POSITIONAL AND THEORETICAL ASTRONOMY

Catalog of Positions and *B*-Magnitudes of Stars in the Circumpolar Region of the Northern Sky Survey (FON) Project

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Abstract—The catalog of equatorial coordinates α and δ and *B*-magnitudes of stars has been created at the Main Astronomical Observatory, National Academy of Sciences of Ukraine (MAO NASU), for the circumpolar region (from 58° to 90°) of the Northern Sky Survey (FON) project within the work on the rational use of resources accumulated in the JDA (Joint Digital Archive) of the Ukrainian Virtual Observatory (UkrVO). The total number of processed plates is 477. The plates were digitized with the using Microtek ScanMaker 9800XL TMA and Epson Expression 10000XL scanners (scanning mode was 1200 dpi, the linear size of plates was 30×30 cm or $13\,000 \times 13\,000$ px). The catalog includes 1 975 967 stars and galaxies with *B* of up to 16.5^m as of the epoch of 1985.28. The coordinates of stars and galaxies were obtained in the Tycho-2 reference system and *B*-magnitudes were obtained in the system of photoelectric standards. The internal errors of the catalog for all the objects are $\sigma_{\alpha\delta} = 0.23''$ and $\sigma_B = 0.12^m$, and those for stars of the *B* range from 8^m-14^m, $0.11''$ and 0.06^m, respectively. The convergence between the calculated and reference positions is $\sigma_{\alpha\delta} = 0.06''$ (for 171 124 stars from Tycho-2), and that between the photoelectric stellar *B*-magnitudes is $\sigma_B = 0.15^m$ (for 5130 stars). The external error from the comparison with UCAC-4 are $\sigma_{\alpha\delta} = 0.33''$ (1 928 367 stars and galaxies have been cross identified).

INTRODUCTION

The catalog of positions and *B*-magnitudes of stars and galaxies has been compiled for the circumpolar region from 58° to 90° of the Northern Sky Survey (FON) project from processing of 477 digitized plates [8, 11]. The work was carried out with the use of resources accumulated in the JDA (Joint Digital Archive) of the Ukrainian Virtual Observatory (UkrVO) [5, 21]. The principle of double overlapping in declination was implemented in certain zones of $\pm 2°$ in height from the center, and the overlapping with displacement of the centers relative to each other by approximately $4°/\cos\delta$ in right ascension was carried out within the zones. The centers of neighbor zones are spaced apart by $\delta = 4°$; the number of plates in them is equal to 8 (zone 88), 25 (zone 84), 24 (zone 80) 53 (zone 76), 51 (zone 72), 58 (zone 68), 50 (zone 64), 102 (zone 60), and 106 (zone 56). The plates were exposed at the Double Wide-Angle Astrograph (DWA) of the Main Astronomical Observatory, National Academy of Sciences of Ukraine (MAO NASU) ($D = 40$ cm, $F = 2$ m, $103''$/mm). The size of most plates is 30×30 cm (or $8° \times 8°$). All the plates have been scanned with a spatial resolution of 1200 dpi using Microtek ScanMaker 9800XL TMA or Epson Expression 10000XL scanner; the size of fields processed was up to $13\,000 \times 13\,000$ px (1 px = $2.17''$). This version of the catalog has been created from processing single scans without plate rotation to 90°, which allows a twofold decrease in storage resourced for data and processing without loss in accuracy. The scanner testing procedure, principles, and steps of processing of the digitized plates are described in [1–3, 6, 17–19], and software testing and its results are described in [7, 10, 12, 16, 20, 22].

ASTROMETRIC REDUCTION TO THE TYCHO-2 CATALOG SYSTEM

The step of diagnosis of scanning biases $\Delta\alpha$ and $\Delta\delta$ and the steps of reduction of the Cartesian coordinates *X* and *Y* of objects into the equatorial coordinates α and δ of the Tycho-2 catalog include calculations

of the tangential coordinates ξ and η according to least squares solution of the following equations for all plate scans with fields of up to $8° \times 8°$ in size:

$$\xi_i = a_1 + a_2 X_i f_{1/2i} + a_3 Y_i f_i + a_4 R_i m_i + a_5 f_{1/2i} + \sum b_{lm} X_i^l Y_i^m,$$

