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The Pul-3 catalogue of 58483 stars in the Tycho-2 system⋆

E. V. Khrutskaya, M. Yu. Khovritchev, and N. M. Bronnikova

Central Astronomical Observatory of RAS, Pulkovskoye chaussee 65/1, 196140 Saint-Petersburg, Russia

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Abstract. A catalogue of positions and proper motions of 58483 stars (Pul-3) has been constructed at the Pulkovo observatory. The Pul-3 is based on the results of measurements of photographic plates with galaxies (Deutsch's plan). All plates were taken using the Pulkovo Normal Astrograph (the first epoch is in the 1950s and the second epoch is in the 1970s).
The Pul-3 catalogue contains stars of mainly 12 to 16.5 mag in 146 fields with galaxies in the declination zone from −5° to +85°. The Tycho-2 has been used as a reference catalogue.
The mean epoch of the Pul-3 is 1963.25. The internal positional accuracy of the Pul-3 catalogue at the mean epoch of observations is ±80 mas. The accuracy of the proper motions is mostly within ±3 mas/yr to ±12 mas/yr. Comparisons of the Pul-3 with Tycho-2 and ARIHIP have been done at the mean epoch of the Pul-3. The Pul-3 external positional accuracy relative to Tycho-2 is ±150 mas.

Key words. astrometry – catalogs

1. Introduction

A number of problems of modern astrometry require high density and high precision astrometric catalogues which contain stars fainter than 12 mag on the International Celestial Reference System (ICRS). One of the possible ways of construction of such catalogues are new reductions of old photographic plates using reference stars from the Hipparcos, ACT or Tycho-2 catalogues.

The Pul-3 catalogue is one realization of this idea. It is based on the results of measurements of 587 photographic plates ((x, y)-data) which had been taken at the Pulkovo observatory in accordance with Deutsch's plan (Deutsch 1952). These plates mostly contain images of faint stars (12 to 16.5 mag).

Originally the construction of a catalogue that contains stellar proper motions with respect to background galaxies was planned using this observational material. The final catalogue of Deutsch's plan is Pul-2 (Bobylev et al. 2000).

The precise equatorial coordinates of these stars had not been determined during the Deutsch's plan realization. This is the main motivation for the Pul-3 catalogue construction.

The Pul-3 catalogue successfully represents the Tycho-2 system for more than 50 000 stars fainter than 12 mag in 146 fields. The stars from the Pul-3 catalogue may be used as reference stars for reductions of positional CCD-observations of extragalactic radio sources and small bodies of the Solar system. The 40-year difference between the Pul-3 observational epoch and the modern epoch will allow to determine high-precision proper motions of the faint stars of the Pul-3 catalogue in future (about 2 mas/yr to 3 mas/yr). Proper motions of stars from the Pul-3 catalogue may be used for stellar kinematic investigations.

The astrograph observations, astrometric reductions of the photographic plates, investigation and exclusion of the systematic errors of stars positions, construction of the Pul-3 catalogue and results of comparisons of the Pul-3 with Tycho-2 and ARIHIP catalogues are described in this paper.

A machine-readable version of the Pul-3 catalogue is available from the Laboratory of Photographic Astrometry of Pulkovo Observatory and at the CDS (I/290).

2. Observations

The observations were made with the Pulkovo Normal Astrograph (F = 3467 mm, D = 330 mm) during the periods from 1935 to 1960 (the first epoch) and from 1969 to 1986 (the second epoch). The radius of the working field was 50′ for all plates.

Three pairs of photographic plates were taken for each of the 146 fields with galaxies in the declination zone from −5° to +85°. The 4.2 mag objective diffraction grating was used for the plates of the third pair. The exposure times were 1^h. All plates were taken near the meridian.

Plates of the first and the second pairs were used for the Pul-3 catalogue construction. A considerable number of plates

Send offprint requests to: E. V. Khrutskaya,
e-mail: deimos@gao.spb.ru

⋆ The catalogue is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/418/357

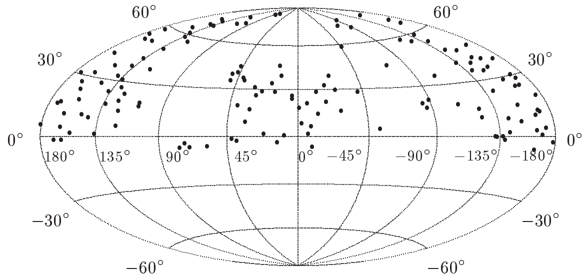

Fig. 1. Distribution of the Pulkovo fields with galaxies in equatorial coordinates.

