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TRANSFORMATION OF DSLR MAGNITUDES TO STANDARD PHOTOMETRIC SYSTEM

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Abstract: The paper discusses the possibility of transforming photometric data obtained using a digital SLR into the standard BVR_c Johnson-Cousins photometric system. It presents the method used, including the transformation equations and the determination of the transformation coefficients, and demonstrates its applicability to several performed measurements.

1 Introduction

We use a regular DSLR (Digital Single Lens Reflex) camera as a detector in our observations of variable stars. It is generally known that a digital SLR has a layer of R, G, and B filters arranged in the form of a grid on individual pixels (Bayer mask). While most of our previous measurements used the entire sensor area, recently, we have focused on the possibilities of photometric data extraction for individual colour channels and their transformation into the standard Johnson-Cousins BVR_c photometric system. We aimed to formulate a suitable method for this and verify its applicability in practice.

2 DSLR and its properties suitable for astronomical photometry

Even though the digital SLR camera was initially designed for everyday use and the creation of daily photography at the amateur and professional level, several authors have already demonstrated that it can also be effectively used for obtaining scientifically valuable photometric data. This is mainly due to the excellent shape of the linear response of the sensor, the 14-bit ADU range at the output, and the wide options for setting the exposure and saving images in RAW format.

The most frequent targets of our observations are eclipsing variable stars and HADS (High Amplitude Delta Scuti)-type stars with a magnitude of around 10-12. As a detector, we use a Canon EOS 500D device equipped with an APS-C type sensor with a resolution of 4752x3168 pixels (15 megapixels). One piece is mounted on a Newton 200/1200 telescope and an EQ-6 mount, and another on a 102/500 refractor and an EQ-3 mount (GoTo upgrade). Their fields of view have dimensions of 1.06° × 0.71° and 2.5° × 1.5°, respectively.

The computer and ASCOM platform control both systems. We control the mount movement and exposure using the Astrophotography Tool or CCDCiel software. The exposure length varies between 30-60 s, and the ISO is set to 400-1600, depending on the brightness of the observed object. Observations are carried out on the Kolonica saddle, which has very good observation conditions, or in the urban environment of Prešov with significant light pollution. Both locations are characterised by relatively few clear nights and changeable weather, yet they allow tens to hundreds of successful measurements during the year.

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We use Muniwin[1] to perform aperture photometry, further processing takes place in the programs MCV (Kim et al., 2004), Peranso[2], or in a script created by us, or we use the well-known O-C gate on the pages of Section of Variable Stars and Exoplanets of Czech Astronomical Society[3]. All images are properly calibrated using dark frames and flat field frames. The resulting product of the observations is light curves, which we contribute to larger-scale observation campaigns.

We perform most measurements in a so-called "clear" filter (also grayscale), i.e. using the entire sensor surface. The star aperture contains pixels of all three colours regardless of their different transmittance or response to the light signal. This generally extended approach gives sufficient accuracy to find the moments of extrema, and the resulting light curves most closely match the standard V filter (Fig. 1).

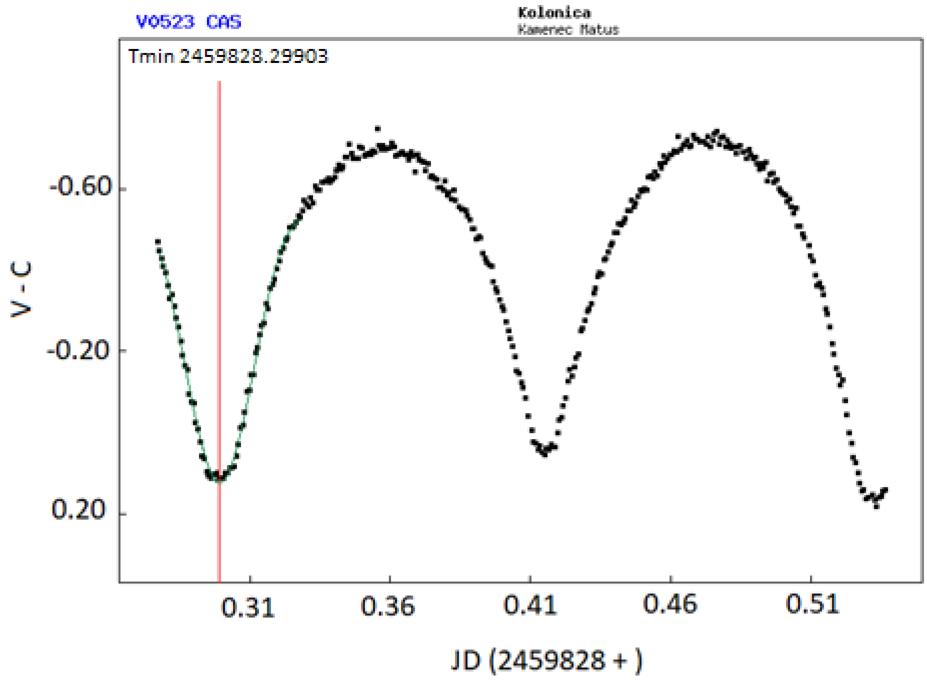

Figure 1: Example of the light curve of V0523 Cas in the "clear" filter, with the primary minimum marked (5 September 2022, Newton 200/1200, Canon 500D)