$$\eta_i = c_1 + c_2 X_i f_{1/2i} + c_3 Y_i f_i + c_4 R_i m_i + c_5 f_{1/2i} + \sum d_{lm} X_i^l Y_i^m,$$

$$l = 0\ldots6, \quad m = 0\ldots6, \quad l+m = n, \quad n = 0\ldots6,$$

(1)

where $i = 1, 2, \ldots, N$ is the number of stars of the Tycho-2 catalog on a plate; X_i, Y_i, and R_i are the coordinates and distance of a star image relative to the plate center; m_i is the photometric instrumental stellar magnitudes; f_{2i} is the star image diameter (*FWHM*); the coefficients a_2, a_3, and a_4 and c_2, c_3, and c_4 describe coma, a_5 and c_5 consider the magnitude equation effect (calculated separately); the coefficients of a complete sixth degree polynomial (27 terms) b_{lm} and d_{lm} generally describe aberrations of the telescope optics aggravated with scanning biases.

PHOTOMETRIC REDUCTION TO THE PHOTOELECTRIC SYSTEM OF *B*-MAGNITUDES

Photoelectric B_{pe} magnitudes of stars from catalogs [9, 15] were used as photometric standards for plotting the characteristic curves of individual plates. The steps and principles of plotting the characteristic curve of a plate with allowance for a field photometric error and use of information on two exposures are described in [3, 4, 11]. The characteristic curves were approximated and photographic B_{ph} ($B = B_{ph}$) stellar magnitudes were calculated for all 477 plates via least squares solution of the set of equations

$$B_i = e_1 + e_2 X_i + e_3 Y_i + e_4 R_i + e_5 R_{i2} + e_5 R_{i4} + \left(\sum f_n m_i^n\right),$$

$$n = 1, 2, \ldots, 5,$$

(2)

where $i = 1, 2, \ldots, N$ is the number of photoelectrically determined standard stars on a plate; X_i, Y_i, and R_i are the coordinates and distance of star images relative to the plate center; m_i is the instrumental photometric stellar magnitudes; the coefficients $e_2 - e_6$ describe the field photometric equation (photometric error), and the coefficients $f_1 - f_5$ correspond to the functional description of the form of characteristic curves. This form of Eq. (2) has been chosen as optimal in the sense of minimization of photometric errors of reduction into the photoelectric standard system B_{pe}.

ALGORITHM FOR CATALOG CREATION

The following steps are implemented when compiling the catalog:

(1) Digitizing of plates using Microtek ScanMaker 9800XL TMA and Epson Expression 10000XL scanners; the scanning mode is 1200 dpi.

(2) Conversion of files from the tiff format into the fits format using the GIMP packet.

(3) Calculation of the Cartesian coordinates X and Y and photometric instrumental parameters m, f_2, etc. in the MIDAS/ROMAOFF environment for all objects recorded on a plate.

(4) Astrometric reduction into the system of equatorial coordinates α and δ of the Tycho-2 catalog as of the epoch of plate exposure for all objects.

(5) Photometric reduction of instrumental stellar magnitudes m into the photoelectric system of B_{pe}-magnitudes.

(6) Calculation of average equatorial coordinates α and δ and B-magnitudes of stars and galaxies within the limits of α-overlapping scans for separate zones. Rejection of artifacts.

(7) Averaging of the coordinates α and δ and B-magnitudes of stars and galaxies in the overlapping zones.

(8) Creation of the catalog of star and galaxy positions α and δ and B-magnitudes and its supplement with data on proper motions μ_α and μ_δ from the UCAC4 catalog.