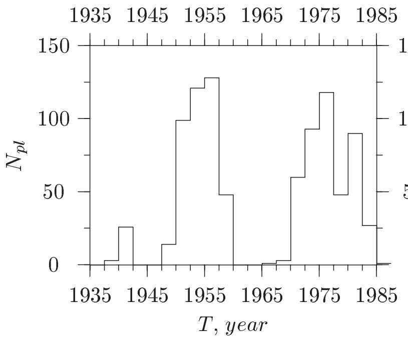

Fig. 2. Distribution of the observing epochs. $N_{\rm pl}$ is a number of plates.

of the third pair were additionally used for magnitude equation investigation.

The distribution of the Pulkovo fields in equatorial coordinates is shown in Fig. 1. The distribution of the observing epochs is shown in Fig. 2.

The measurements of the plates were made at the Pulkovo observatory in the 1970s and 1980s with an ASCORECORD measuring machine. The (x, y)-data for about 60 000 stars were obtained at the two epochs of observations. Photographic magnitudes of these stars were determined at the Pulkovo observatory (Bronnikova et al. 1996).

The Pulkovo plates contain stars mainly of 12 to 16.5 mag. The histogram of magnitudes of the Pul-3 stars is shown in Fig. 3. The maximum density of stars in the Pulkovo plates is 500 stars per square degree.

3. Astrometric reduction

The Tycho-2 catalogue was used as a reference catalogue for astrometric reductions of the photographic plates. The great star density of the Tycho-2 provides 40 to 65 reference stars (depending on galactic latitude) in the working field of the Pulkovo plates.

Only approximate equatorial coordinates of the optical centers of all plates had been known in the initial stage of the construction of the Pul-3 catalogue and thus a recalculation of them has been done (Khovritchev 2002).

A six-parameter plate model has been used for astrometric reduction of the plates.

Differences $\Delta\xi = \xi - \tilde{\xi}$ and $\Delta\eta = \eta - \tilde{\eta}$ for reference stars have been analysed to investigate residual systematic errors. Here ξ, η are apparent tangential coordinates from Tycho-2 data and $\tilde{\xi}$, $\tilde{\eta}$ are "observational" tangential coordinates of the same stars that were obtained from (x, y)-data and plate constants.

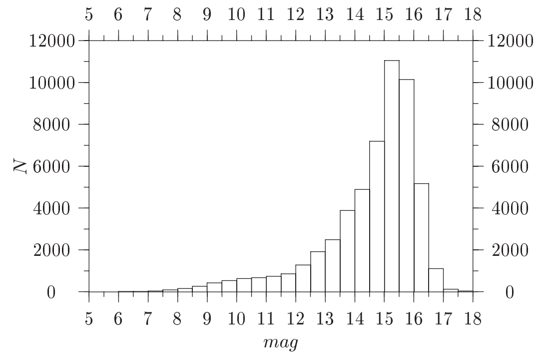

Fig. 3. Histogram of photographic magnitudes of the Pul-3 stars.

4. Determination of the coma parameters

The coma parameters have been derived from fields of the Pulkovo zenithal zone (9 fields, $\delta = 59° \pm 5°$, 1890 residuals of the reference stars).

The coma parameters were obtained by two methods. The first method was based on analysis of the $\Delta\xi$, $\Delta\eta$ residuals. The working field was divided into 36 squares 20 mm × 20 mm. The residuals of each square were divided into seven groups depending on magnitude (mag < 8.5, five groups from 8.5 to 13.5 mag with 1 mag step, and mag ≥ 13.5).