This method is unsuitable for observing specific physical phenomena visible only in narrow spectral bands. This is one of the disadvantages of an SLR compared to scientific CCD and CMOS cameras with filter wheels. On the other hand, the Bayer SLR mask allows shooting in three different colour channels simultaneously. Our recent experiments focused on the possibility of extracting these channels and their subsequent standardisation.

We performed several specific tests to find specific properties of the SLR used. The linearity of our response was, as expected, excellent up to the saturation level at every ISO setting (Fig. 2).

[1] https://c-munipack.sourceforge.net/
[2] https://www.cbabelgium.com/peranso/
[3] http://var2.astro.cz/

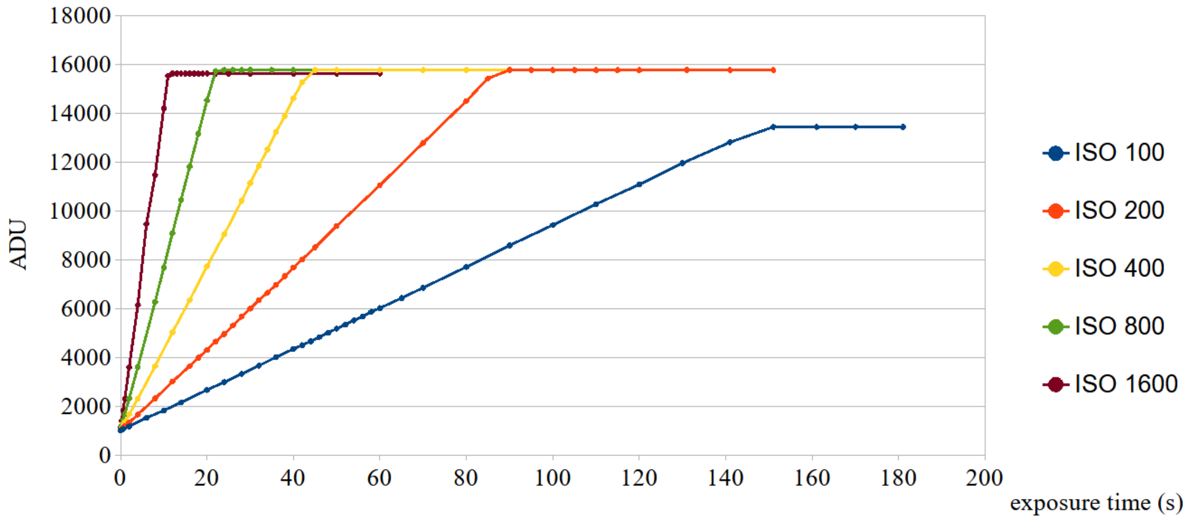

Figure 2: Canon 500D linearity at different ISO levels.

The spectral response of our instrument suggests the possibility of transforming the sensor's B, G, and R channels into the standard B, V, and R_c filters of the standard Johnson-Cousins BVR_c system. Due to the uneven distribution of the light signal in the channels (there are twice as many green pixels compared to blue and red) and the considerable width of the B and R channels, it was possible to expect the most significant degree of inaccuracy in the B and R channels. On the other hand, the profile of the G channel of the SLR corresponds very well to the standard V filter.

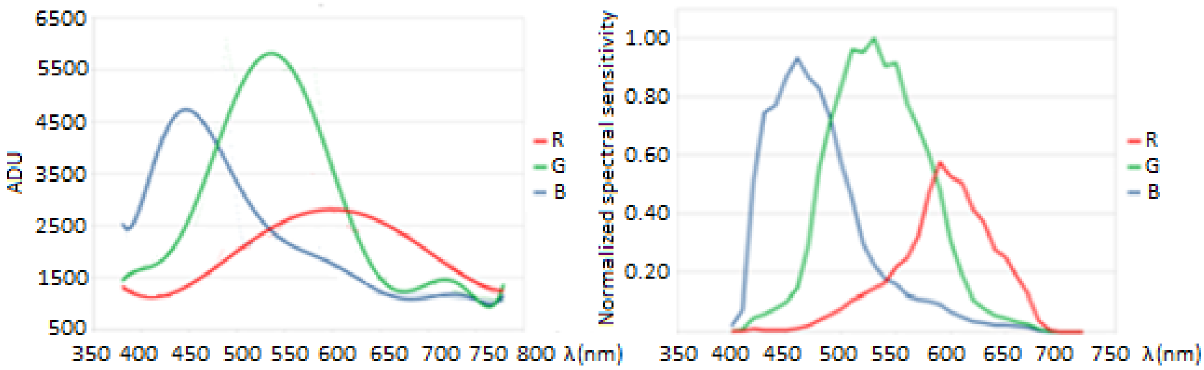

Figure 3: Spectral response of Canon 500D, our measurement on the left, Jiang et al. (2013) on the right

The Canon 500D uses the CR2 format for RAW images. This format enables lossless preservation of raw photometric data for all three colour channels. Before processing, RAW images must be converted to the universal FITS format. Subsequently, it is possible to extract individual colour channels into three sets of images. We do this either using our script or directly in the Muniwin environment.