Let us make some remarks about certain creation steps. The scanning mode 1200 dpi has been selected as optimal for attaining good accuracy of photographic astrometry and photometry results at acceptable requirements for time and resources for processing and storage of information from plates. The processing is understood as calculation of the Cartesian coordinates X and Y and photometric parameters (instrumental stellar magnitudes m, image diameters f_2, intensities at the image centers I_c, etc.) for all objects at
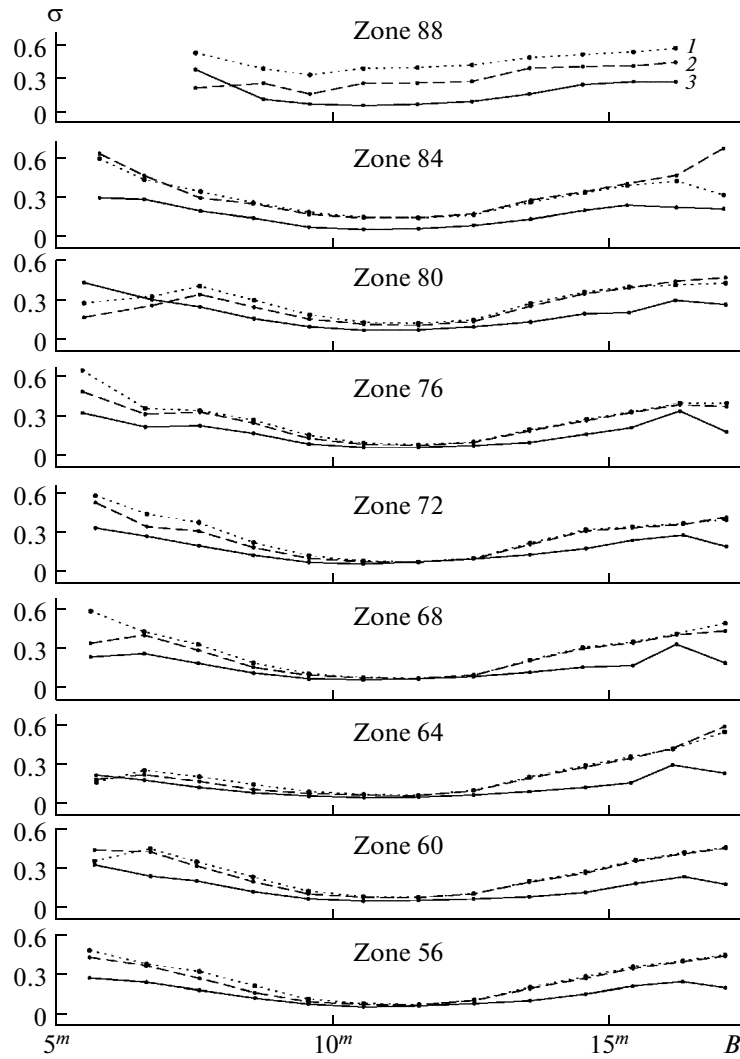
Fig. 1. Internal errors of equatorial coordinates σ_α (dotted curves *1*) and σ_δ (dashed curves *2*), and *B*-magnitudes σ_B (solid curves *3*) of identified objects as functions of the stellar magnitude for nine circumpolar zones of the FON program. The numbers k_p of plates processed, n_i of identified (two and more times) objects (stars and galaxies) in segments overlapping in α for a specific zone, and errors of the mean values of the equatorial coordinates σ_α and σ_δ and *B*-magnitudes σ_B of stars and galaxies are given for each zone in the table below.

Zone	kp	σ_α	σ_δ	σ_B	n_i
88	8	0.497"	0.377"	0.207^m	1946
84	25	0.316	0.327	0.181	130004
80	24	0.328	0.314	0.169	219779
76	53	0.286	0.279	0.179	452689
72	61	0.300	0.291	0.191	487302
68	58	0.292	0.284	0.150	521877
64	50	0.282	0.272	0.127	607029
60	102	0.318	0.311	0.155	1318346
56	106	0.299	0.288	0.169	1343861

Table 1. Distribution of the internal errors of equatorial coordinates σ_α and σ_δ, photographic magnitudes σ_{Bph}, mean diameters of star images f_2, mean intensities at the centers of object images I_c, and the number of catalog objects k over ranges of stellar *B*-magnitudes

