Research Article

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Astrometry and photometry of digitized plates of Baldone Schmidt telescope

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Abstract: During the 40-year photographic period of astronomical observations, the Baldone Astrophysical Observatory has accumulated more than 22,000 direct and 2,500 spectral images. In 2018, the digitization of direct astrophot images with a resolution of 1200 dpi was completed. A processing methodology for obtaining the equatorial coordinates and photometric characteristics of the objects recorded in digitized astronegatives using the LINUX/MIDAS/ROMAFOT environment has been developed at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine. Program package with success already works in seven observatories. A description of the operation of this program complex in stages and analysis of the obtained results is given. The steps describe the astrometric and photometric reduction process of digital records, as well as the reduction of the obtained instrumental magnitudes to the Johnson UBVR photometric system. The methodology of characteristic curve construction in the case of one exposure is described in detail. From all digitized astrophotplates to date Approximately 2200 V film negatives, 300 U plates and several R, B plates were processed. As a result, catalogs of the positions and magnitudes of Pluto, 1848 asteroids and comets were obtained. 31 new positions were recorded in the VizieR Pluto catalog VI/155. It was found that the root-mean-square errors of the reduction of the measured coordinates to the equatorial coordinate system of the Tycho-2 catalog have values $\sigma_{RA,DEC} = 0.1-0.2''$, and the root-mean-square errors of the reduction of instrumental photometric quantities m to the Johnson system of stellar UBVR-values are also in within $\sigma_{UBVR} = 0.1 - 0.2^m$.

Keywords: astronegative, scanning, processing of digitized records, characteristic curve, UBVR photometry, G, BP, RP GAIA DR2, asteroids, Pluto

1 Introduction

One of the main tasks of astronomers is to obtain observational data on various objects in the universe and save this data for future use, as observational material is the basis of research. Initially, the observational data were stored directly or processed in paper records or later in the form of printed matter stored in libraries. After the discovery of the photographic process, for almost 100 years, astronomers have recorded their observations on a layer of photoemulsion and stored them in the archives of astronomical plates.

The Baldone Schmidt telescope (80 cm correction lens / 120 cm mirror diameter / 240 cm focal length / field of view 19 square degrees) is located at the Baldone Observatory (IAU Code 069), 103 m above the Earth's geoid on the Riekstkalns Hills ($\lambda = 24.4041^\circ$ E, $\delta = 56.7734^\circ$ N), 4.5 km

from the small town Baldone. The telescope started operations on December 1966. Direct observations were made in U ($\lambda_0 = 362 \text{ nm}$; $\Delta\lambda = 81 \text{ nm}$), B ($\lambda_0 = 431 \text{ nm}$; $\Delta\lambda = 96 \text{ nm}$), V ($\lambda_0 = 533 \text{ nm}$; $\Delta\lambda = 103 \text{ nm}$), R ($\lambda_0 = 631 \text{ nm}$; $\Delta\lambda = 144 \text{ nm}$), I ($\lambda_0 = 798 \text{ nm}$; $\Delta\lambda = 175 \text{ nm}$) photometric bands (Duncans 1979) and were realized using the emulsion and filter combinations listed in Table 1.

The initial focus of the Baldone astronomers scientific interests were on stellar astronomy and in particular on the study of carbon stars and their properties (Alksnis *et al.* 1998a,b; Alksne *et al.* 1991). Therefore, the majority of the direct and spectral plates were taken at the galactic equatorial region where carbon stars are concentrated. The large field of view of the telescope made it easy to monitoring the novae bursts in the Andromeda galaxy (Alksnis *et al.* 2008). A relatively smaller number of astronomical plates have been obtained to study characteristics of clusters in the vicinity of carbon stars (Daube 1982; Alksne and Daube 1981a,b), and the orbit of Pluto (Eglitis *et al.* 2018a,b). The archive of astronomical plates contains a unique set of images, which differs from others in that it contains regular observations in selected areas of the sky. It provides an op-

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Table 1. Combinations of emulsions and filters used to provide observations in U, B, V, R, I systems.

