CATALOG OF POSITIONS AND B MAGNITUDES OF STARS IN THE CIRCUMPOLAR REGION OF NORTHEN SKY SURVEY (FON) PROJECT

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ABSTRACT. The catalog of star positions and B-magnitudes for the circumpolar region (from 58º to 90º in declination) of Northern Sky Survey project has been created under the motto of the rational use of resources accumulated in UkrVO JDA (Joint Digital Archive) in MAO NASU. The total amount of processed plates is 477. Digitizing of astronegatives has been carried out using Microtek ScanMaker 9800XL TMA and Epson Expression 10000XL scanners, with the scanning mode – 1200 dpi, the linear size of the plates – 30x30 cm or 13000x13000 px. The catalog contains 1 975 967 stars and galaxies with $B \leq 16.5^m$ for the epoch of 1985.28. The coordinates of stars and galaxies were obtained in the Tycho-2 reference system, and B-value in the system of photoelectric standards. The internal accuracy of the catalog for all the objects is $\sigma_{\alpha\delta} = \pm 0.23$ "and $\sigma_B = \pm 0.12^m$ (for stars in the range of $B = 8^m$ -14^m errors are $\sigma_{\alpha\delta} = \pm 0.11$" and $\sigma_B = \pm 0.06^m$). Convergence between the calculated and reference positions is $\sigma_{\alpha\delta} = \pm 0.06$ "(for 171 124 stars from Tycho-2), and the convergence with photoelectric stellar B-magnitudes is $\sigma_B = \pm 0.15^m$ (for 5130 stars). External accuracy from the comparison with UCAC-4 is $\sigma_{\alpha\delta} = \pm 0.33$ "(1 928 367 stars and galaxies were cross identified).

Keywords: virtual observatory tools – astrometry – techniques: photometric – methods: data analysis – catalogs

1. Introduction

For the creation of the circumpolar region star catalogue 477 plates of the FON project (Kislyuk, 2000; Yatsenko, 2011) were digitized and processed. The catalogue covers the region from 58º to 90º in declination and includes positions and B-magnitudes of stars. The work is done with the involvment of collected resources of UkrVO JDA (Joint Digital Archive) (Vavilova, 2012; Vavilova, 2012).

The process of digitizing the UkrVO archives was not limited to photographic surveys relatively homogeneous in quality. Plates, obtained in a variety of observational programs and received on different instruments with different methods, different structures of object images, digitized with different models of scanners were taken into processing. The variety of digitized material required constant upgrading of software and finding new approaches to its solution. The algorithms and methods developed in this investigation permit to resolve many problems of plates processing from different observational archives.

The FON plates were obtained with four-fold overlapping on both coordinates. For this catalogue in some areas with distances ±2º from the centers of plates on the declination the two-fold overlapping was used. The overlapping along the strips on the right ascension is made with 4º/cosδ shift of plate centers. The centers of adjacent strips are spaced apart from each other by 4º on declination. The number of plates in the RA stripes shown in the Table 1.

All the plates were obtained with MAO NASU DWA (Double Wide-angle Astrograph, D/F=40/200, 103"/mm, h=186m). The linear dimensions of the most plates are 30x30 sm (8x8°).

Table 1. Number of plates in each RA stripe.

DEC	N	DEC	N	DEC	N
88º	8	76º	53	64º	50
84º	25	72º	51	60º	102
80º	24	68º	58	56º	106

The plates were digitized using Microtek ScanMaker 9800XL TMA and Epson Expression 10000XL commercial scanners with the resolution 1200 dpi. The dimensions of the digital image fields are up to 13000x13000 px (1px = 2.17"). This version of the catalogue is obtaines from the processing of single scans without turning the plate by 90°. This permits to save resources for storage and processing the data in half without losses in accuracy (Andruk, 2016). The results of scanners' testing, principles and stages of astronegative digital image processing are stated in the series of publications (Andruk, 2005, Andruk, 2007, Andruk, 2010, Golovnya, 2010, Protsyuk, 2014, Protsyuk, 2014, Protsyuk, 2014). The results of the software testing arer described in (Kazantseva, 2015; Protsyuk, 2014; Andruk, 2014; Muminov, 2014; Vavilova, 2014; Yizhakevych, 2014).