B_{ph}	σ_α	σ_δ	σ_{Bph}	f_2	I_c	k
5.65^m	$0.343''$	$0.349''$	0.225^m	60.9	137.4	27
6.65	0.319	0.286	0.206	58.5	129.0	306
7.58	0.276	0.223	0.149	48.4	128.7	1203
8.57	0.155	0.125	0.085	34.2	125.9	3317
9.57	0.082	0.063	0.043	21.9	120.9	8664
10.56	0.052	0.045	0.030	14.1	112.7	20800
11.56	0.047	0.043	0.033	9.9	100.4	44846
12.56	0.066	0.061	0.043	7.6	83.3	94604
13.57	0.143	0.132	0.062	6.4	60.9	216205
14.58	0.222	0.207	0.105	5.6	34.9	643629
15.43	0.289	0.272	0.151	5.2	22.5	766411
16.31	0.381	0.356	0.224	4.9	19.7	173426
17.10	0.421	0.396	0.177	4.6	16.7	2529
14.71	0.239	0.224	0.123	5.9	36.8	1975967

the plates digitized. Scan processing is implemented in the MIDAS/ROMAFOT package; photometric flattening of the scans is made by means of accounting the individual flat field calculated for each plate [12, 13]. The number of objects recorded for the plates exposed in the Galaxy regions attained 300000, and 25933 millions objects of different nature were recorded in a total at 477 plates processed. The equatorial coordinates α and δ for all the objects were calculated as of the epochs of exposing of individual plates in the Tycho-2 catalog system. The reduction was usually carried out for total fields of plates of 8° × 8° in size, except for plates of polar regions (84° and 88°) with much smaller processed fields. The photographic B_{ph}-magnitudes of the objects were calculated on the basis of equation of form (2) for the characteristic curves of plates calibrated against photoelectric stellar B_{pe}-magnitudes.

During the first step of catalog creation, the calculated coordinates and *B*-magnitudes of stars and galaxies were averaged within the plate field overlaps in certain zones (overlapping in α). The objects that were recorded at least at two plates were included in the catalog (correspondingly, coordinates and stellar magnitudes were measured and calculated for them as for identified objects). The list of objects was compiled of stars and galaxies by the following criteria:

(1) Difference in equatorial coordinates did not exceed 2.17'' (1 px ≈ 2.17'');

(2) Difference in stellar magnitude was no more than ±2^m (considering variable stars).

The errors σ_α, σ_δ, and σ_B in equatorial coordinates and *B*-magnitudes of stars and galaxies for k measurements were calculated by the equations

$$\sigma_\alpha = \left[\frac{\sum(\alpha_k - \delta_c)^2}{k(k-1)}\right]^{1/2}, \quad \sigma_\delta = \left[\frac{\sum(\delta_k - \delta_c)^2}{k(k-1)}\right]^{1/2}, \quad \sigma_B = \left[\frac{\sum(B_k - B_c)^2}{k(k-1)}\right]^{1/2}. \tag{3}$$

Figure 1 shows the internal errors σ_α, σ_δ, and σ_B of the equatorial coordinates and *B*-magnitudes of identified objects as functions of the stellar magnitude for nine circumpolar zones of the FON program. The number of plates processed k_p for each zone, the number of identified (two and more times) objects (stars and galaxies) n_i in segments overlapping in α for a specific zone, and errors the mean values of calculated equatorial coordinates (σ_α, σ_δ) and *B*-magnitudes (σ_B) of stars and galaxies are given.