3 Formulation of transformation equations

According to Henden & Kaitchuck (1982), the most accurate transformation requires measuring a large number of stars at different, even very distant, locations in the sky and finding

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the transformation and extinction coefficients for each filter used, taking into account, in addition to instrumental effects, the influence of atmospheric extinction on the magnitude and colour of the source.

Considerable simplification is provided by an alternative approach that derives the transformation coefficients from the stars measured on the same image. The second order's extinction coefficient is often replaced by zero because its influence is negligible. Suppose the stars are close enough to each other (in units of angular degrees). In that case, the effect of first-order extinction on the stars' brightness and colour index is also subtracted since the light from both stars crosses practically the same thickness of the atmosphere. Our fields of view also meet this condition, while the measured stars are separated from each other by tenths of an angular degree at most.

The distance between the variable and the reference star is usually less significant than 0.2°. This allows us to use a simplified form of the transformation equations without extinction coefficients and find only the transformation coefficients for standardised magnitude and colour indices. According to Benson (1998), catalogue and instrumental colour indices are related by

$$\triangle (B-V) = T_{bg} \Delta (b-g), \quad (1)$$
$$\triangle (V-R) = T_{vr} \Delta (v-r). \quad (2)$$

where T_{bg} and T_{gr} are the transformation coefficients for the standardised colour indices, the resulting form of the transformation equations is then:

$$B_1 = B_2 + \Delta b + T_b T_{bg} \Delta (b-g), \quad (3)$$
$$V_1 = V_2 + \Delta g + T_g T_{bg} \Delta (b-g). \quad (4)$$
$$V_1 = V_2 + \Delta g + T_g T_{gr} \Delta (g-r), \quad (5)$$
$$R_1 = R_2 + \Delta r + T_r T_{gr} \Delta (g-r). \quad (6)$$

Where B_1, V_1, R_1 are standardised magnitudes of the variable star, B_2, V_2, R_2 are the catalogue standard magnitudes of the comparison star b, g, r denote the instrumental magnitudes in the Bayer mask filters, T_b, T_g and T_r are the transformation coefficients for the standardised magnitude in the respective filter.

For bulk data processing in a spreadsheet, we use equations in a modified form:

$$B_1 = b_1 + (B_2 - b_2) + T_b T_{bg} \Delta[(b_1 - g_1) - (b_2 - g_2)], \quad (7)$$
$$V_1 = g_1 + (V_2 - g_2) + T_g T_{bg} \Delta[(b_1 - g_1) - (b_2 - g_2)]. \quad (8)$$
$$V_1 = g_1 + (V_2 - g_2) + T_g T_{gr} \Delta[(g_1 - r_1) - (g_2 - r_2)], \quad (9)$$
$$R_1 = r_1 + (R_2 - r_2) + T_r T_{gr} \Delta[(g_1 - r_1) - (g_2 - r_2)]. \quad (10)$$

Two transformation equations can be used to transform the V filter, but only one is necessary for transformation. The choice depends on whether we choose to calculate the coefficient according to the B or R channel or whether we transform according to the instrumental colour index $(b-g)$ or $(g-r)$. As a rule, we prefer the R channel because it shows less dispersion of the measured values.

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4 Finding transformation coefficients

To verify this method, we selected the open star cluster Melotte 111, which contains enough suitable stars for us. In this case, the star field is not dense enough to cause overlapping objects. The calibration stars are sufficiently isolated from the surrounding field (Fig. 4). We observed on May 11, 2022, shortly after its passage through the meridian. We made 20 exposures with a length of 30 s and ISO 800.