Emulsion	Filter	Number of images
	-	
ZU21	-	262
ZU1	-	119
ZP3	-	21
A500N	-	20
	U	
ZU21	UG1	337
ZU2	UG1	229
ZU21	UFS3	86
ZU1	UG1	62
	B	
ZU21	GG13	2783
ZU2	GG13	1692
NT-1AS	GG13	337
A500N	GG13	206
	V	
A600N	ZS17	2102
A600	ZS17	1692
A600U	ZS17	409
A600RP	ZS17	235
	R	
ZP1	RG1	7075
ZP1	KS13	1692
ZP3	RG1	764
A700N	KS13	241
	I	
IN	KS19	877
IN	RG1+BG3	441
I840	RG1	26
IVN	KS19	101

portunity to solve many astronomical tasks, including the study of the dynamics (Platais 1994) variability phenomena of the stars (Alksnis 2003) over a period of 40 years without spending decades making additional observations. In addition, the archive data has proven useful in the field of research of small bodies: asteroids and comets in the solar system too (Shatokhina *et al.* 2019). The total time distribution of the obtained astrophotographic plates in different photometric systems is shown in Figure 1.

The digitalization of the Baldone Schmidt archive started at 2012 using one flat bed scanner Epson Expression 10000XL; three more were added in 2014, and was completed in 2018. The processing LINUX/MIDAS/ROMAFOT methodology developed at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine was used to obtain the rectangular coordinates and photometric characteristics of the objects recorded in the digitized astronegatives, (Andruk *et al.* 2005). The program package is already being used with success at the Main Astronomical Observatory NASU (Kyiv, Ukraine), Research

Figure 1. The total number of astrophotoplates and their number obtained in U, B, V, R, I photometric systems in different years.

Institute “Mykolaiv Astronomical Observatory” (Ukraine), Baldone Observatory, Institute of Astronomy, University of Latvia (Riga), Ulugh Beg Astronomical Institute UAS (Tashkent, Uzbekistan) (Yuldoshev *et al.* 2019b), Institute of Astrophysics of the Academy of Sciences of the Republic of Tajikistan (Dushanbe) (Mullo-Abdolov *et al.* 2018), Walter Hohmann Observatory, Essen (Germany) (Relke *et al.* 2015) and Astronomical Observatory of Kyiv Shevchenko National University (Ukraine) (Kazantseva *et al.* 2015). Applications require a specifically installed LINUX environment. The specific size and resolution of astronomical photographic plates require small changes in the programs, as well as working with them requires certain skills. The developers of the program will help those interested to do all this.

In order to study the accuracy of commercial Epson scanners in terms of their practical application for astrometric and photometric tasks in astronomy (Protsyuk *et al.* 2014), to capture images of star fields, six types of plates were exposed with six different telescope: Baldone Schmidt Telescope of Institute of Astronomy of University of Latvia, Double Wide Angle Astrograph of Mainn Astronomical

observatory of National Academy of Sciences of Ukraine, Zonal Astrograph Research Institute of Nikolaev Astronomical Observatory, Normal Astrograph of Ulugh Beg Astronomical Institute of the Uzbek Academy of Sciences, Wide Angle Astrograph of Astronomical observatory of Taras Shevchenko Kyiv National University and Wide Angle Astrograph of Astronomical Observatory, Odessa National University, to estimate the astrometric and photometric errors of scanners, we made six scans for each of six plates with a different resolution from 600 till 2450 dpi. Using the Epson scanners and the developed software allowed us to digitize and process the plates and obtain the astrometric characteristics of objects with an internal accuracy better than $\sigma_{\alpha\delta} = \pm 0.1''$ for plates with angular scale up to $2.5''/\text{px}$ at a resolution of 1200 dpi. The studies of internal accuracy of astrometric and photometric characteristics of objects show that the best option for digitizing is the 1200 dpi for plates with angular scale up to $2.5''/\text{px}$. High-resolution modes require more processing and digitizing time, and do not give the gain for accuracy. Therefore, 1200 dpi has been chosen as the most economical solution as the basic resolution in the digitization process (Yuldoshev *et al.* 2019a).