During the next step, new mean values of the coordinates and *B*-magnitudes were calculated in the overlapping zones. Coordinates, *B*-magnitudes, and their errors for two zones ($\alpha_{1,2}$, $\delta_{1,2}$, $B_{1,2}$, $\sigma_{\alpha 1,2}$, $\sigma_{\delta 1,2}$,
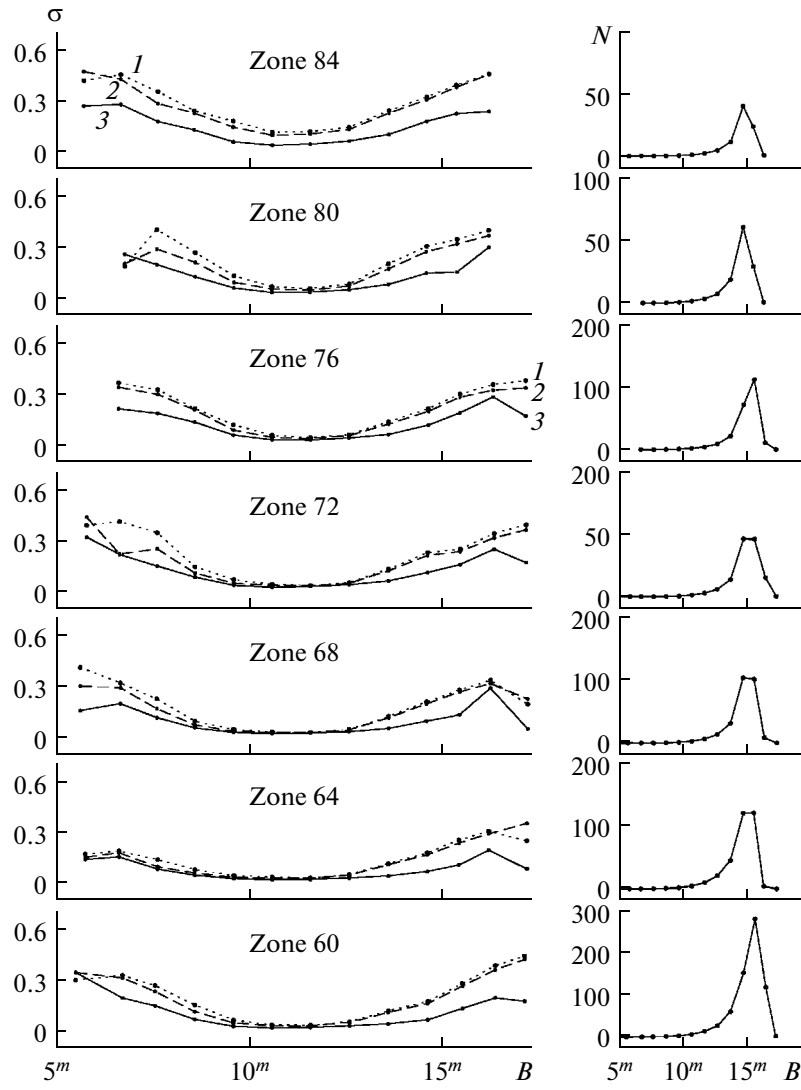
Fig. 2. (left) Astrometry errors σ_α (dotted curves *1*), σ_δ (dashed curves *2*), and *B*-magnitudes σ_B (solid curves *3*) as functions of the stellar magnitude (within zones of overlapping in α and δ) for seven circumpolar zones of the FON program. (right) Histograms of object distributions over *B*-magnitudes. The errors of the mean values of the equatorial coordinates σ_α and σ_δ and *B*-magnitudes σ_B of stars and galaxies and the final number N_i of objects identified (stars and galaxies) in overlapping zones for each zone are given in the table below.

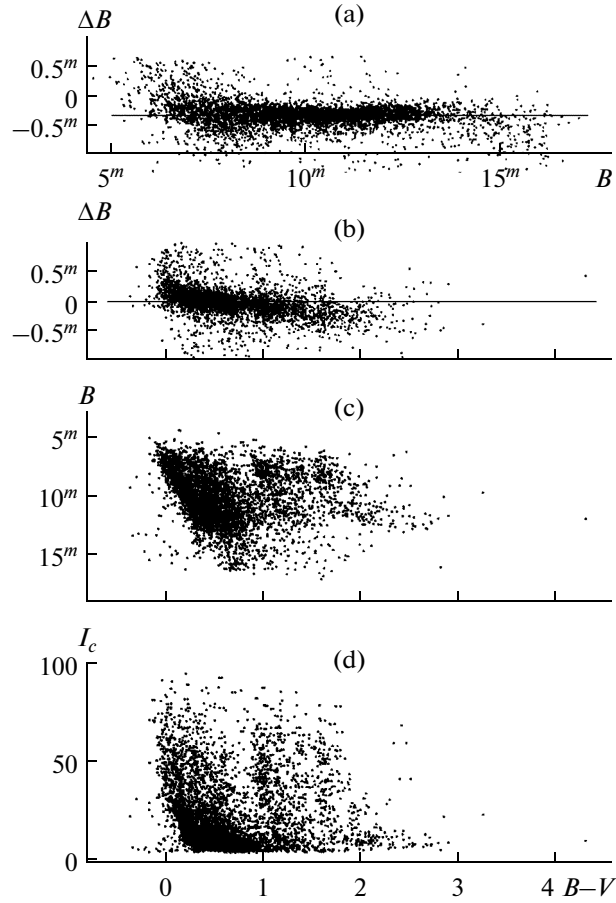| Zone	kp	σ_α	σ_δ	σ_B	n_i
84	25	0.316"	0.301"	0.170^m	83220
80	24	0.280	0.252	0.133	122393
76	53	0.246	0.229	0.152	235486
72	61	0.230	0.215	0.138	256063
68	58	0.222	0.211	0.113	274089
64	50	0.192	0.179	0.083	330653
60	102	0.254	0.239	0.123	681568

