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Hipparcos extragalactic link by means of absolute proper motions of stars related to galaxies: Kyiv solution

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Abstract. Absolute proper motions of stars with respect to galaxies obtained within the KSZ and MEGA programmes were used in the determination of spin parameters of the Hipparcos catalogue system relative to the inertial reference frame. The Kyiv part of the Bonn-Potsdam-Kyiv project "Hipparcos extragalactic link by photographic astrometry" is discussed. Solutions using bright stars, faint stars as well as the whole magnitude range of stars were found. "The faint KSZ stars" solution ($\omega_x = -0.27 \pm 0.80 mas/yr, \omega_y = +0.15 \pm 0.60 mas/yr, \omega_z = -1.07 \pm 0.80 mas/yr$) is considered as the most reliable and is recommended for the correction of the Hipparcos catalogue system.

Key words: astrometry – reference systems – stars: kinematics

1. Introduction

Positions of 118000 stars, their proper motions and parallaxes obtained from measurements with ESA's astrometric satellite Hipparcos have a high degree of internal consistency. The accuracy of mutual positions of celestial objects in the Hipparcos catalogue is on a few milliarcsecond (mas) level. However, the satellite was not able to observe extragalactic objects directly so that the Hipparcos catalogue system may in principle contain spurious rotation. Therefore, the Hipparcos system needs calibration which includes determination of orientation of the system in a certain epoch and its spin correction. There are some methods of calibration of the Hipparcos data (Lindegren & Kovalevsky 1995, Kovalevsky, Lindegren et al. 1996) based on the use of both new measuring instruments (VLBI, VLA, HST) and traditional methods of ground-based astrometry. One can determine either only the orientation at epoch of the Hipparcos system (VLA, MERLIN), or only its spin correction (using absolute proper motions of stars with respect to galaxies or photographic observations of optical counterparts of extragalactic radio sources). Some methods allow to find jointly both the orientation of the Hipparcos system in a certain epoch and its spin correction (VLBI, MERLIN, HST, use of Earth rotation parameters).

In this paper we present the results of the application of absolute proper motions of stars with respect to galaxies in selected fields of the sky, obtained within the KSZ and MEGA programmes, to determine a spin correction of the final Hipparcos catalogue system. In spite of the comparably low accuracy of these data, it is possible to link the Hipparcos system with random errors less than $\pm 1 mas/yr$ as it has been shown in (Yatsenko et al. 1987). The present investigation represents the Kyiv part of the Bonn-Potsdam-Kyiv project "Hipparcos extragalactic link by photographic astrometry" (Brosche et al. 1995).

2. Characteristics of ground-based observational data

2.1. Catalogue of faint stars

In the third decade of this century astronomers of the Pulkovo observatory proposed a programme for determination of absolute proper motions of stars using faint galaxies as an inertial reference frame (Deutsch 1952). The programme, called the Catalogue of Faint Stars (KSZ - abbreviated from Russian Katalog Slabykh Zvezd), required the collaboration of many observatories from the former Soviet Union, China, Rumania, and Spain. The project covers 306 ($2^\circ \times 2^\circ$) selected fields with galaxies on the whole sky, including 205 ones in declination zone from -25° to $+90^\circ$. The first epoch of photographic observations were obtained practically by all participating observatories. For the second epoch only Golosiiv (Kyiv) and Pulkovo observatories have completely finished the observations whereas the Moscow, Tashkent, and Shanghai observatories have almost finished them. Unfortunately, only episodic observations of the second epoch were carried out by the other KSZ programme participants. At present nearly 20 individual catalogues of absolute proper motions within the KSZ programme were compiled. The whole complex of catalogues consists of more than 80000 stars in KSZ fields.

Rather substantial investigations including the compilation of some individual and combined KSZ catalogues have been carried out at the Main Astronomical Observatory of National

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Table 1. Some characteristics of KSZ catalogues

Observatory	Zones degrees	Latitude degrees	Focus, m	Number of fields	stars	catalogues
Pulkovo	+90÷−5	+60	3.5	89	16032	2
Tashkent	+90÷−25	+41	3.5	157	31799	7
Golosiiv	+90÷−15	+50	5.5	136	30410	4
Moscow	+90÷−10	+55	6.4	10	1540	1
Shanghai	+90÷−25	+31	6.9	8	1310	3

Academy of Sciences of Ukraine (Golosiiv Observatory) for many years. Some general catalogues were compiled here using available individual KSZ catalogues obtained at different observatories and published before 1987. These catalogues were applied to different astrometric studies and investigations of stellar astronomy problems (Kharchenko 1987, Rybka 1990). A description of some Golosiiv KSZ catalogues is given in Kharchenko et al. (1991).