The U plates and V films obtained with the Baldone Schmidt are a good addition to the FONAC catalogue data obtained as a result of processing the FON program observations which supposed to provide the four-fold overlapping of the northern sky by several similar telescopes of objects down to $B \leq 16^m.5$. Photometric values of stars were derived from data of AST, GSC 1.1, USNO A2.0. The catalog includes 19 568 347 astrometric and photometric data of stars and galaxies at the epoch 1988.1 (Andruk *et al.* 2016a,b). The accuracy of FONAC dependence on object brightness is evaluated as $\pm 0.18 - 0.25''$ for positions and $\pm 0.18 - 0.25^m$ for brightness. As a rule, errors increase for stars brighter than 7.5^m and fainter than $11^m.5$.

2 Corrections for systematic scanner errors

Most of the Commercial) scanners have systematic astrometric errors, in particular the values of scanning errors along the Y coordinate, i.e., in the direction of motion of the CCD, are especially large. When scanning with a spatial resolution of 1200 dpi, a 1.2 m Schmidt telescope plate measuring 24 x 24 cm has a working field size of approximately 10500x10500 px. For the Epson Expression 10000XL scanners, the amplitude of the differences in the equatorial

coordinates between the calculated and catalogue values reaches $\Delta\alpha = \pm 0.5''$ and $\Delta\delta = \pm 1.8''$ (Protsyuk *et al.* 2014).

The results of scanning and processing of test plate No. 16036 (photographed with an exposure of $t = 12$ min on August 20, 1987 in the V band (A600N film + filter ZC17)) are presented in Figure 2. The bias of systematic differences between the calculated and catalogue values of the equatorial coordinates $\Delta\alpha, \Delta\delta$ relative to the rectangular coordinates of the X, Y plate (panels 1a, 1c) and also relative to the magnitude V of the Tycho-2 catalogue (panels 1b, 1d) is shown on the left. The mean square errors of the differences of the equatorial coordinates are equal to: $\sigma_\alpha = 0.237''$ and $\sigma_\delta = 0.605''$.

After correcting for systematic errors of the scanner and accounting for optics aberrations, the distribution of residual random differences is presented in Figure 2 to the right (panels 2a, 2c and 2b, 2d, respectively) and the errors have the following meanings: $\sigma_\alpha = 0.069''$ and $\sigma_\delta = 0.079''$.

The correction of the measured X, Y coordinates for the systematic errors of the scanner is done in practice as follows. Dividing the plate length in slices along $L_Y \approx 10500$ (along the scanning direction) by the number of reference stars (for the studied region, for example, from the Tycho2 catalogue) $K \approx 1900$, we obtain the initial approximation step $s = L_Y/K \approx 5 \text{ px}$ ($s = 10500/1900 \approx 5 \text{ px}$), i.e. there must be at least one star from the Tycho-2 reference catalog for/on each step of length s .

If there are two or more reference stars in the slice, the reference points are calculated for the middle of the slice as the average deviation of these stars $\Delta X = \Delta\alpha/M$ and $\Delta Y = \Delta\delta/M$ (where the scanning scale M is $1\text{px} \approx 1.82''$) from the true position on the plate. In absence of reference stars in the step in calculating the deviations of the reference points $\Delta X, \Delta Y$ is absent, the interpolation is done according to the values of two neighbouring slices.

During the processing of the plate, the deviation values for the determined stars $\Delta X, \Delta Y$ are calculated by interpolation relative to neighbouring reference points. The details about the systematic errors of the scanner are shown on panels 1e, 2e, 3e. The points correspond to the values of real deviations, and the continuous line is responsible for the reduction numerical model. Note that the full reduction of the rectangular coordinates X, Y to the equatorial coordinate system α, δ is done in three successive cycles (approximations), in each cycle the length of the step s increases by the value of the step $s + s$ itself. The magnitude of the errors of the differences in the equatorial coordinates between the calculated and catalogue values $\sigma_\alpha, \sigma_\delta$ in the third and fourth cycles coincide or are very close in value.