Fig. 3. Photometry errors of the catalog: (a) the difference ΔB for the catalog stellar B_{ph}-magnitudes and photoelectric B_{pe}-magnitudes versus B_{pe}; (b) ΔB vs. $(B - V)_{pe}$ for $N_{pe} = 5130$ stars; (c, d) B_{ph}-magnitude and the intensity at the star image center I_c vs. $(B - V)_{pe}$.

and $\sigma_{B1, 2}$) were found for each object. The coordinates, *B*-magnitudes, and their errors were finally calculated for catalog stars and galaxies by the equations

$$\alpha = (\alpha_1 \sigma_{\alpha 1}^{-2} + \alpha_2 \sigma_{\alpha 2}^{-2})/(\sigma_{\alpha 1}^{-2} + \sigma_{\alpha 2}^{-2}),$$

$$\delta = (\delta_1 \sigma_{\delta 1}^{-2} + \delta_2 \sigma_{\delta 2}^{-2})/(\sigma_{\delta 1}^{-2} + \sigma_{\delta 2}^{-2}), \tag{4}$$

$$B_{ph} = (B_1 \sigma_{B1}^{-2} + B_2 \sigma_{B2}^{-2})/(\sigma_{B1}^{-2} + \sigma_{B2}^{-2}),$$

$$\sigma_\alpha = (\sigma_{\alpha 1}^{-2} + \sigma_{\alpha 2}^{-2})^{-1/2},$$

$$\sigma_\delta = (\sigma_{\delta 1}^{-2} + \sigma_{\delta 2}^{-2})^{-1/2}, \tag{5}$$

$$\sigma_B = (\sigma_{B1}^{-2} + \sigma_{B2}^{-2})^{-1/2}.$$

Table 1 (see also Fig. 4a) presents the distribution (over stellar *B*-magnitudes) of the internal errors σ_α, σ_δ, and σ_{Bph} of the equatorial coordinates and photographic magnitudes, diameters of star images f_2, intensities at the centers of object images I_c, and the number of catalog objects k_p.

Figure 2 shows the astrometry errors σ_α, σ_δ, photometry errors σ_B (within zones of overlapping in α and δ) for seven circumpolar zones of the FON program. The errors of the mean values of the equatorial coordinates σ_α and σ_δ and *B*-magnitudes N_i of stars and galaxies are given for each region.

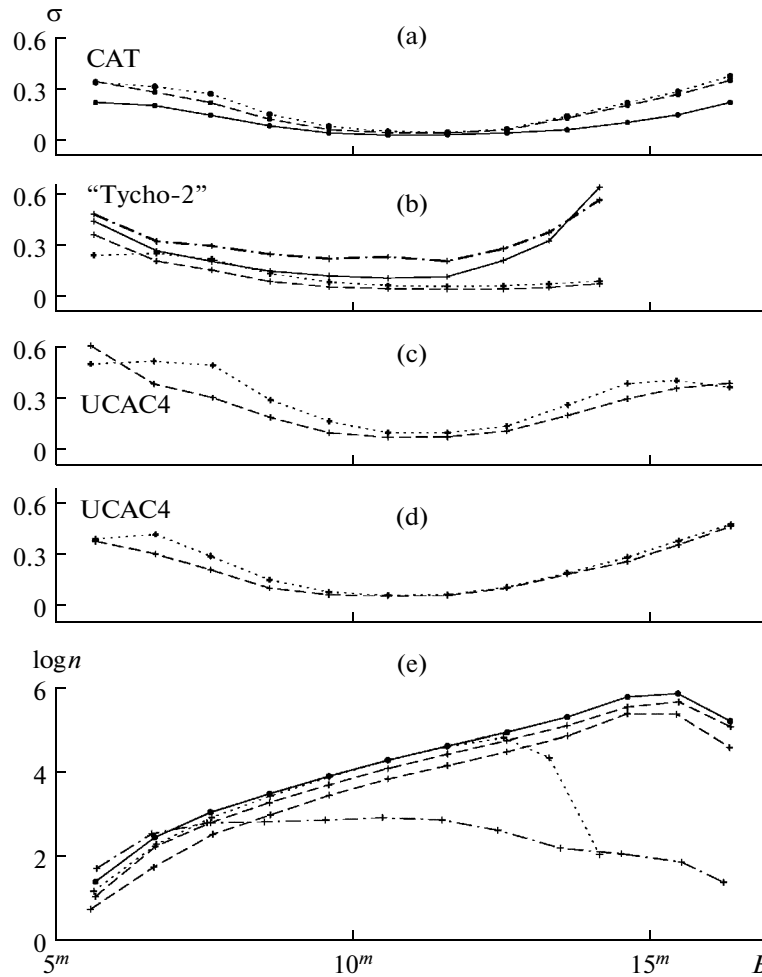The resulting catalog was compiled by combining data on all the zones.