The mean residuals $\overline{\Delta\xi}$, $\overline{\Delta\eta}$, the mean tangential coordinates $\overline{\tilde{\xi}}$, $\overline{\tilde{\eta}}$ and the mean magnitude $\overline{\rm mag}$ were determined for each group of 36 squares. Coma parameters (c_ξ, c_η, ${\rm mag}_{0\xi}$, ${\rm mag}_{0\eta}$) were obtained by the least-squares method from equations:

$$\overline{\Delta\xi} = c_\xi \overline{\tilde{\xi}}(\overline{\rm mag} - {\rm mag}_{0\xi}), \quad \overline{\Delta\eta} = c_\eta \overline{\tilde{\eta}}(\overline{\rm mag} - {\rm mag}_{0\eta}).$$

The second method was based on the radial components of residuals Δr. The working field was divided into 6 ring zones with width 10 mm. The residuals of each zone were divided into magnitude groups as in the first method. The coma parameters were estimated by the least-squares method from the equation:

$$\overline{\Delta r} = c_r \overline{r}(\overline{\rm mag} - {\rm mag}_{0r}).$$

Here $\overline{r}$ is the mean distance from optical center of a plate to stars of the appropriate group and c_r, ${\rm mag}_{0r}$ are coma parameters.

In both methods a weighted least-squares procedure was used. The weights were assigned according to the number of stars in each group.

The final coma parameters have been determined as a weighted mean from the results of the two methods.

$$c = 1.6 \pm 0.2\,{\rm mas} \cdot {\rm mm}^{-1} \cdot {\rm mag}^{-1}; \quad {\rm mag}_0 = 11.3 \pm 1.2.$$

Next, the corrected coordinates $\tilde{\xi}_{\rm coma}$, $\tilde{\eta}_{\rm coma}$ were obtained by taking into account the coma term. The examples $\Delta\xi$ as function of $\tilde{\xi}$ for stars 12.5 to 13.5 mag before coma exclusion and after coma exclusion are shown in Fig. 4.

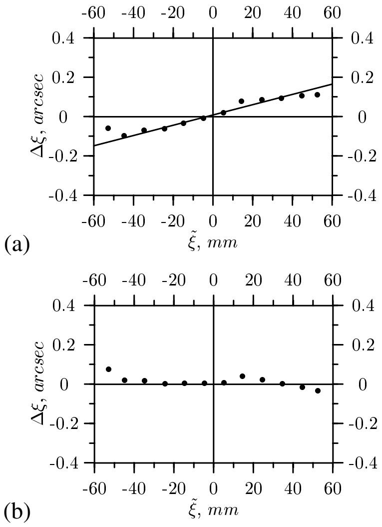

Fig. 4. Dependence $\Delta\xi$ on $\tilde{\xi}$ for stars of 12.5 to 13.5 mag. **a)** before coma exclusion, **b)** after coma exclusion.

5. Magnitude-dependent systematic errors

Systematic errors depending on the magnitude of the stars were analysed using differences $\Delta\xi = \xi - \tilde{\xi}_{\rm coma}$, $\Delta\eta = \eta - \tilde{\eta}_{\rm coma}$.

Since the magnitude of the faintest reference stars from Tycho-2 is 14.5, and the Pulkovo fields contain a considerable number of stars in the magnitude range 14.5 to 16.5, the photographic plates (70 pairs) that had been taken with the 4.2 mag diffraction grating were processed to determine magnitude equation corrections for faint stars (14.5 to 16.5 mag) without extrapolation.

The magnitude equation does not depend on plate emulsion, but strongly depends on declination zone. Examples of the magnitude equation for different declination zones are shown in Fig. 5

All observational material was divided into nine 10-degree declination zones to determine the parameters of the magnitude equation. The differences $\Delta\xi$, $\Delta\eta$ of the reference stars were divided into 21 mag groups from 6.0 to 16.5 with a 0.5 mag interval for each zone. The mean differences $\overline{\Delta\xi}$, $\overline{\Delta\eta}$ and their standard errors $\sigma_{\overline{\Delta\xi}}$, $\sigma_{\overline{\Delta\eta}}$ were determined for each group. The dependence of the mean differences on magnitude has been approximated as polynomials for each zone:

$$\overline{\Delta\xi}(\text{mag}) = \sum_{k=0}^{n_1} a_k \cdot \text{mag}^k, \quad \overline{\Delta\eta}(\text{mag}) = \sum_{k=0}^{n_2} b_k \cdot \text{mag}^k.$$

In most cases the magnitude equation for bright stars (brighter than 9 mag) strongly differs from the one for faint stars (13 to 16.5 mag). Polynomial splines with one node (usually about 11 mag) have been applied for magnitude equation representation in these cases. The maximum splines order is 3. Equality of values of polynomials and their first derivatives has been adopted as node conditions.