Figure 2. On the four upper panels on the left show the course of scanner systematic errors before correcting for systematic scanner errors, on the right - the values of errors after eliminating scanner systematic errors and telescope optics aberrations. On the three lower panels, the systematic errors of the scanner for the Y coordinate are sequentially shown in an enlarged form, the individual deviations for the reference stars correspond to the points, the continuous line and circles (3e) are the result of the approximation of the systematic errors of the scanner.

3 Astrometric reduction in the Tycho-2 catalogue system

For wide stellar fields exposed to the plates, both when diagnosing systematic errors of the scanner σ_α and σ_δ , and when reducing the rectangular coordinates X, Y of objects to the equatorial coordinate system α , δ of the Tycho-2 catalogue, the tangential coordinates ξ , η were calculated using the least squares according to formulas of the form (1, 2):

$$\xi_i = a_1 + a_2 X_i f_i + a_3 Y_i f_i + a_4 R_i m_i + \sum b_{lm} X_i^l Y_i^m, \quad (1)$$

$$\eta_i = c_1 + c_2 X_i f_i + c_3 Y_i f_i + c_4 R_i m_i + \sum d_{lm} X_i^l Y_i^m, \quad (2)$$

where $l = 0 \div 6$, $m = 0 \div 6$, $l - m = n$, $n = 1 \div 6$ and $i = 1, 2, \dots, N$ is the number of stars of the Tycho-2 catalogue on

Figure 3. The processing results of the plate No. 16036. On the left systematic errors of alpha and delta along the field of the plate before corrections, on the right is the residual differences (random errors) alpha and delta for the counted and catalog values of the equatorial coordinates.

the plate; X_i , Y_i and R_i - coordinates and distance of the images of stars relative to the center of the plate; m_i are instrumental photometric magnitudes of stars; f_i - star image diameters (FWHM); the coefficients a_2 , a_3 , a_4 and c_2 , c_3 , c_4 are responsible for the full sixth degree polynomial (27 terms); b_{lm} and d_{lm} in the generalized case describe aberrations of telescope optics burdened by systematic errors of the scanner.

The Figure 3 shows the results of processing the test astronegative No. 16036. The systematic errors of the telescope σ_α , σ_δ along the field of the plate (mask of aberrations of the telescope optics) are shown on the left, the error values have the following values: $\sigma'_\alpha = 0.846''$ and $\sigma'_\delta = 0.956''$; the distribution of residual differences $\Delta'\alpha$, $\Delta'\delta$ for the calculated and catalogue values of the equatorial coordinates is also given on the right for the plate field. Negative and positive differences in coordinates correspond to icons in the form of horizontal and vertical dashes, the size of which corresponds to that shown in the middle of Figure 3 scale of values. The error values are determined from averaging data in cells with size 250 x 250 pixels.

For the error estimate in the reduction of rectangular coordinates to the equatorial coordinate system α , δ of the Tycho-2 catalogue, two plates No. 247 and No. 248 were pro-

Figure 4. Root mean square errors the equatorial coordinates (RA – Blue line, DEC – red line) and magnitudes (U(ph) – green line) for different intervals of U(ph). Number of stars in the interval is given by numbers.

Figure 5. Root mean square errors the equatorial coordinates (RA – Blue line, DEC – red line) for different intervals of B(T). Number of stars in the interval is given by numbers.

cessed, which were successively recorded in the Johnson U band (emulsion ORWO ZU21, filter UG1) on December 20, 1968 with exposure for 20 minutes. According to the results of processing these two plates for common stars in the overlapping zone, for the intervals of photographic stellar magnitudes U_{ph} , the root mean square errors of determining (from internal convergence) the equatorial coordinates and photographic stellar magnitudes σ_{RA} , σ_{DE} , $\sigma_{U_{ph}}$ were calculated. The error data are shown in the Figure 4. Common objects on plates are 22671

For the average values of the equatorial coordinates counted for these two plates, in the Figure 5, the rms errors of the differences σ'_{RA} , σ'_{DE} , the calculated and catalogue values of the equatorial coordinates of Tycho-2 stars are given for intervals of stellar B_T -magnitudes.