Fig. 4. Errors of the catalog for a circumpolar region of the FON program (n_C = 1975967 stars and galaxies of up to 16.5^m) versus the stellar magnitude B: (a) internal errors of the coordinates σ_α (dotted curves *1*) and σ_δ (dashed curves *2*) and B-magnitudes σ_B (solid curves *3*) for all the catalog objects; (b) error distribution as compared to the reference astrometric system of the Tycho-2 catalog (n_T = 171 124); (c, d) errors σ_α and σ_δ as compared to the UCAC-4 catalog (n_U = 1 943 665) separately for the regions 70°−90° and 58°−70°; distribution of the number n of catalog stars and compared stars over B-magnitude.

CATALOG ERRORS

Figure 4b and Table 2 show the results of comparison with 171 124 stars from the Tycho-2 catalog. Table 2 presents errors of the coordinates σ_α and σ_δ and photometric magnitudes σ_{BT}, σ_{BJ}, star image diameters f_2, intensities at the object image centers I_c, and the number of catalog objects compared. The astronomy reduction errors for reference stars from the Tycho-2 catalog are $\sigma_{\alpha\delta}$ = 0.06″.

The photometry errors were found from the comparison of stellar magnitudes from our catalog with the photoelectric magnitudes (5130 stars) from catalogs [9, 15]. Table 3 presents the distribution of photometry errors σ_B of the catalog over the stellar magnitude ranges with respect to the reference photoelectric standard system. The comparison results are shown in Fig. 3. The color correction is seen on the dependence curves of $\Delta B = B_{ph} - B_{pe}$ on the photoelectric stellar magnitude B_{pe} and on the color index $B - V$. The diagrams of the $(B - V)$ dependences of B_{ph} and I_c clearly correspond to the Gaussian distribution of stellar population.

We compared our catalog with the UCAC-4 catalog (Figs. 4c, 4d) [23]. The comparison was performed for only two regions, 58°−70° and 70°−90°, for technical reasons. Table 4 presents the distribution of errors of the equatorial coordinates σ_α and σ_δ and the number of objects over the stellar magnitude ranges.

Table 2. Results of comparison of the catalog with Tycho-2 (B_{ph} are the ranges of the photographic stellar magnitudes, σ_α, σ_δ, σ_{BT}, and σ_{BJ} are the errors of equatorial coordinates and photometric magnitudes, f_2 are the star image diameters, I_c is the intensity at the object image centers, and k is the number of catalog objects)

B_{ph}	σ_α	σ_δ	σ_{BT}	σ_{BJ}	f_2	I_c	k
5.62^m	$0.245''$	$0.369''$	0.491^m	0.450^m	53.0	132.1	16
6.68	0.257	0.211	0.329	0.272	55.4	131.6	209
7.60	0.223	0.158	0.302	0.210	45.9	129.7	912
8.58	0.137	0.090	0.252	0.152	33.0	126.6	2934
9.58	0.087	0.058	0.226	0.123	21.7	121.3	8317
10.56	0.066	0.048	0.237	0.110	14.1	112.9	20445
11.55	0.061	0.045	0.211	0.118	9.9	100.7	43304
12.50	0.065	0.046	0.285	0.215	7.7	84.8	70937
13.27	0.076	0.055	0.382	0.332	6.7	70.1	23930
14.11	0.092	0.077	0.572	0.647	6.0	52.5	120
11.89	0.069	0.050	0.271	0.189	10.3	92.9	171124