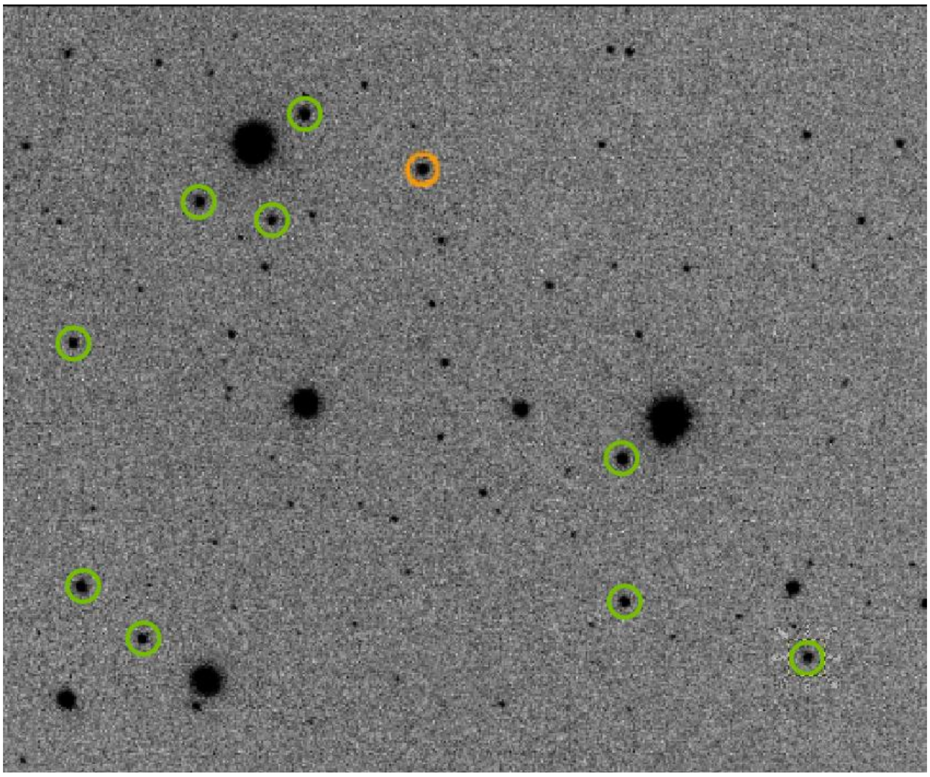

Figure 4: Melotte 111 frame cutout with selected calibration stars

We performed aperture photometry on properly calibrated images using Muniwin. We identified 24 calibration stars in the field. For each star, we determined its average instrumental magnitude for filters B, G+G, and R. As reference magnitudes, we used the values from the photometric table of the corresponding standard Landolt field, listed under the same name on the AAVSO[4] website.

First, we loo anor transformation coefficients T_{bg} a T_{gr} for standardised colour indices $(B-V)$ a $(V-R)$, by plotting dependencies of $(B-V)$ vs $(b-g)$, and $(V-R)$ vs $(g-r)$ (Benson 1998) (Fig. 5).

[4] https://www.aavso.org/

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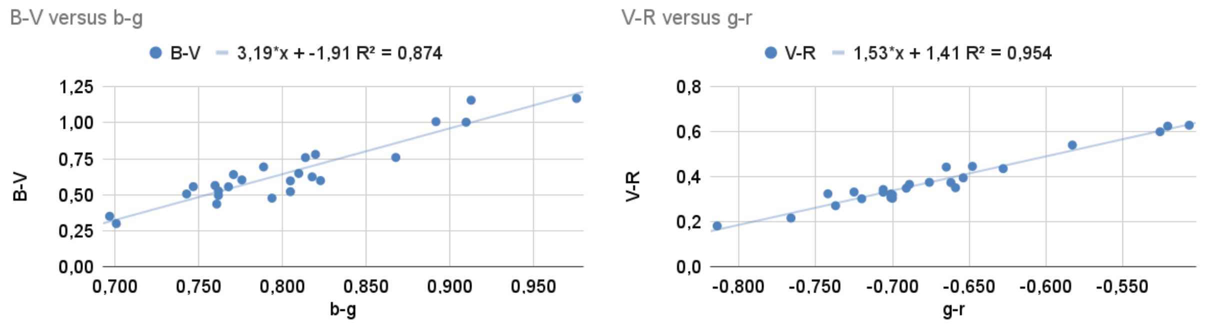

Figure 5: Catalogue vs instrumental colour indices.

Coefficient T_{bg} is given by the slope of $(B-V)$ vs $(b-g)$, and T_{gr} is given by the slope of $(V-R)$ vs $(g-r)$.

The next step was to find the transformation coefficient for the standardised magnitude in each filter of the Bayer mask (Fig. 6), as follows:

T_b is given by the slope of $(B-b)$ vs $(B-V)$,

T_g is given by the slope of $(V-g)$ vs $(B-V)$, or $(V-g)$ vs $(V-R)$,

T_r is given by the slope of $(R-r)$ vs $(V-R)$.

For linear fits, the linear regression function in the spreadsheet environment was used in all cases. For the three colour filters, we obtained a total of five coefficients with the values listed in Table 1.