A new version of the general catalogue, the so-called General compiled catalogue of absolute Proper Motions (GPM), will include nearly 60000 stars with magnitudes from 8 to 15.5 in 185 areas with 550 galaxies. At present, the first part of this catalogue (GPM1) has been completed for bright stars of the Hipparcos Input Catalogue (Rybka & Yatsenko 1996). The second part will contain all remaining stars with a limiting photographic magnitude 15.5. The GPM1 catalogue consists of absolute proper motions of 977 Hipparcos stars in 180 areas north of $-25°$ degrees of declination. Table 1 gives some characteristics of the KSZ catalogues used for the construction of the GPM1 catalogue.

2.2. *Programme for a complex study in the main meridional section of the galaxy*

The main task of the programme for a complex study in the main Meridional section of the Galaxy (MEGA) is the investigation of kinematics and structure of the Galaxy (Einasto et al. 1987). The programme includes the construction of catalogues of proper motions of stars with respect to galaxies in selected fields of the sky along the main meridian of the Galaxy, their positions, stellar magnitudes in UBVR and Vilnyus systems, parameters of stellar classification: absolute stellar magnitudes, effective temperatures, metallicities of all stars to 12^m in 47 areas of the sky. Approximately one third of the KSZ fields being close to the main meridian of the Galaxy (within $\pm 20°$) has been included in the MEGA programme.

Within the MEGA programme a general catalogue of absolute proper motions for 14111 stars with limiting magnitude of $B = 16^m$ relative to 206 galaxies was obtained by Kharchenko (1987). The catalogue was compiled using observations with double astrograph ($D = 0.4m, F = 5.5m$) at Golosiiv observatory. The first epoch plates (with emulsions Kodak Oa-0, Agfa Astro, Ilford Zenith) have been taken by many astronomers in 1953-1962., the plates of the second epoch (ORWO ZU-21 emulsion) have been obtained by N.Kharchenko in 1981-1984. In addition, the AGK3 and SAO catalogues have been used for the compilation of the general catalogue. Table 2 lists all catalogues used in this compilation.

Table 2. Number of stars from different catalogues used in the MEGA general catalogue

Catalogues	Number of stars	catalogues
Golosiiv (KSZ)	14111	3
AGK3	377	1
SAO	53	1
Pulkovo (KSZ)	2343	1
Moscow (KSZ)	647	1
Tashkent (KSZ)	1156	5

Special methods developed at Golosiiv observatory including the selection of kinematically homogeneous group of reference stars, the removal of systematic errors in proper motions (especially magnitude equation), and the calibration of stellar magnitudes were applied to compile the general catalogue.

The mean square errors of proper motions in the GPM1 and MEGA general catalogues are $\pm 8 mas/yr$ on average.

3. Determination of the rotation of the Hipparcos catalogue system

The systematic part of the proper motion differences which can be ascribed to a rotation difference between the Hipparcos catalogue system (H) and the extragalactic frame (E) can be expressed by means of the observation equations (using the notations according to Lindegren & Kovalevsky (1995):

$$\begin{aligned} \Delta\mu_\alpha \cos\delta &= -\omega_x \cos\alpha \sin\delta - \omega_y \sin\alpha \sin\delta + \omega_z \cos\delta, \\ \Delta\mu_\delta &= \omega_x \sin\alpha - \omega_y \cos\alpha. \end{aligned}$$

Here α, δ are the equatorial coordinates, $\Delta\mu_\alpha \cos\delta$, $\Delta\mu_\delta$ are the proper motion differences in the sense Hipparcos-Catalog (GPM1 or MEGA) in right ascension and declination, respectively, and ω_x,ω_y,ω_z, are the components of the rotation vector. Equations can be formed and solved in two cases using 1) proper motion differences of each star and 2) mean proper motion differences (normal points) for each field. In other words

Table 3. Preliminary solutions of the equations

Solution	N/n	ω_x	ω_y (mas/yr)	ω_z	σ_0
KSZ+MEGA	225	+2.67 ± 0.97	+2.53 ± 0.76	−1.45 ± 0.74	±9.8
	995	+2.35 ± 0.65	+1.92 ± 0.51	−1.28 ± 0.50	±13.8
KSZ	179	+2.02 ± 1.09	+1.44 ± 0.88	−2.17 ± 0.85	±10.0
	832	+1.90 ± 0.73	+1.09 ± 0.58	−1.78 ± 0.58	±14.5
MEGA	-	-	-	-	-
	163	+6.99 ± 0.96	+5.84 ± 1.09	−0.01 ± 0.43	±7.5
KSZ-MEGA	-	-	-	-	-
	69	+3.49 ± 1.43	+6.17 ± 1.02	+1.93 ± 0.86	±9.6

Note: "Field solutions" are given in upper lines (N is number of fields) and "star solutions" are given in lower lines (n is number of stars).