2. Separation of stars into two exposition sets

The FON plates were obtained with two expositions: the long and short of 16-20 minutes and 30-60 second respectively. For astrometric catalogue star images of short expo-

sition are not used and should be excluded at the initial step before the astrometric solution. Stages and functional dependences of different parameters in the separation of detected objects into two sets are shown on Fig.1. Upper panels demonstrate the correlation between instrumental photometric values of long and short expositions m_2 и m_1 at initial and final stages of separation on the left and right sides of the figure correspondingly. Differences of magnitudes Δm reduced to the mean value are given on the panels **b, d** in relation to m_1 and the distance from the center of the plate R. The differences of distances between centers of images Δr are given on the panel **c** in relation to m_1. The differences of rectangular coordinates ΔX, ΔY are presented on the panels **e, f** relative to the rectangular coordinates Y, X. The lower panels (**g, h, j**) show the real and pre-calculated histograms of distribution Δm, ΔX, ΔY, shown with solid and dashed lines, respectively. It will be recalled that the value of the ΔX, ΔY differences' rotation in relation to the center of rectangular coordinates Y, X depends on the declination of the plate. The mutual rotation of two frames is absent at the equator.

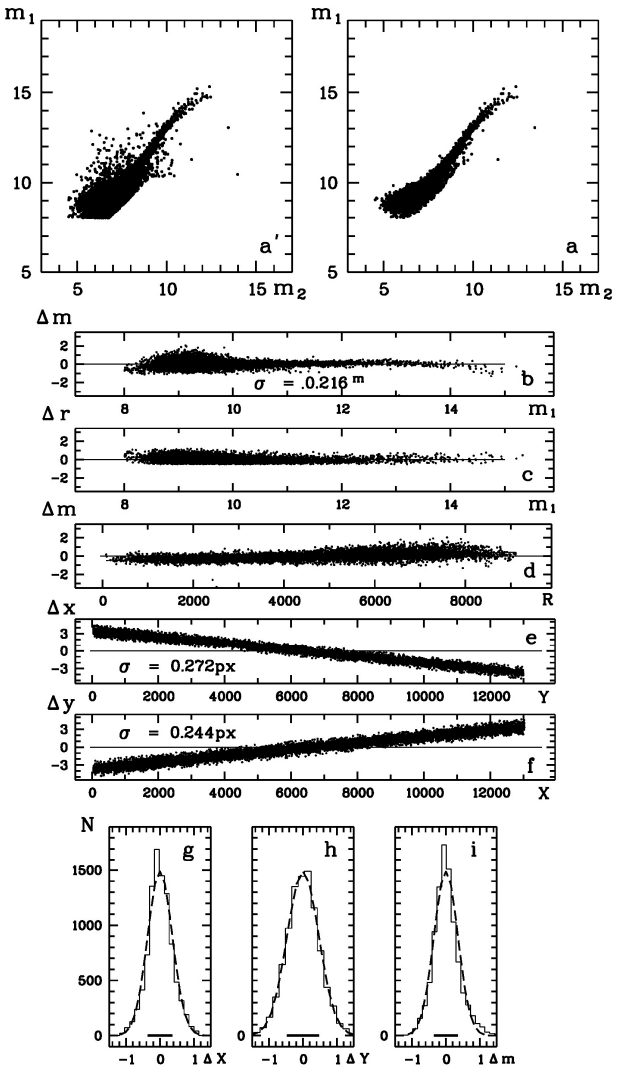

Figure 1: Stages of processing and functional dependences of different parameters in separation of star images into two exposition sets on the example of the test plate.

3. The magnitude equation

When calculating the tangential coordinates the special attention is given to the accounting of the magnitude equation mdtX and mdtY. It was found that for the plates exposed on astrographs the magnitude equation becomes significant for stars from $B \approx 11^m$ and its influence increases with the brightness of stars.

Fig. 2 shows the magnitude equation for the long exposition of the test plate with two expositions and Fig.3 presents the residual differences after its elimination. Fig.2 demonstrates the differences Δα, Δδ between observed and catalogue positions in relation to star image diameters $f_{½}$, instrumental photometric values m_1, magnitudes B and color indices B-V of Tycho-2 before the corrections for systematic errors of the scanner. From plots it is obvious that the magnitude equation is linear on all sections of $f_{½}$ and B and there the quadratic dependence on instrumental photometric values m_1 exists. Fig.3 shows the trend of residual differences in coordinates after the correction for the magnitude equation and the errors of the scanner.