The coefficients a_k, b_k of the polynomials (or appropriate spline coefficients) have been determined by the least-squares method. Weights have been assigned in the least-squares procedure according to $\sigma_{\overline{\Delta\xi}}$, $\sigma_{\overline{\Delta\eta}}$.

The most significant corrections for magnitude were obtained for stars brighter than 9 mag and fainter than 14 mag. The quality of exclusion of the magnitude-dependent systematic errors is shown in Fig. 6. The corrected coordinates of all stars $\tilde{\xi}_{\rm mag}$, $\tilde{\eta}_{\rm mag}$ were determined by subtraction of the derived magnitude equation.

6. Color-dependent systematic errors

The differences $\Delta\xi = \xi - \tilde{\xi}_{\rm mag}$ and $\Delta\eta = \eta - \tilde{\eta}_{\rm mag}$ were represented as a function of color index using values B and R from the USNO-A2.0 catalogue after exclusion of the magnitude-dependent systematic errors.

The color equation does not depend on plate emulsion, but strongly depends on declination zone. All material of observations was divided into nine 10-degree declination zones. Next, differences $\Delta\xi$, $\Delta\eta$ were divided into groups according to $(B-R)_{\rm usno\,a2.0}$ from −4 to 5 mag with 0.25 mag interval in each zone. The mean values $\overline{\Delta\xi}$, $\overline{\Delta\eta}$ and their standard errors $\sigma_{\overline{\Delta\xi}}$, $\sigma_{\overline{\Delta\eta}}$ were determined for each group in all zones. Similar polynomials and splines which had been applied for magnitude equation investigation were used for color equation representation. The values $(B-R)_{\rm usno\,a2.0}$ have been used as polynomial and spline arguments. In some cases (for $\overline{\Delta\eta}((B-R)_{\rm usno\,a2.0})$) splines with two nodes have been applied.

Investigation has shown that color corrections for ξ are within the interval ±50 mas, and they are not significant in some zones of declination. The color corrections for η strongly depend on declination zone.

The most significant color corrections were obtained in the equatorial zone. The $\Delta\eta$ in this zone for stars of B type is −110 mas and 110 mas for ones of M 9 type. After exclusion of color-dependent systematic errors, residual errors were decreased for early-type and late-type stars to −40 mas and to 40 mas correspondingly. The insufficient precision of the values B and R in the USNO-A2.0 catalogue may be the cause of the small residual color-dependent systematic errors that remained in the final coordinates.

On the whole, recalculation of the plate optical centers and taking into account all revealed systematic errors provide an improvement of the accuracy by 64 mas and 51 mas for α and δ correspondingly.

7. The Pul-3 catalogue

The completely corrected equatorial coordinates were calculated for all stars on each plate. The new proper motion of each star was determined as differences between the mean positions of the second and the first epochs divided by the epoch differences $t_2 - t_1$ (t_1 and t_2 are the mean values of the first and second epochs of this star). The formal standard error of the individual proper motion was determined using the formula: $\epsilon_{\mu_x} = \sqrt{\epsilon_x^2(t_1) + \epsilon_x^2(t_2)}/(t_2 - t_1)$, where x denotes α or δ and ϵ_x denotes the standard error of the mean position. The formal standard errors of proper motions of the Pul-3 catalogue are mostly within ±3 mas/yr to ±12 mas/yr.

The positions of each star at the first and at the second epochs were transformed to the mean epoch of observation.

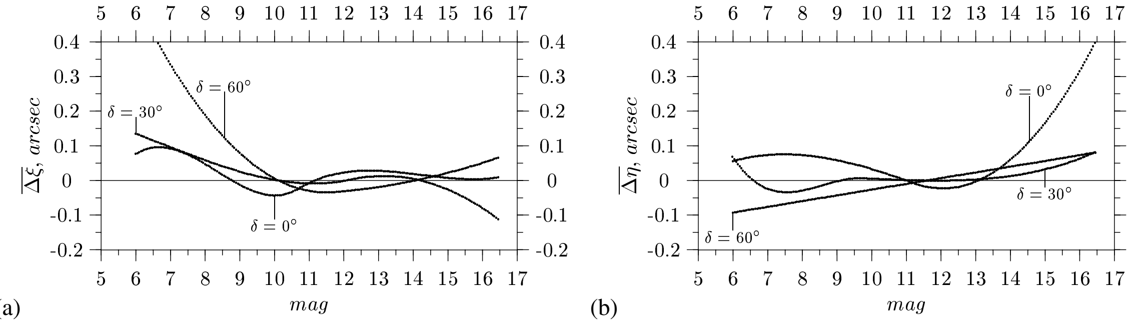

Fig. 5. The examples of magnitude equation $\overline{\Delta\xi}$(mag) **a)**, $\overline{\Delta\eta}$(mag) **b)** for different declination zones.