Table 3. Distribution of photometry errors of the catalog over the stellar magnitudes (B_{ph} and σ_{Bph} are the ranges of photographic stellar magnitudes and photometry errors, f_2 are the star image diameters, I_c is the intensity at the object image center, and k is the number of catalog objects)

B_{ph}	σ_{Bph}	f_2	I_c	k
5.67^m	0.524^m	61.3	131.8	60
6.60	0.278	56.7	131.2	372
7.52	0.201	48.9	132.2	671
8.49	0.157	35.3	129.5	716
9.51	0.104	22.6	127.1	782
10.47	0.103	14.9	121.1	887
11.47	0.096	10.2	107.4	794
12.41	0.110	7.8	89.6	450
13.46	0.146	6.4	67.1	169
14.48	0.198	5.7	46.1	124
15.49	0.318	5.5	25.8	79
16.20	0.342	5.2	18.7	26
9.95	0.149	24.9	115.0	5130

Position errors of our catalog as referring to the UCAC-4 catalog are $\sigma_{\alpha\delta} = 0.33''$ (1 928 367 stars and galaxies have been identified).

Figure 4e shows the distribution of the number n of objects of our catalog and the catalogs compared over *B*-magnitude.

CONCLUSIONS

(1) Complex software has been developed and used in practice at MAO NASU for processing digitized plates and compiling the catalog of positions and magnitudes of stars and galaxies.

(2) The version of the catalog for the circumpolar region of the FON program includes 1 975 967 stars and galaxies of up to $B = 16.5^m$ as of the epoch 1985.28. The star and galaxy positions have been calculated in the system of Tycho-2 catalog and *B*-magnitudes in the photoelectric standard system. The internal accuracy of the catalog for all objects $\sigma_{\alpha\delta} = 0.23''$ and $\sigma_B = \pm 0.12''$ (for stars with $B = 8^m \ldots 13^m$, the errors are $0.11''$ and 0.06^m, respectively). The convergence of the coordinates with the Tycho-2 reference system is $\sigma_{\alpha\delta} = 0.06''$ (for

Table 4. Results of comparison with the UCAC-4 catalog. The columns give the values of: errors of the equatorial coordinates σ_α and σ_δ, and the number of stars compared k

B_{ph}	σ_α	σ_δ	k	σ_α	σ_δ	k
	zone 58°…70°			zone 70°…90°		
5.65	0.398″	0.386″	12	0.508″	0.613″	6
6.66	0.427	0.311	185	0.523	0.388	60
7.58	0.299	0.219	683	0.499	0.307	363
8.57	0.160	0.110	2056	0.293	0.189	1050
9.57	0.086	0.071	5434	0.166	0.097	3056
10.56	0.066	0.062	13190	0.098	0.071	7402
11.56	0.071	0.066	28878	0.098	0.074	15523
12.56	0.115	0.110	60648	0.138	0.109	32888
13.57	0.199	0.192	135397	0.264	0.201	77481
14.58	0.292	0.267	371706	0.392	0.301	257551
15.44	0.389	0.365	493831	0.410	0.362	250418
16.32	0.486	0.475	126799	0.368	0.394	41354

171124 stars), and that with photoelectric B_{pe}-magnitudes is $\sigma_B = 0.15^m$ (for 5130 stars). The errors as compared to the UCAC-4 catalog are $\sigma_{\alpha\delta} = 0.33''$ (1928367 stars and galaxies have been identified).

(3) The measurement and plate processing technique and the software developed at the Astrometry Department of MAO NASU is successfully used for all exposure plates of the FON program with the aim of compiling the catalog of positions and B-magnitudes of northern sky stars (from 0° to 90°).

The catalog of positions and B-magnitudes of stars from the circumpolar region of the FON program is to be posted on the websites of MAO NASU and UkrVO. The catalog of 1975967 stars and galaxies of up to $B = 16.5^m$ includes the equatorial coordinates α and δ as of the epoch 1985.28 and equinox of 2000, stellar B-magnitudes, their errors, and the number of identifications, as well as some additional information, i.e., averaged diameters of star images f_2 and intensities at the object image centers I_c.

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