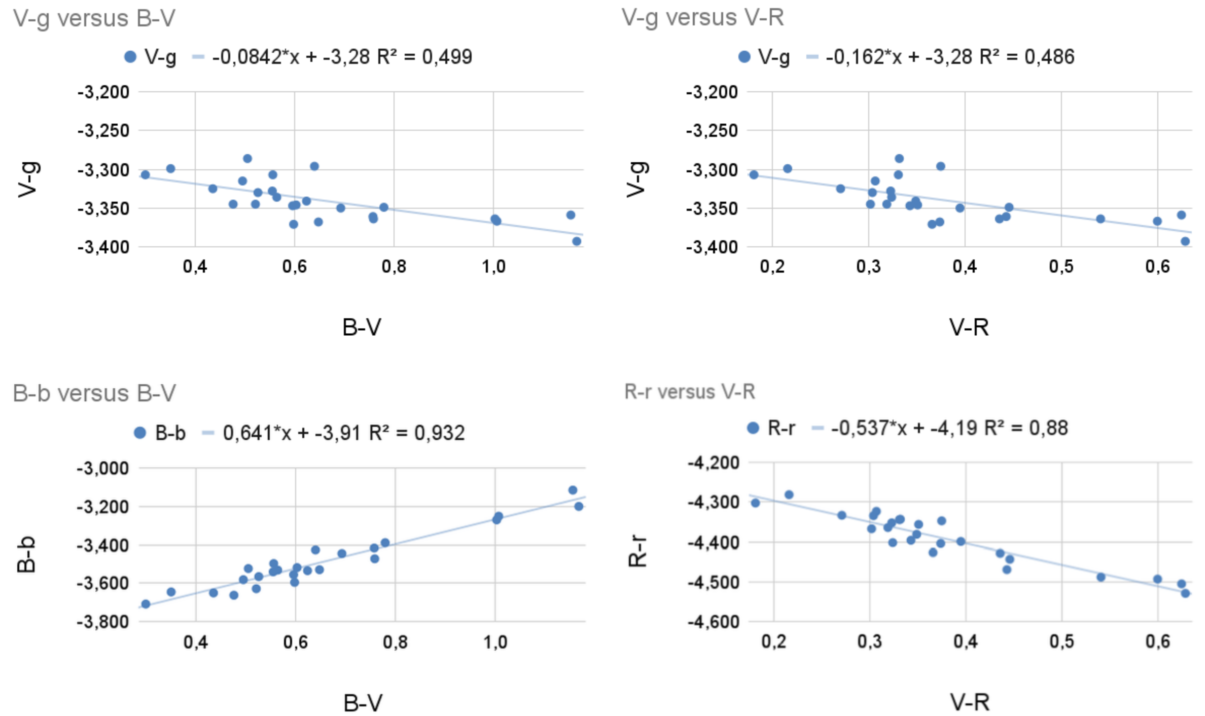

Figure 6: Finding transformation coefficients for standardised magnitudes.

After substituting them into relations (3) to (6), we obtained the resulting transformation equations, with the help of which it was possible to calculate the transformed B, V, and R_c magnitudes of each star. As a comparison, we chose the brightest star from the entire set with a V magnitude of 10.006.

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Table 1: Transformation coefficients for Melotte 111

T_{bg}	T_{gr}	T_b	T_g	T_r
3.186	1.526	0.641	-0.162	-0.537

For each star, we determined the deviation of the transformed magnitude from the catalogue magnitude, which is listed in the photometric table. The average values of these differences ranged at the level of 0.113, 0.019, and 0.032 mag for the B, V, and R_c filters. We can say that in a specific field, it is possible to most accurately determine the transformed magnitudes for the standard V filter using the mentioned procedure. The least reliable seems to be the blue filter of a digital SLR, where the deviations are the highest (Fig. 7).

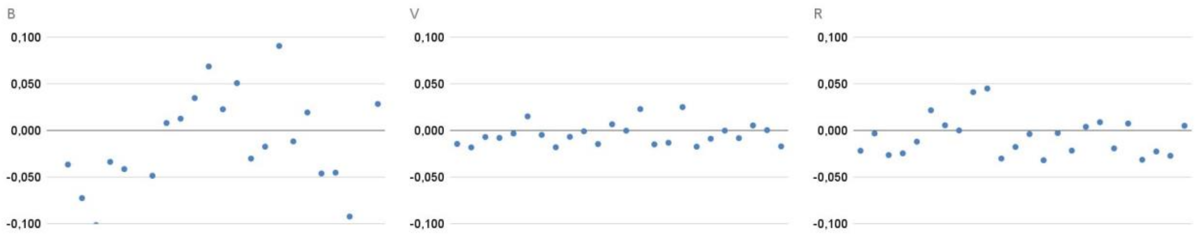

Figure 7: Deviations of transformed B, V, and R_c magnitudes from catalogue values

5 Applications of the transformation method

We verified the described method of transformation of all three channels of a digital SLR on two star clusters (Melotte 111, IC4665) in the spring and summer of 2022. In the case of IC4665, the Canon 500D was mounted on a Newton 200/1200 type telescope.