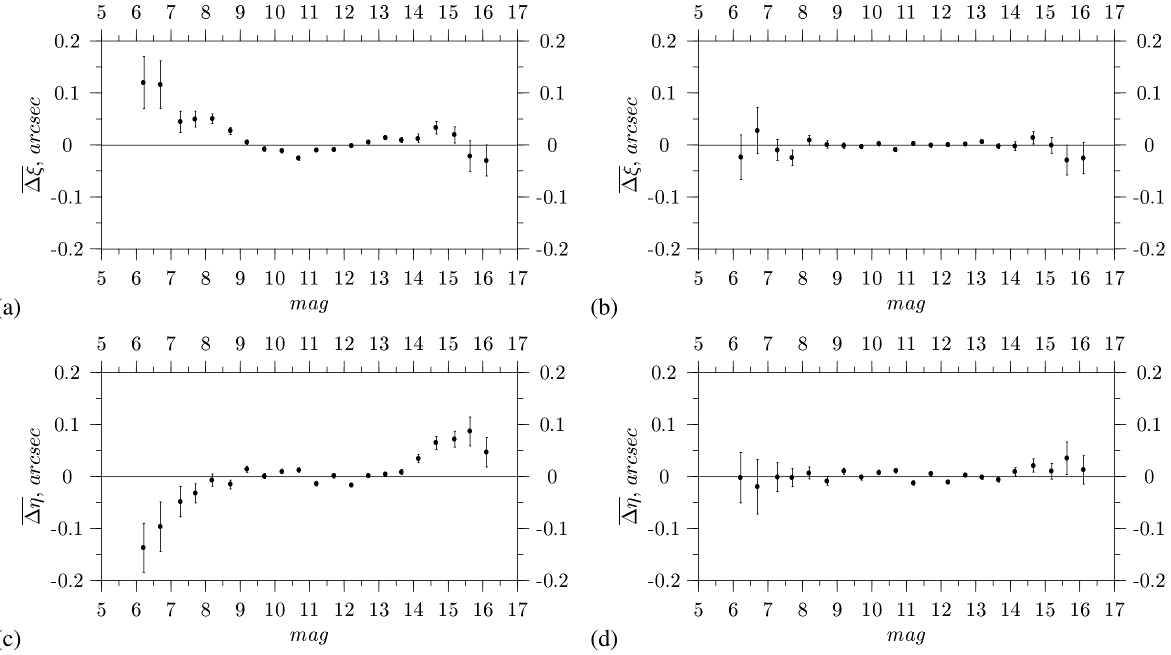

Fig. 6. The dependences of $\overline{\Delta\xi}$, $\overline{\Delta\eta}$ on magnitude before exclusion of the magnitude equation (**a**), **c**)) and after exclusion of the magnitude equation (**b**), **d**)).

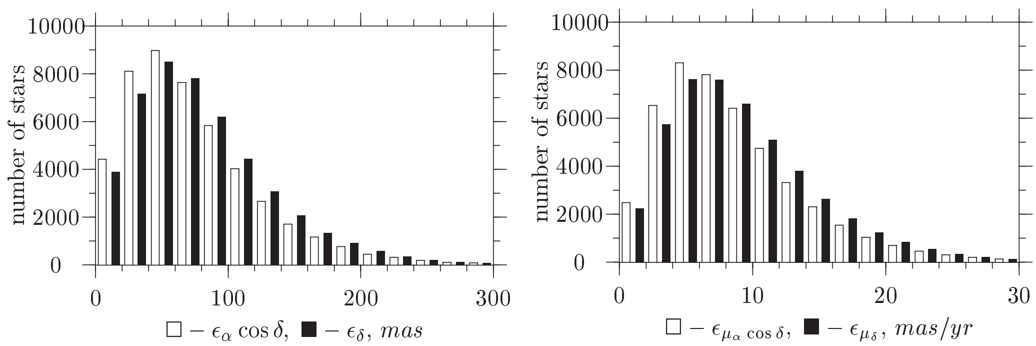

Fig. 7. Histograms of the standard errors of positions and proper motions of stars of the Pul-3.