4 Photometric reduction to Johnson's UBV system

The Johnson photographic UBV system at the 1.2m Schmidt telescope of the Baldone Observatory was implemented as follows: U band = ORWO ZU1 plates + UG1 filter, B band = ORWO ZU2 plates + GG13 filter, V band = A600 film + ZS17 filter, R band = plates ORWO ZP1 + filter RG1. In the paper (Andruk *et al.* 2017a,b; Eglitis *et al.* 2016a,b,c; Pakuliak *et al.* 2016) were given examples of the reduction of instrumental photometric magnitudes m to the UBV system of stellar magnitudes are given.

4.1 Creation of an empirical characteristic curve for calibrating images with a single exposure

In order to generate the empirical characteristic curve we chose two random, obtained at good quality weather, long exposition plates No. 1809 and No. 1834. Its were exposed for 40 and 60 minutes in the U band (emulsion ORWO ZU2, filter UG1) on 21.11.1971 at the 1.2m Schmidt telescope of the Observatory in Baldone. The astronegatives were digitized using an Epson Expression 10000XL scanner (Eglitis *et al.* 2017). The sky region containing the cluster NGC 7419 ($RA = 23^h 01^m 30^s$, $DEC = 60^{\circ} 32'$) was exposed on the plates. On the Figure 6 top panel is presented the following data: along the X axis – the scale of U values in the Johnson system, along the Y axis – the scale of instrumental values; points and crosses are stars with photoelectric and CCD measurements, respectively.

The linear part of the characteristic curve for astronegative 1' (No. 1834) is approximately in the range $U = 10 - 15^m$ and characterizes the contrast of the astronegative $\gamma = -0.53$, the dispersion of the points is $\sigma_U = 0.189^m$. On the flat part of the characteristic curve (from $U > 15^m$ till $U < 18^m$), all faint and extremely faint stars up to $U = 18^m$ are fixed, which are used as standards for constructing the latter. The dashed line (below $m < 6^m$) is the extrapolation region.

On the panels b, c, d of Figure 6 are shown a section of the characteristic curve ΔU with respect to the distance from the center of the plate R , the color index $B - V$, and the value U itself. To the right and lower from the curve 1'-curve 1 ($\gamma = -0.49$) for the astronegative No. 1809, which we further used in the form of a table to construct individual characteristic curves of various astronegatives (Andruk *et al.* 2019).

Figure 6. Characteristic curves for plates No. 1834 (1') and No. 1809 (1), exposed in the U band at the 1.2 m baldone Schmidt telescope (panel a). In panels b, c, and d, a section of the characteristic curve 1' for the distance from the center of the plate, relative to the color index B-V and along the magnitude U, respectively. Dots and crosses correspond to photoelectric and CCD measurements of stars.

4.2 Examples of constructing individual characteristic curves. Reduction to Johnson's UBV system

The stages of constructing a specific characteristic curve using the empirical characteristic curve information are presented using random plate No. 775 captured in the R band (exposure time 7 minutes) on 14.10.1969 as an example. On panel a), the empirical curve 1 is indicated by a continuous line, and part of the real characteristic curve (without the faint stars in the underexposure region) is indicated as 0 and consists of points. To construct a characteristic curve for this plate, we first cut off for bright and very faint stars (as unnecessary in this case) and shift down and to the right (curves 2 and 3) of the remainder part of the empirical characteristic curve 1 (shown in Figure 7, panel b).

Figure 7. Stages of constructing the characteristic curve for plate No. 775 exposed in the R band at the 1.2 m Baldone Schmidt telescope.

Then, the contrast of the empirical curve 2 ($\gamma = -0.49$) is reduced to the contrast of the plate with $\gamma = -0.42$ (curve 4) and it is shifted vertically downward (curve 5) - shown in panel c). Shifting the curve 5 to the right is the last step for plotting of part 6 by the curve for plate No. 775, displayed in the red region of the spectrum (panel d). Crosses indicate the extreme points of the constructed characteristic curve for bright (a) and extremely weak (b) stars. In constructing the characteristic curve for this plate, we used the stellar magnitudes R Johnson obtained as a result of reduction according to equations of the form (3) and (4). Note that all kinds of shifts of the empirical curve 1 and the change in its contrast relative to the real characteristic curve 0 for this plate are made from a comparative analysis of the linear parts of these two curves using data on the lower left points of the real characteristic curve 0.