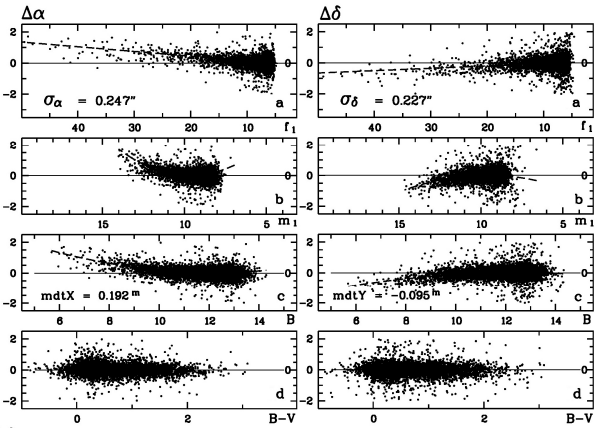

Figure 2: The magnitude equation for the long exposition detected on the plates with two expositions of the FON project.

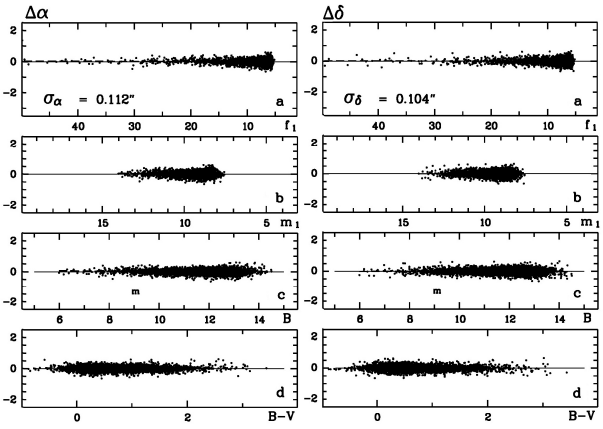

Figure 3: The residual differences in coordinates after the corrections for the magnitude equation and the scanner errors.

4. Astrometric solution in the Tycho-2 reference system

In each step of catalogue creation the star catalogue TYCHO-2 was taken as reference. The accuracy of it is $\boldsymbol{\sigma_{RA,DEC}} = \pm 0.060''$, $\boldsymbol{\sigma_{\mu}} = \pm 0.0025''$/yr, $\boldsymbol{\sigma_{m}} = \pm 0.10^{m}$ for its all 2 539 913 stars.

For all scans of plates with the field dimensions up to 8x8° the tangential coordinates ξ, η were calculated by equations (1). The same formulae were used on the stage of scanner systematic errors Δα, Δδ studying.

$$\xi_i = a_1+a_2X_if_{½i}+a_3Y_if_i+ a_4R_im_i+a_5f_{½i} + \sum b_{lm}X_i^lY_i^m,$$
$$(l=0\div6,\ m=0\div6,\ l+m=n,\ n=1\div6) \qquad (1)$$
$$\eta_i = c_1+c_2X_if_{½i}+c_3Y_if_i+ c_4R_im_i+c_5f_{½i} + \sum d_{lm}X_i^lY_i^m,$$
$$(l=0\div6,\ m=0\div6,\ l+m=n,\ n=1\div6)$$

Here, i = 1,2,…n – number of reference stars; X_i, Y_i and R_i – rectangular coordinates and distances of stars from the centers of plates; m_i – photometric measured data of stars; $f_{½i}$ – diameters of star images (FWHM); coefficients a_2, a_3, a_4 and c_2, c_3, c_4 define coma affects, coefficients a_5, c_5 – taking into account the magnitude equation, which is calculated separately; coefficients of the full sixth-order polynomial b_{lm} и d_{lm} (27 terms) in the generalized case describe the aberrations of telescope optics with the systematic errors of the scanner included. A step-by-step description of scanner systematic errors exclusion is set out in (Andruk, 2015).

Fig. 4 shows the results of the test plate processing. On the left side the trend of telescope systematic errors σ_α, σ_δ over the plate field is shown. Right panels demonstrate the trend of the residual differences Δα, Δδ. Negative and positive values of differences are shown by horizontal and vertical strokes which have linear dimensions according to the scale of values presented on the figure. Errors are obtained by averaging within 250x250 px cells.

