousins), we used relations (Kinoshita et al., 2007):

$$\Delta(V_C - I_C) = 0.91\Delta(v' - i') \quad (14)$$

$$\Delta(V_C - R_C) = 0.98\Delta(v' - r'). \quad (15)$$

[1] simbad.u-strasbg.fr
[2] https://www.sdss.org/

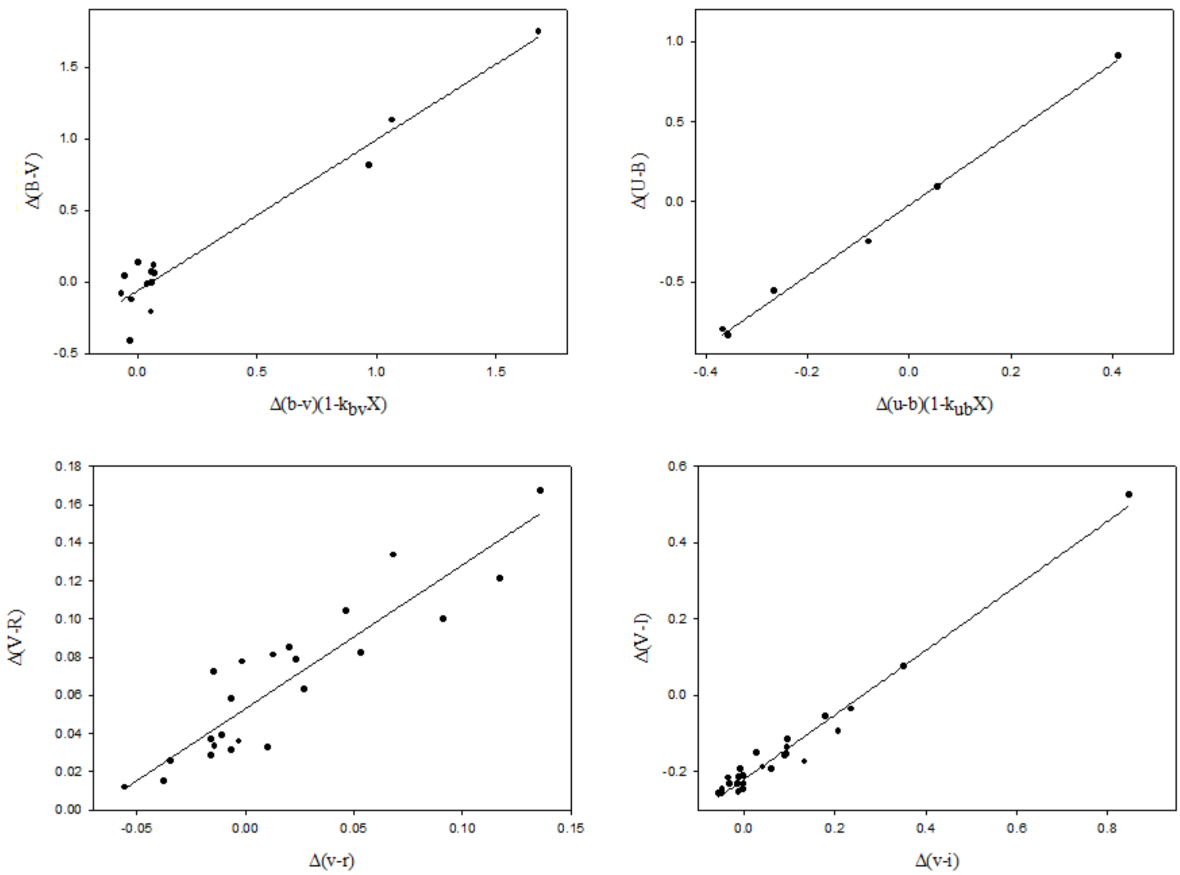

Fig. 2. Relations between the color indices of the instrumental system of the telescope MTM-500 and the color indices of the standard Johnson – Cousins system from observations of the star clusters NGC 2168 and NGC 2169

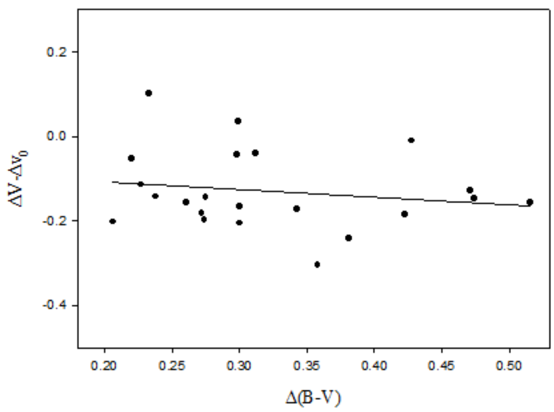

Fig. 3. Dependence of the difference in brightness values in the Johnson – Cousins system and the instrumental system of the MTM-500 telescope on the difference in color indices B – V

As the result of the calculation, the reduction coefficients are obtained:

$\alpha = -0.17 \pm 0.08$ mag

$\beta = 1.05 \pm 0.1$ mag

$\gamma = 2.21 \pm 0.03$ mag

$\delta = 0.76 \pm 0.02$ mag

$\eta = 0.85 \pm 0.08$ mag.

4 Conclusion

The relationship between the instrumental system of the MTM-500 telescope and the standard Johnson – Cousins system was obtained from the differential measurements of stars in open clusters NGC 2168 and NGC 2169 in accordance with the method described by Hardie (1962). The reduction formulas for the visual magnitudes and colors in the differential form are:

$$\Delta V = \Delta v - k'_v \Delta X - (-0.17 \pm 0.08)\Delta(B - V)$$

$$\Delta(B - V) = (1.05 \pm 0.10)\Delta(b - v) - (1.05 \pm 0.10)k'_{bv}\Delta X - (1.05 \pm 0.10)k''_{bv}\Delta(b - v)\bar{X}$$

$$\Delta(U-B) = (2.21 \pm 0.03)\Delta(u-b) - (2.21 \pm 0.03)k'_{ub}\Delta X - (2.21 \pm 0.03)k''_{ub}\Delta(u-b)\bar{X}$$

$$\Delta(V-R) = (0.76 \pm 0.02)[\Delta(v-r) - k_{vr}\Delta X]$$

$$\Delta(V-I) = (0.85 \pm 0.08)[\Delta(v-i) - k_{vi}\Delta X].$$

These expressions are applicable to a variable object and a comparison star, in cases where their images are obtained on different frames or on large air masses. ΔX is a different of the air mass, and $\bar{X}$ is the mean air mass for two objects.

The secondary extinction coefficients $k''_{ub} = -0.05 \pm 0.01$ mag, and $k''_{bv} = -0.03 \pm 0.01$ mag were obtained from observations of a pair of stars with different colors.

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