On Figure 8 are shown examples of constructed characteristic curves for all four UBV bands of the Johnson system. To construct the characteristic curves for specific plates, combinations of sequences of photoelectric U, B, V,

Figure 8. Characteristic curves with different exposures for astronegatives captured in four UBVR bands of the Johnson system at the 1.2m Baldone Schmidt telescope.

R measurements of stars and an empirical characteristic curve were used. For different exposures, four characteristic curves for passband U (panel a), two characteristic curves for passband B (panel b) and three characteristic curves for passband V and R (panels c and d, respectively) are shown. Designations in Figure 8 are the following: points – corrected for contrast y data from the empirical curve, circles – data on photoelectric measurements of stars in the UBVR system. For each characteristic curve, the exposure time, the values of the contrast coefficients γ and the errors in constructing the characteristic curves σ are indicated.

$$U'_i; B'_i; V'_i; R'_i = c_1 + c_2 X_i + c_3 Y_i + c_4 X_i^2 + c_5 Y_i^2 + c_6 D_i + \sum d_n m_i^n \quad (3)$$

where $n = 1, 2, \dots, 5$ and $i = 1, 2, \dots, N$ is the number of determinations for standard stars on the plate; X_i , Y_i and D_i are

Figure 9. Photometric field error for plates exposed in U, B, V, R bands.

the coordinates and the distance of the images of stars relative to the center of the plate; m_i are instrumental photometric magnitudes of stars; the coefficients c_2, c_3, c_4, c_5, c_6 are responsible for the photometric equation (photometric error) of the field, and the coefficients d_1, d_2, d_3, d_4, d_5 correspond to the functional description of the form of characteristic curves. This type of equations (3) is selected as optimal for calculating the stellar magnitudes U' , B' , V' or R' . On the panels e, f, g, h and i of Figure 7 for $k = 337$ stars, the differences between the calculated R' and catalogue R values $\Delta R = R' - R$ ($\sigma = 0.13^m$) with respect to the rectangular coordinates X and Y , at the distance from the center of the plate D , for the color indices $V-R$, and the stellar magnitudes R Johnson are given.

As an example for specific astronegatives, on Figure 9 is presented a visualization of the systematic part of the photometric errors along the field of the plates exposed in the U, B, V, R bands (panels a, b, c, d, respectively). Values of error values are obtained by averaging for cells of size 250×250 px.

4.3 On the photometric reduction of digitized astronegatives to Johnson's BVR system using the magnitude G, BP, RP GAIA DR2

The 1.2m plates of the Schmidt telescope of the Baldone Observatory are exposed and processed on the U, B, V, R bands of the Johnson system. For specific astronegatives, the reduction of the measured photometric values of m to a system of photographic Johnson magnitudes U, B, V, R was made using photoelectric measurements of stars in the same system. When the catalog of photoelectric measurements of stars contains only U, B, V values and there are no R [as, for example, in the catalog (Mermilliod 1991), the authors used the following for photometric calibration (construction of characteristic curves) of R plates. From the research catalogue (Andruk 1996; Kornilov *et al.* 1991; Relke *et al.* 2015) of photoelectric measurements of stars in the U (W) BVR system, it was found that there is a functional relationship between the color indices B-R and B-V of the following form (4):

$$B - R = 0.019 + 1.914(B - V) - 0.303(B - V)^2 + 0.105(B - V)^3, \quad (4)$$

where $\sigma_{(B-R)} = 0.053^m$; but for the first, second, third and fourth coefficients errors are ± 0.001 ; ± 0.006 ; ± 0.014 ; ± 0.008 respectively.

This result was obtained from 11,524 photoelectric measurements of stars and is shown in Figure 10. For the same stars, comparing the B-R photoelectric quantities with the color indices $(B - V)_T$ of the Tycho-2 catalogue, the following values were obtained for equations of the form (5)

$$B - R = 0.103 + 1.468(B - V) - 0.061(B - V)^2 - 0.005(B - V)^3, \quad (5)$$

where $\sigma_{(B-R)} = 0.207^m$; but for the first, second, third and fourth coefficients errors are ± 0.003 ; ± 0.004 ; ± 0.001 ; ± 0.001 respectively.