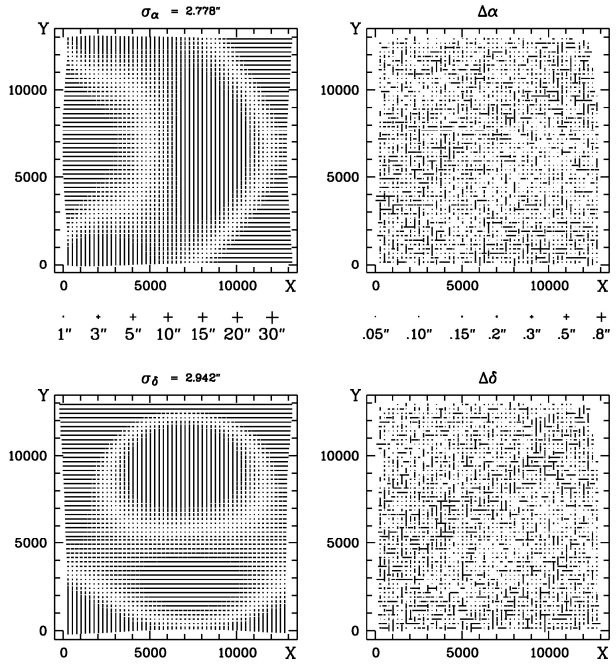

Figure 4: The distribution of errors and residual differences over the plate field as a result of the astrometric solution.

5. Photometric reduction into the system of photoelectric B-magnitudes

The reference system for the photometric solution is based on the photoelectric B_{pe}-values from catalogues (Kornilov, 1991, Mermilliod, 1991). The stages and principles of astronegative characteristic curve restoration accounting the field photometric equation and the data of two expositions are described in (Andruk, 2012). The approximation of the characteristic curve and determination of photographic B-magnitudes B_{ph} for all 477 plates were carried out by the least square method solution of the set of equation (2):

$$B_i = e_1 + e_2X_i + e_3Y_i + e_4R_i + e_5R_i^2 + e_6R_i^4 + \sum f_nm_i^n$$
$$(n=1,2,\ldots5) \qquad (2)$$

Here, i = 1,2,…n is the number of photoelectric data for standard star on the plate; X_i, Y_i и R_i are the rectangular coordinates and the distances from the center of the plate; m_i – instrumental photometric evaluations; coefficients e_2, e_3, e_4, e_5, e_6 define the field photometric equation; f_1, f_2, f_3, f_4, f_5 describe the functional form of the characteristic curve. The equation (2) was chosen as minimizing the errors of the reduction into the reference B_{pe} system in the best way.

6. Catalogue creation

When creating the catalogue the next steps were undertaken:

1. Digitizing of astronegatives using Microtek ScanMaker 9800XL TMA and Epson Expression 10000XL scanners with 1200 dpi resolution.
2. Conversion of the tiff-format files to the fit-format files using the GIMP package.
3. Calculation of the rectangular coordinates X, Y, photometric instrumental evaluations m, $f_{½}$ and other parameters using the MIDAS/ROMAFOT package for all registered objects.
4. Astrometric reduction of all objects into Tycho-2 reference system to obtain their position α, δ at the epoch of plates' exposure.
5. Conversion of instrumental photometric evaluations m into the reference system of photoelectric B_{pe}-magnitudes.
6. Calculation of mean values of equatorial coordinates α, δ and stellar magnitudes B for stars and galaxies in the limits of RA-overlapping of scans for each RA stripe. Elimination of artefacts.
7. Averaging of α, δ, B values in the overlapping areas between RA stripes.
8. Preparation of the catalogue of positions α, δ and stellar magnitudes B and its supplementation with proper motions data μ_α, μ_δ from UCAC4 (Zacharias, 2013).

The processing of scans was carried out using MIDAS/ROMAFOT software package. The photometric equalization of scans was made by taking into account the individual flat-field calculated for each plate separately (Andruk, 2005). The number of registered objects on the astronegatives, exposured in the areas of Milky Way reaches 300 000. The total number of objects found on the

whole set of 477 plates is around 25.933 million ones of different origin. Equatorial coordinates α, δ for all objects are obtained in the reference system of Tycho-2 at the epoch of exposition of each plate. As a rule, the reduction was made for full fields of plates with dimensions 8ºx8º, the exception was made for the high-latitude zones (84º and 88º) with a much smaller dimensions of processed fields. Photographic B_{ph}-magnitudes of objects were derived from equations (2) for characteristic curves of astronegatives calibrated with photoelectric B_{pe}-magnitudes.