Table 4. GPM1 "star solutions"

Solution	ω_x	ω_y (mas/yr)	ω_z	σ_0
Combined	+1.53 ± 0.75	+1.07 ± 0.60	−2.07 ± 0.59	±15.0
	+1.53 ± 0.60	+0.81 ± 0.47	−2.03 ± 0.47	±11.9
$\Delta_{\mu_\alpha} cos\delta$	+4.90 ± 1.44	+3.16 ± 1.74	−2.38 ± 0.61	±115.2
	+1.43 ± 1.17	+1.01 ± 1.41	−2.03 ± 0.50	±112.3
Δ_{μ_δ}	+0.24 ± 0.88	+0.77 ± 0.63	-	±114.8
	+1.59 ± 0.68	+0.79 ± 0.49	-	±111.4
Combined weighted	-	-	-	-
	+1.55 ± 0.57	+0.80 ± 0.44	−2.04 ± 0.52	±11.9

Note: Upper lines give the solutions using original GPM1 catalogue and lower lines give the "corrected catalogue solutions" (i.e. with taking into account the zero point offsets of proper motions).

we will have a so-called "star solution" and a "field solution" respectively. Both solutions must coincide if the stars were homogeneously distributed within the fields and the fields were homogeneously distributed over the sky. Formally, the mean square errors of unknowns in the "star solution" are less than those in the "field solution" because of the larger number of observation equations.

The results of the solution of the system of equations for combined and separate use of the GPM1 and MEGA data are given in Table 3 for the "field solutions" (upper lines) and "star solutions" (lower lines).

Table 3 shows that the KSZ and MEGA solutions differ from each other significantly. Applying the same equations for the proper motion differences in the sense "KSZ minus MEGA" the solution given in the last line of Table 3 has been found. As one can see, actually proper motions of stars in the GPM1 and MEGA catalogues belong to different reference frames. Therefore, one should not use these data jointly. It should be also noted that the distribution of the MEGA fields on the sky is not an optimum to determine the rotation parameters of the Hipparcos system.

Table 5. Change of the angle ω_x with exclusion of bright stars

Range of magnitude	Number of stars	ω_x (mas/yr)
7.9 − 12.6	710	+1.83 ± 0.71
8.2 − 12.6	658	+1.62 ± 0.72
8.5 − 12.6	586	+2.26 ± 0.80
8.8 − 12.6	514	+0.74 ± 0.83
9.1 − 12.6	415	−0.27 ± 0.80
9.4 − 12.6	334	−0.67 ± 1.01
9.7 − 12.6	240	−0.29 ± 1.10

For this reason, later on, only the GPM1 catalogue data were used for the Hipparcos link purpose. The initial GPM1 data were analysed more carefully and new combined solution of the sys-

Table 6. Final GPM1 solutions

Range of magnitudes	N/n	ω_x	ω_y (mas/yr)	ω_z	σ_0
All stars	179/839	+1.43 $\pm$ 0.51	+0.45 $\pm$ 0.43	-2.07 ± 0.44	$\pm$4.6
$(4.7 - 12.6)$		+1.53 $\pm$ 0.59	+0.85 $\pm$ 0.52	-2.09 ± 0.49	$\pm$11.9
Bright stars	156/390	+2.73 $\pm$ 1.12	+1.95 $\pm$ 0.84	-2.17 ± 0.83	$\pm$8.1
$(4.7 - 9.0)$		+2.33 $\pm$ 0.91	+0.95 $\pm$ 0.74	-2.67 ± 0.79	$\pm$13.0
Faint stars	154/415	-0.27 ± 0.80	+0.15 $\pm$ 0.60	-1.07 ± 0.80	$\pm$7.3
$(9.1 - 12.6)$		+0.53 $\pm$ 0.72	+0.45 $\pm$ 0.60	-1.27 ± 0.70	$\pm$10.6