Because often in the measured and primary processed stellar fields of the digitized plates under study there are absent (fully or partially) stars with photoelectric measurements in the Johnson R system, the authors used (and recommend for use) for constructing characteristic curves of astronegatives of the RP value from the GAIA DR2 catalogue (Brown *et al.* 2018). According to the research results, for 11,185 stars from this sample, the RP GAIA DR2 values are related to the stellar magnitudes of the R Johnson system as follows (see equation 6 and the panel c demonstration in Figure 11):

$$G - R = -0.019 + 0.544(BP - RP) - 0.121(BP - RP)^2, \quad (6)$$

Figure 10. Comparing the B-R photoelectric quantities with the color indices (B-V) of the Tycho-2 catalog.

where $\sigma_{(G-R)} = 0.066^m$; but for the first, second and third coefficients errors are ± 0.001 ; ± 0.004 ; ± 0.003 respectively.

It was also found that the b and G values of GAIA DR2 are reduced to the B and V values of the Johnson system using equations (7) and (8) of the following formulas of the form:

$$G - B = -0.011 - 0.661(BP - RP) - 0.364(BP - RP)^2, \quad (7)$$

where $\sigma_{(G-B)} = 0.069^m$; but for the first, second and third coefficients errors are ± 0.001 ; ± 0.004 ; ± 0.003 respectively.

$$G - V = -0.026 - 0.038(BP - RP) - 0.165(BP - RP)^2, \quad (8)$$

where $\sigma_{(G-V)} = 0.059^m$; but for the first, second and third coefficients errors are ± 0.001 ; ± 0.004 ; ± 0.003 respectively.

The reduction results are shown in Figure 11 a, b panels. The figure shows the reduction errors σ and the number of stars k . The reduction equations (6), (7), and (8) can be useful for determining stellar B, V, R values for plates exposed in the blue, visual, and red parts of the spectrum with insufficient or no photometric standards.

Figure 11. Relationship between the B, V, R Johnson photoelectric stellar magnitudes and the BP, G, RP GAIA DR2 stellar magnitudes.

5 The first results

The digitized data of open star clusters in UBVR color bands, obtained at the Baldone Observatory, will be used to supplement the photometric characteristics of stars in the catalogs of the Northern Sky Survey. In addition to the star images, the numerous observations of stellar areas comprise the records of moving objects of the Solar system. Extracted this data from the digitized processing results, we compiled a catalog of 1848 positions and magnitudes of asteroids and comets (<http://gua.db.ukr-vo.org/starcatalogs.php>). About 300 photographic plates and 2200 film negatives exposed in U and V color bands have been used to asteroid identification. In contrast to the classical methods of image visualization, we used an analytical method to identify asteroids, based on a comparison of the obtained processing results and the calculated asteroid ephemeris of the JPL online service (<http://ssd.jpl.nasa.gov>). The catalog includes

1678 and 170 asteroid positions and magnitudes from observations in the V and U bands, respectively. It also contains seven positions and magnitudes of comets. Its data analysis is described in detail in the publication (Eglitis *et al.* 2019a,b). Among the objects in this catalog are asteroids of particular interest. It was found that 490 faint asteroids have the first predisccovery observations with the Baldone Schmidt telescope. The discovery of these objects took place only 20-40 years later. Their individual location and the O-C difference compared to the other asteroid positions in the catalog are shown in Figure 12 and Figure 13.

Figure 12. Distribution of O-C differences along right ascension for all and first predisccovery asteroid observations in the catalog.

Figure 13. Distribution of O-C differences declination coordinates for all and first predisccovery asteroid observations in the catalog.

Earlier, in 2016, the first asteroid positions in the R and B color bands were obtained. The catalog of coordinates, and magnitudes for 40 asteroids is presented at the Baldone observatory WinSCP server <ftp@Schmidt.lu.lv> and

the results are also presented in publications (Eglitis *et al.* 2016a; Shatokhina *et al.* 2017).