Final equatorial coordinates of each star of the Pul-3 catalogue were derived as mean values from all available equatorial coordinates of this star. The standard errors of positions of the Pul-3 catalogue at the mean epoch of observations are mostly within ±25 mas to ±125 mas.

The mean errors of positions and proper motions of the Pul-3 catalogue are presented in Table 1. Values $\epsilon_\alpha \cos\delta$, ϵ_δ, $\epsilon_{\mu_\alpha \cos\delta}$, ϵ_{μ_δ} are internal errors and values $\sigma_{\alpha\cos\delta}$, σ_δ, $\sigma_{\mu_\alpha \cos\delta}$, σ_{μ_δ} are external errors relative to the Tycho-2 catalogue at the mean epoch of the Pulkovo observations for the different declination zones.

The histograms of the standard errors of positions and proper motions of Pul-3 are presented in Fig. 7. The dependences of the standard errors of positions on magnitude are shown in Fig. 8.

Table 1. The estimation of precision of the Pul-3 catalogue for different declination zones.

Declination zone	Internal precision				External precision (relative to Tycho-2)			
	$\epsilon_\alpha \cos\delta$	ϵ_δ	$\epsilon_{\mu_\alpha \cos\delta}$	ϵ_{μ_δ}	$\sigma_{\alpha\cos\delta}$	σ_δ	$\sigma_{\mu_\alpha\cos\delta}$	σ_{μ_δ}
	mas		mas/yr		mas		mas/yr	
$-5° \div 5°$	90	98	9.8	10.7	141	160	9.2	10.2
$5° \div 15°$	86	86	9.2	9.4	136	159	8.7	10.0
$15° \div 25°$	79	88	7.9	8.9	130	148	9.2	9.1
$25° \div 35°$	85	85	9.1	9.2	154	159	10.2	11.2
$35° \div 45°$	79	78	8.8	8.8	151	157	9.7	10.1
$45° \div 55°$	79	82	8.5	8.6	157	159	11.4	12.5
$55° \div 65°$	77	80	8.4	8.7	162	175	9.9	12.1
$65° \div 75°$	74	78	8.0	8.5	126	142	8.0	9.8
$75° \div 85°$	73	78	8.5	8.5	127	142	8.8	9.9
for full catalogue	80	84	8.7	9.1	142	155	9.2	10.1

Table 2. Extract of the Pul-3 catalogue.