We also performed transformations of the light curves of seven selected variable stars. Our main goal was to prove whether the given method can be used to obtain relevant light curves for standard B, V, and R filters using a DSLR. By applying the method to selected variable stars and their near fields, we tried to find out what measurement accuracy we could achieve. In each star field, suitable comparison stars were identified, and transformation coefficients were determined. While in some star clusters, we can identify tens of suitable stars, the normal surroundings of variable stars contain a much smaller number of candidates in our field of view, most often around 4 to 5; in exceptional cases, there were 7. Nevertheless, in all cases, it was possible to observe the expected linear dependence of the instrumental deviations from the colour indices and determine the transformation coefficients from them.

The transformed light curves showed very good applicability of the method in all cases, but at the same time confirmed the assumptions related to the properties of the used detector. We recorded the greatest dispersion of data in filter B, the situation is somewhat better in filter R (Fig. 8). The reason is undoubtedly the significant difference in the width of the spectral response of both bands compared to standard photometric filters, the disproportionate number of pixels used compared to the G filter, and a non-negligible influence can also be the presence of additional filters on the sensor of the unmodified device.

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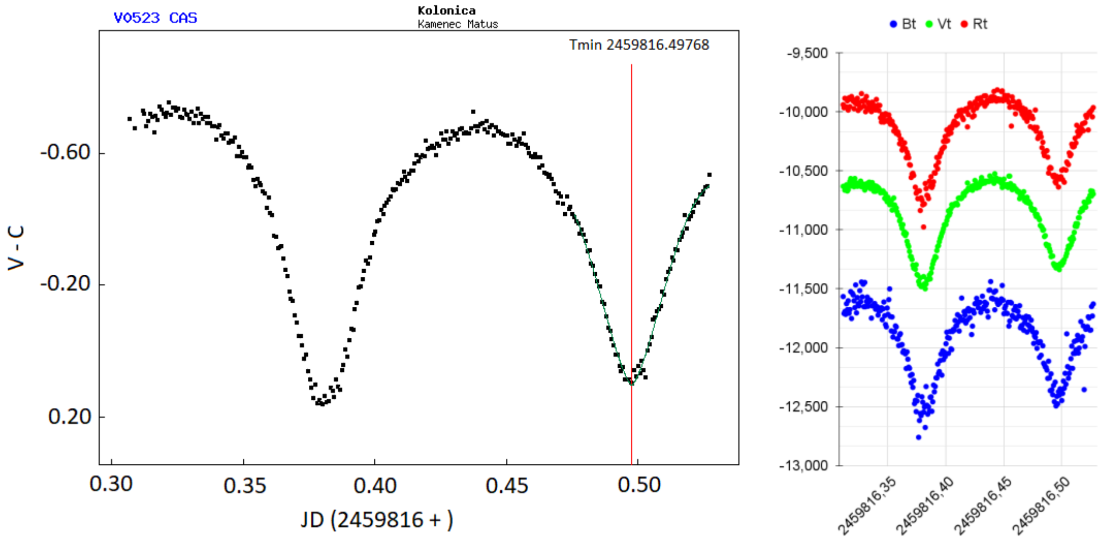

Figure 8: On the left, the light curve in the clear filter; on the right, the transformation into B, V, and R_C filters (V0523 Cas, 24 August 2022, Kolonica)

Changes in the brightness of variable stars are not always strictly periodic, and there may be changes in their phase (e.g. in the depth of minima). We, therefore, verified the relevance of the data obtained by transformation in several ways:

- by comparison with the interval of brightness changes in the V filter (if this data was available)
- by comparison with already published measurements of other observers
- by determining the average value of the standard deviation for each filter

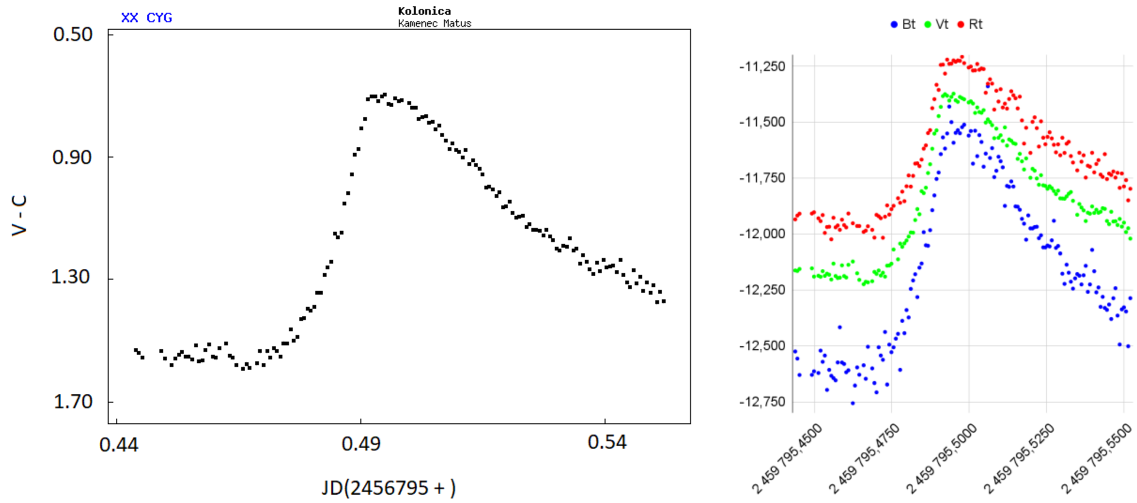

Figure 9: On the left, the light curve in the "clear" filter; on the right, the transformation into B, V, and R_c filters (XX Cyg, 3 August.2022, Kolonické sedlo)