The final positions and B-magnitudes of stars and galaxies as well as their errors were calculated by equations (3) and (4):

$$\begin{aligned} \alpha &= (\alpha_1/\sigma_{\alpha 1}^2 + \alpha_2/\sigma_{\alpha 2}^2) \;/\; (1/\sigma_{\alpha 1}^2 + 1/\sigma_{\alpha 2}^2) \\ \delta &= (\delta_1/\sigma_{\delta 1}^2 + \delta_2/\sigma_{\delta 2}^2) \;/\; (1/\sigma_{\delta 1}^2 + 1/\sigma_{\delta 2}^2) \\ B_{ph} &= (B_1/\sigma_{B1}^2 + B_2/\sigma_{B2}^2) \,/\, (1/\sigma_{B1}^2 + 1/\sigma_{B2}^2) \end{aligned} \qquad (3)$$

$$\begin{aligned} \sigma_\alpha &= (1 \,/\, (1/\sigma_{\alpha 1}^2 + 1/\sigma_{\alpha 2}^2))^{1/2} \\ \sigma_\delta &= (1 \,/\, (1/\sigma_{\delta 1}^2 + 1/\sigma_{\delta 2}^2))^{1/2} \\ \sigma_B &= (1 \,/\, (1/\sigma_{B1}^2 + 1/\sigma_{B2}^2))^{1/2} \end{aligned} \qquad (4)$$

7. The accuracy of the catalogue

The comparison of 171 124 reference stars of the catalogue with Tycho-2 gives the errors of the astrometric reduction $\sigma_{\alpha\delta} = \pm 0.06"$.

The errors of photometry were derived from comparison of calculated stellar magnitudes with the photoelectric values of 5130 stars from the photometric reference catalogues. The errors are $\sigma_B = \pm 0.12^m$.

The comparison of the catalogue with UCAC-4 gives the positional errors in relation to UCAC4 at the level of $\sigma_{\alpha\delta} = \pm 0.33"$ (1 928 367 stars and galaxies were cross-identified in both catalogues).

8. Conclusion

The comprehensive software was developed and implemented in the Department of the Astrometry MAO NASU to process the digitized astronomic negative plates as well as to obtain the final product in the form of a catalogue of positions and stellar magnitudes of stars and galaxies. The above version of the catalogue created in the circumpolar zone of FON project contains 1 975 967 stars and galaxies down to $B \le 16.5^m$ at the epoch 1985.28. The positions of objects are obtained in the reference system of Tycho-2. The stellar magnitudes B are in the system defined by photoelectric standards. The internal accuracy of the catalogue for all objects is $\sigma_{\alpha\delta} = \pm 0.23"$ and $\sigma_B = \pm 0.12^m$. For the stars in the interval of magnitudes $B = 8^m$ -13^m the errors are $\sigma_{\alpha\delta} = \pm 0.11"$ and $\sigma_B = \pm 0.06^m$.

The convergence of the coordinates with the Tycho-2 reference system obtained on 171 124 stars is $\sigma_{\alpha\delta} = \pm 0.06"$. The convergence of magnitudes with the photoelectric values B_{pe} for 5 130 stars is $\sigma_B = \pm 0.15^m$. The positional errors of the catalogue derived on 1 928 367 cross-identified stars in comparison to UCAC4 are $\sigma_{\alpha\delta} = \pm 0.33"$.

The algorithms and methods of plate digitizing and processing and the software developed in the Department of Astrometry MAO NASU is now applied for the total set of exposured plates of the FON project with the aim of creating the catalogue of positions and B-magnitudes of the whole northern sky from 0º to 90º on declination.

The created star catalogue of the positions and stellar magnitudes of the circumpolar zone of the FON project will be posted on the web pages of the MAO NASU and UkrVO. The catalogue contains the equatorial coordinates of 1 975 967 stars and galaxies (α, δ) on the equinox 2000.0 and the epoch 1985.28 as well as the stellar magnitudes (Bph). We provide the errors definitions of these values and number of determinations as well as an additional information in the form of the average values for the diameters of star images $f_{½}$ (FWHM) and the values of the maximal intensity in the center of object images (cInt).

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