Note: Upper lines give the "field solutions" (N is number of fields) and lower lines give the "star solutions (n is star number).

tem of equations as well as separate solutions for proper motion differences in right ascension ($\Delta_{\mu_\alpha}\cos\delta$) and declination ($\Delta_{\mu_\delta}$) were obtained (see the first three upper lines in Table 4). The "field solutions" and "star solutions" were found to be practically the same. However, the solutions for ($\Delta_{\mu_\alpha}\cos\delta$) and ($\Delta_{\mu_\delta}$) differ significantly. It has been supposed that such differences were caused by the errors of determination of absolute proper motions in separate fields on the one hand and by small weights of unknowns ω_x and ω_y determed using only the ($\Delta_{\mu_\alpha}\cos\delta$) differences.

Random errors of absolute proper motions of stars in the GPM1 catalogue consist of two main components: random errors of relative proper motions of stars and random errors of their absolutisation. The last ones may be considered as systematic errors within the same field determining the zero point offsets for each field. Two additional unknowns (the zero point offsets of proper motions for each field in ($\Delta_{\mu_\alpha}\cos\delta$) and ($\Delta_{\mu_\delta}$) were added to the link equations. The errors of absolutisation of the other fields were supposed to be equal zero on average. After determining the offset corrections the catalogue of absolute proper motions has been improved and afterwards the corrected catalogue was applied for the determination of the Hipparcos link angles. This solution was called the "corrected catalogue solution". The corresponding results are given in Table 4 (lower lines). As one can see from Table 4 (comparing upper and lower lines) the combined solutions using the original (uncorrected) and corrected catalogues differ insignificantly (except their errors) but hte differences between ($\Delta_{\mu_\alpha}\cos\delta$) and ($\Delta_{\mu_\delta}$) solutions practically disappeared if the corrected catalogue is used. Therefore, later on, only the corrected catalogue was used.

In addition, some solutions of the system were carried out using different methods of weighting the observation equations. Since the accuracies of the Hipparcos and KSZ proper motions are known, the link equations may be weighted as well as different weights may be fixed, depending on the stellar magnitudess. The last line in Table 4 gives the weighted combined solution of equations for the corrected GPM1 catalogue. One can see that both the weighted and unweighted joint solutions are practically the same and afterwards all solutions were carried out without the weighting.

As a next step towards a discussion of the results the residuals of the link equations were examined and tested for non-randomness. From consideration of the covariance matrix follows that correlations between unknowns are practically absent (the correlation coefficients in modulus do not exceed 0.2) and the residuals in ($\Delta_{\mu_\alpha}\cos\delta$) and ($\Delta_{\mu_\delta}$) solutions are normally distributed. In order to examine any systematic dependence on star positions, their magnitudes and colours, the residuals of the link equations were developed in series of orthogonal functions using products of Hermite and Legendre polynomials as well as Fourier terms. No significant above-named dependencies have been obtained.

According to the recommendation of the "Working group on the link of the Hipparcos catalogue to the extragalactic reference frame", an additional analysis of the solutions was carried out in spite of the solutions were not changing practically with inclusion to the link equations of the terms depending from brightness of stars. In general, the Hipparcos rotation angles $\omega_x, \omega_y, \omega_z$ may be distorted by a magnitude equation. Therefore, the dependencies of the components of angle ω on brightness of stars were investigated in different way. Some solutions were carried out excluding gradually bright stars. As we found the solutions were different, the angle ω_x was strongly dependent on the magnitude range of the stars used in the solution (see Table 5).

From Table 5 follows that the angle ω_x changes its sign beginning from the magnitude m = 9.1 which divides the whole file of stars into two approximately equal parts - bright stars and faint stars.

4. Conclusions

Table 6 gives the final "field solutions" (upper lines) and "star solutions" (lower lines) using the whole range of stellar magnitudes and only bright stars or faint stars.

Thus, we conclude that since the proper motions of stars in the KSZ programme were obtained relative to faint galaxies, we may consider that proper motions of only faint stars do practically not depend on a magnitude equation. Therefore, "the faint KSZ stars" solution ($\omega_x = -0.27 \pm 0.80 mas/yr, \omega_y =$

$+0.15 \pm 0.60 mas/yr, \omega_z = -1.07 \pm 0.80 mas/yr$) is preferable and may be recommended as the most reliable one for the linkage of the Hipparcos catalogue system.

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