$N_{\rm pul3}$	α h m s	δ ° ′ ″	$\epsilon_\alpha \cos\delta$ ″	ϵ_δ ″	$\mu_\alpha \cos\delta$ mas/yr	μ_δ mas/yr	$\epsilon_{\mu_\alpha\cos\delta}$ mas/yr	ϵ_{μ_δ} mas/yr	T yr	$B_{\rm pul}$	$n_{\rm pos}$	fl	$N_{\rm tycho-2}$	$N_{\rm hip}$	N possI	B usno–a2.0	R
0010001	00 05 12.579	+27 44 00.97	0.13	0.29	+005.23	−012.74	14.56	34.54	1961.980	15.4	4	001	0000000000	000000	293	16.0	15.4
0010002	00 05 13.389	+27 45 50.77	0.02	0.08	+008.00	−024.79	01.52	10.36	1961.980	13.1	4	001	0000000000	000000	293	12.6	12.3
0010003	00 05 31.757	+27 33 23.92	0.18	0.05	+031.45	−026.88	18.38	06.10	1961.980	15.0	4	001	0000000000	000000	349	15.2	13.8
0010004	00 05 35.894	+27 36 39.08	0.07	0.09	+001.31	−009.56	08.20	09.72	1961.980	12.1	4	001	1735018631	000000	349	12.5	11.7
0010005	00 05 39.723	+28 03 41.96	0.04	0.10	+002.61	−017.12	04.65	12.61	1961.980	13.4	4	001	0000000000	000000	293	13.0	11.7
0010006	00 05 43.187	+27 55 52.13	0.11	0.03	+027.07	+026.14	11.89	05.76	1961.980	15.0	4	001	0000000000	000000	293	14.7	14.2
0010007	00 06 00.547	+28 16 37.33	0.07	0.07	−020.58	+002.19	06.70	08.02	1961.980	07.5	4	001	1735015731	000502	293	08.3	10.7
0010008	00 06 02.571	+28 11 02.53	0.06	0.03	+018.32	−009.87	05.86	03.08	1961.980	13.4	4	001	0000000000	000000	293	13.2	12.8
0010009	00 06 09.520	+28 03 49.68	0.09	0.04	+024.20	−018.14	12.50	04.92	1961.980	12.9	4	001	0000000000	000000	293	12.5	12.0
0010010	00 06 13.494	+27 44 25.18	0.04	0.14	+049.22	+032.70	00.00	00.00	1959.030	11.6	3	001	1735016641	000000	293	12.0	11.4
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
1570339	23 54 19.809	+19 53 02.52	0.06	0.09	−096.46	−207.40	06.93	04.62	1964.710	14.1	4	001	0000000000	000000	405	13.3	11.4
1570340	23 54 24.893	+19 38 04.76	0.03	0.07	−027.65	−025.13	03.50	06.27	1964.710	12.6	4	001	0000000000	000000	405	12.4	11.7
1570341	23 54 32.863	+19 57 49.00	0.04	0.07	+018.67	−028.39	03.34	05.58	1964.710	13.4	4	001	0000000000	000000	405	13.3	12.0
1570342	23 54 38.142	+19 56 13.84	0.08	0.07	−005.99	−008.17	08.28	07.71	1964.710	15.3	4	001	0000000000	000000	405	15.4	14.3
1570343	23 54 41.021	+20 05 52.18	0.12	0.07	+025.45	+003.43	10.92	07.72	1964.710	13.3	4	001	1728001071	000000	405	12.9	12.3
1570344	23 54 46.568	+20 57 46.35	0.06	0.11	−070.67	−097.38	10.36	10.42	1964.710	14.8	4	001	0000000000	000000	000	00.0	00.0
1570345	23 54 46.810	+19 23 23.29	0.06	0.04	−029.47	−049.92	07.21	02.23	1964.710	14.2	4	001	0000000000	000000	405	14.5	13.7
1570346	23 54 47.808	+19 56 16.39	0.04	0.06	−038.21	−056.16	03.45	09.46	1964.710	09.8	4	001	1725006691	000000	405	10.8	09.3
1570347	23 55 03.493	+20 23 04.94	0.03	0.04	+262.32	+015.92	13.75	03.51	1964.710	09.3	4	001	1728001871	117918	405	09.7	08.5
1570348	23 55 18.531	+19 32 00.15	0.10	0.13	−001.59	−004.09	10.35	13.50	1964.710	11.8	4	001	0000000000	000000	000	00.0	00.0

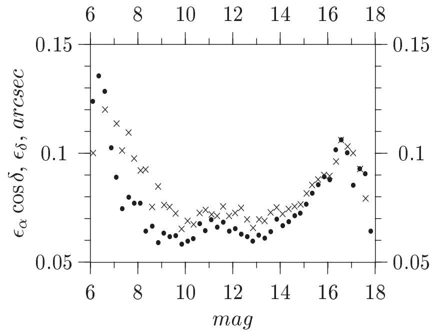

Fig. 8. The dependences of internal mean errors $\epsilon_\alpha \cos\delta$ (•) and ϵ_δ (×) on magnitude in the Pul-3 catalogue.

For illustration, an extract of the Pul-3 catalogue is shown (Table 2). The Pul-3 catalogue contains positions (α, δ) at the mean observational epoch of star (T) for equator and equinox J2000, proper motions, magnitude ($B_{\rm pul}$), number of observations ($n_{\rm pos}$) and values B and R from the USNO-A2.0 catalogue.

8. Comparisons of the Pul-3 catalogue with Tycho-2 and ARIHIP catalogues

The comparison of the Pul-3 catalogue of positions and proper motions with Tycho-2 (7588 common stars) and ARIHIP (Wielen et al. 2001) (795 common stars) was done at the mean epoch of the Pul-3 catalogue. Systematic differences (Tycho-2–Pul-3) with dependence on α and on δ are presented in Figs. 9 and 10.

The results of the comparison demonstrate that most systematic differences (Tycho-2–Pul-3) are within ±10 mas for coordinates and ±0.5 mas/yr for proper motions.