As the next result of the developed methodics, the positions of Pluto were also obtained from the digitized observations of the Baldone archive. Pluto is a fairly complex object for observation by ground-based instruments – distance, size and the inclination of the orbit against the ecliptic creates some technical difficulties, particularly, use of exact methods of laser and radar are impossible. At the same time, since the discovery of Pluto, observations have only covered a little more than one-third of the planet's orbit. Therefore, every successful series of observations, as well as a single nightly observation are important and need to be recorded in the catalog and processed. The Vizier database currently includes 20,527 catalogs, of which only six catalogs contain the astrometric positions of Pluto. Previously, using digitizing and processing techniques at the Ukrainian Virtual Observatory (UkrVO) (<http://gua.db.ukr-vo.org>), a catalog of 59 positions and magnitudes of Pluto was compiled (Kazantseva *et al.* 2015). The following catalog of 90 positions and magnitudes of Pluto for the period 1961–1996 (Eglitis *et al.* 2019a,b) was compiled on the basis of digitized photographic observations of the UkrVO and the Baldone Observatory. As a result of the new treatment, we obtained 31 new positions and magnitudes of Pluto. The catalog also contains 5 records of the Baldone Observatory, that were not included in earlier research (Rylkov *et al.* 1996). The resulting positions of Pluto were compared with the JPL ephemeris (<http://ssd.jpl.nasa.gov/horizons>). The distribution of the O-C differences along both coordinates is shown in Figure 14. The mean O-C values for all positions constitute -0.10 – -0.14 arc seconds on both coordinates (RA, Dec) and their standard errors are 0.58 and 0.55 arc seconds, respectively.

Figure 14. The distribution of O-C Pluto on both coordinates

6 Conclusions

To date, approximately 300 U plates, several R plates and 2200 V film negatives captured in the U, R and V bands of the Johnson system have been processed from the 1.2m archive of the Baldone Schmidt telescope, which contains 22,633 astronomical negatives. The combination of digitizing technique with developed algorithms of scanner errors elimination and reduction models provided the coordinates and magnitudes determinations for all celestial objects exposed on these negatives. Obtained equatorial coordinates and stellar magnitudes for stars will be used to supplement the photometric data of the Northern Sky Survey catalogs and study the kinematics of open clusters in the Universe. As an alternative addition, catalogs of the positions and magnitudes of Pluto, 1848 asteroids and comets were obtained from these digitized astronomical observations (Eglitis *et al.* 2016a,b, 2019a,b). It was found that root-mean-square errors of the reduction of the measured coordinates to the equatorial coordinate system of the Tycho-2 catalog have values $\sigma_{RA,DEC} = 0.1$ – $0.2''$, and that the rms errors of the reduction of instrumental photometric magnitudes m to the Johnson system of stellar UBVR-values are also in within $\sigma_{UBVR} = 0.1 - 0.2^m$. Based on the characteristic curve for an astronegative photographed with an exposure of 40 minutes in the Johnson U band, was created an empirical calibration curve in the form of a table. This empirical curve (actually it's part for faint stars when photometric standards are absent) is used to construct characteristic curves of various astronegatives (captured with a single exposure) and for other photometric systems implemented in a photographic manner. Based on the created program using an empirical curve, part of U plates and V films from the Baldone observatory archive, as well as part of B plates from Nikolaev observatory have already been processed. It is planned that U and V are the magnitudes of stars obtained as a result of processing the corresponding astronegatives from the Baldone observatory archive will be planed to use as a supplement to the magnitudes of the stars of the FON project (Andruk *et al.* 2017a,b; Eglitis *et al.* 2018a,b; Pakuliak *et al.* 2016).

With the goal of photometric calibration of astronegatives (both plate and film at the next step of processing), a relationship between the photoelectric stellar magnitudes of the Johnson BVR system and the stellar magnitudes G, BP, RP GAIA DR2 are established.

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Data availability statement: The programs can be freely obtained at the Main Astronomical Observatory (Kyiv, Ukraine) by contacting V.Andruk (andruk@mao.kiev.ua).

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