In the case of pulsating variable stars of the HADS type, we could observe a visible difference in amplitudes in filter B and filter V, resp. R (Fig. 9). This is because when a pulsating star brightens, it shrinks and heats up at the same time. This changes the colour index

$(B-V)$ during the phase. For this reason, the transformation coefficients for the standardised colour index should always be determined for transformation.

When observing V0799 Aur on March 14, 2022, in Prešov, the Canon 500D was mounted on a 102/500 refractor. The lower amplitude of brightness changes, less powerful optics, and a higher level of light pollution caused a significant inaccuracy of the B channel, and the transformed light curve became unusable. Therefore, we repeated the measurement of this star, during two consecutive nights in October 2022 on the Kolonica Saddle. We obtained visibly better quality results thanks to better observation conditions and more powerful optics (Fig. 10).

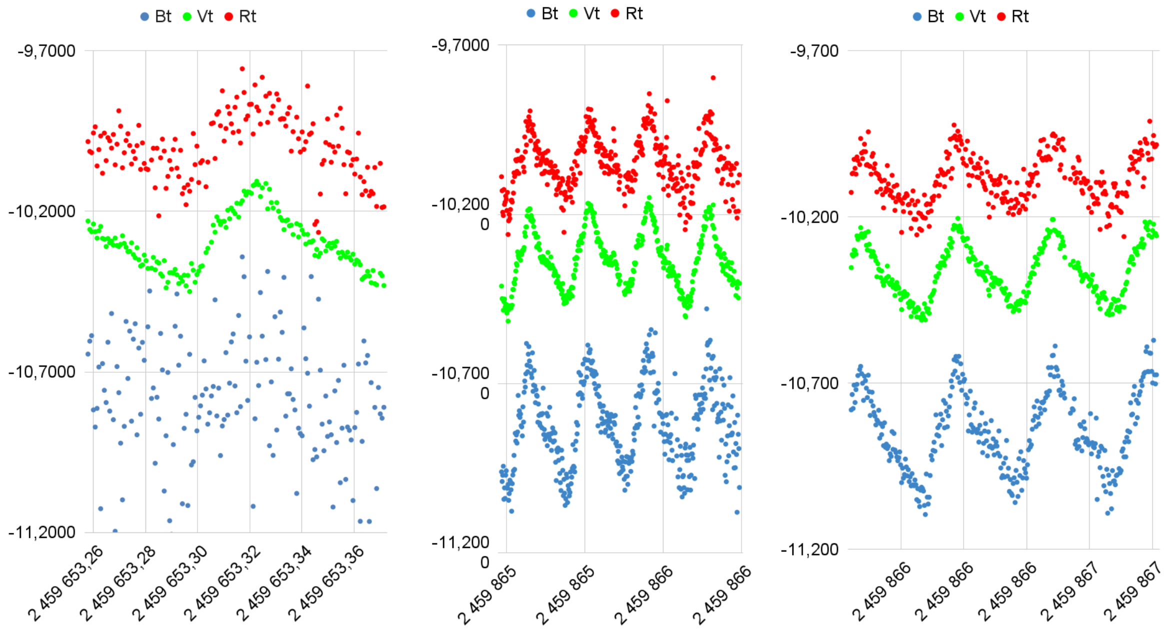

Figure 10: Transformed lightcurves of V0799 Aur, on the left 14 March 2022, Prešov, 102/500, in the middle and on the right 12 October 2022, resp. 13 October 2022, 200/1200, Kolonica Saddle Canon 500D

The measurement of V0799 Aur, carried out on 13 August 2022, also had the character of a comparative verification of the accuracy of the transformation method used (Fig. 11). To eliminate the influence of different observation conditions and different observation times, we observed it simultaneously with a G2-1600 CCD camera mounted on a Schmidt-Cassegrain 200/1200 type telescope. In both cases, the measurements were properly processed, and the data was transformed by equations and coefficients derived for each device individually. The reference star used was the same for both measurements. Figure 11 shows that, except for a significantly higher dispersion for the DSLR, both transformations show very good agreement.