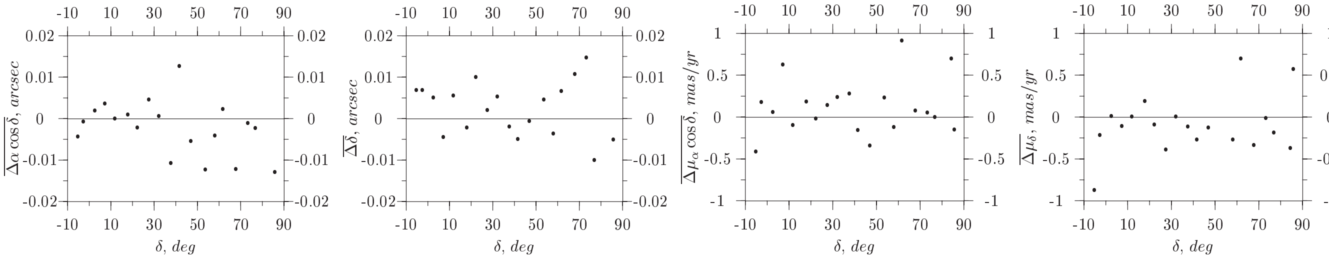

Fig. 9. The mean systematic differences (Tycho-2 – Pul-3) with dependence on declination.

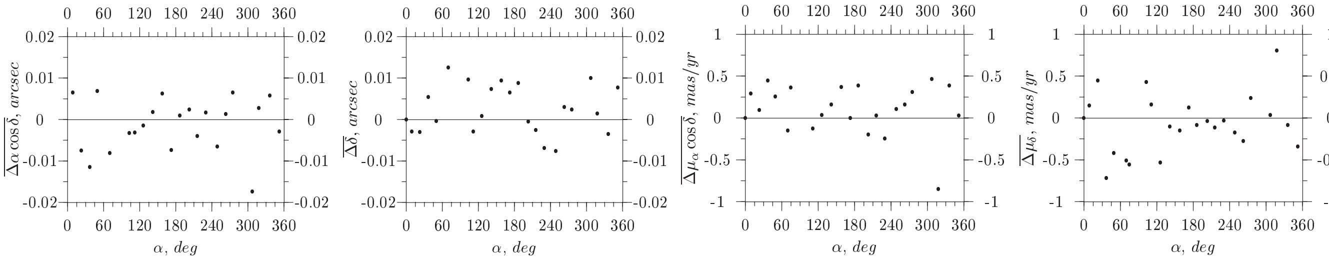

Fig. 10. The mean systematic differences (Tycho-2 – Pul-3) with dependence on right ascension.

The mean differences (ARIHIP – Pul-3) are small also:

$\overline{\Delta\alpha\cos\delta} = +6\,\mathrm{mas}$, $\overline{\Delta\delta} = -4\,\mathrm{mas}$,
$\overline{\Delta\mu_\alpha\cos\delta} = +0.28\,\mathrm{mas/yr}$, $\overline{\Delta\mu_\delta} = +0.76\,\mathrm{mas/yr}$.

9. Comparisons of the stellar proper motions of the Pul-3 catalogue with absolute stellar proper motions of the Pul-2 catalogue

The new proper motions of stars of the Pul-3 catalogue have been compared with absolute proper motions of the same stars in the Pul-2 catalogue. The components of the angular velocity vector of rotation $\omega = (\omega_x, \omega_y, \omega_z)$ of the Pul-3 catalogue (Tycho-2 system) relative to the Pul-2 were obtained from differences in proper motions (Pul-3–Pul-2).

$\omega_x = -0.76 \pm 0.91\,\mathrm{mas/yr}$,
$\omega_y = -0.75 \pm 0.74\,\mathrm{mas/yr}$,
$\omega_z = -2.05 \pm 0.71\,\mathrm{mas/yr}$.

Our results are in excellent agreement with estimations of components of the angular velocity vector of rotation that had been derived from differences between Hipparcos proper motions and the Lick absolute proper motions ($\omega_x = -0.70 \pm 0.25\,\mathrm{mas/yr}$, $\omega_y = -0.27 \pm 0.20\,\mathrm{mas/yr}$, $\omega_z = -2.14 \pm 0.20\,\mathrm{mas/yr}$)) (Kovalevsky et al. 1997).

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