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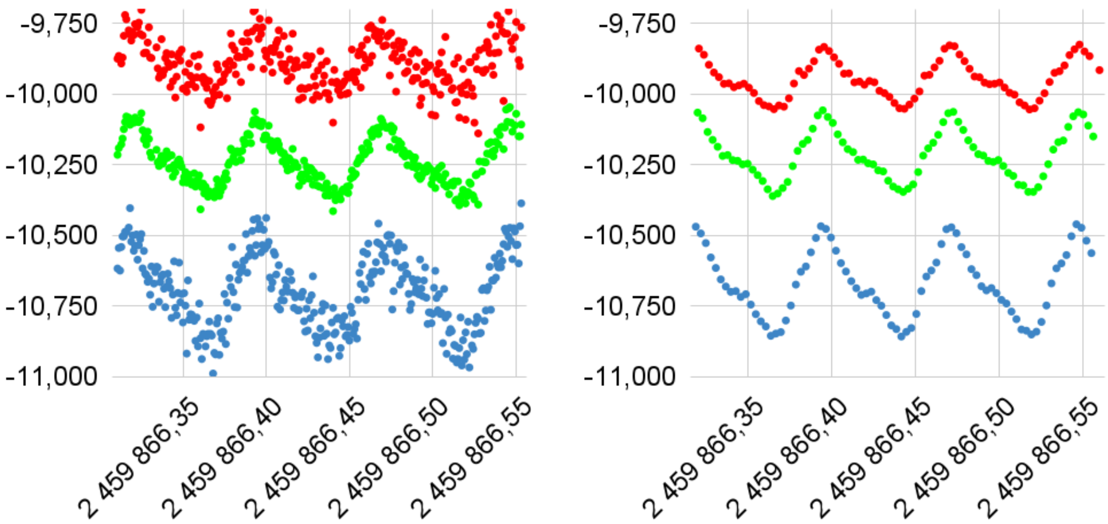

Figure 11: Simultaneous observation of V0799 Aur at the same time, in the same place (13 October.2022, Canon 500D on the left, G2-1600 on the right)

6 Data analysis and results

The differences in the transformed and catalogue magnitudes for the observed clusters are summarized in Table 2, which also contains similar measurements by Park et al. (2016).

Table 2: Differences between transformed and catalogue magnitudes for selected star fields

			Park et al. (2016)	
Filter	Melotte 111	IC4665	M52	IC4665
B	0.113	0.095	0.064	0.095
V	0.019	0.06	0.041	0.094
R	0.032	0.078	0.039	0.07

Table 3 shows the standard deviations of the eclipsing and pulsating variable star observations we made and transformed. All contributing deviations were included in the calculation in terms of error propagation rules thus:

- deviations of instrumental magnitudes (given by photometric software)
- deviations of catalogue magnitudes (obtained from photometric tables)
- deviations in the determination of transformation coefficients (determined in the spreadsheet environment)

As can be seen from the table, we observe the highest inaccuracy in filter B, which corresponds to our expectations. Deviations in this channel are most likely caused by the relatively low sensitivity of the B filter and the significant difference in its profile compared to the standard filter. DSLR devices are primarily intended for daytime photography, so the G filter will probably be the most optimised one. The resulting accuracy is also strongly influenced by the accuracy of the catalogue values. Therefore, they should be obtained from the most reliable source possible.

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Table 3: Standard deviations of transformed BVR magnitudes

Session	Object	Place	*B*	*V*	R_c
05 August 2022	GW Cep	KOL	0.285	0.056	0.015
13 October 2022	V0799 Aur	KOL	0.403	0.058	0.108
14 March 2022	V0799 Aur	PO	0.700	0.058	0.051
17 October 2022	V0380 Dra	KOL	0.367	0.041	0.042
05 August 2022	BS Cas	KOL	0.029	0.007	0.014
03 August 2022	XX Cyg	KOL	0.100	0.020	0.053
24 August 2022	V0523 Cas	KOL	0.099	0.035	0.021

7 Conclusions

Instrumental B, G, and R magnitudes. taken with a DSLR, can be transformed into the standard Johnson-Cousins BVR_c photometric system, respectively, into its bands B, V, and R_c. Since the colour index of some types of variable stars changes with phase, the method of calculating transformation coefficients for both standardised colour deviations and standardised colour indices appears to be reliable.

The most extensive spread of values, and thus the lowest measurement accuracy, is to be expected for the transformed filter B. This was manifested on the one hand in the difference between the transformed magnitudes and the catalogue values during cluster measurements (Tab. 2), on the other hand, in the standard deviation of the measurement when applying the method to eclipsing and pulsating variable stars (Tab. 3).

So it can be expected that small details, caused by specific physical effects on the observed object, will not be possible to follow on the transformed curve in filter B. The best values are given by filter V, where accuracy at the level of 0.03 – 0.05 mag can normally be achieved with a DSLR, in some cases up to 0.005 mag, and even in the case that a relatively small number of stars is used (approx. 5) to calculate the transformation coefficients. Comparative measurement, carried out in the same place and at the same time using a DSLR and a CCD camera showed the reliability of the method used and the relevance of the data obtained in this way compared to other types of detectors.

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