Mon. Not. R. Astron. Soc. **393,** 133–138 (2009) doi:10.1111/j.1365-2966.2008.14168.x

The XPM Catalogue: absolute proper motions of 280 million stars

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Accepted 2008 October 29. Received 2008 October 27; in original form 2008 June 27

ABSTRACT

We combined data from the Two-Micron All Sky Survey (2MASS) and USNO-A2.0 catalogues in order to derive the absolute proper motions of about 280 million stars distributed all over the sky excluding a small region near the Galactic Centre, in the magnitude range $12 < B < 19$ mag. The proper motions were derived from the 2MASS Point Sources and USNO-A2.0 catalogue positions with a mean epoch difference of about 45 years for the Northern hemisphere and about 17 years for the Southern one. The zero-point of the absolute proper motion frame (the 'absolute calibration') was specified with the use of about 1.45 million galaxies from 2MASS. Most of the systematic zonal errors inherent in the USNO-A2.0 catalogue were eliminated before the calculation of proper motions. The mean formal error of absolute calibration is less than 1 mas yr^{-1}. The XPM Catalogue will be available via CDS in Strasbourg during 2010. The generated catalogue contains the International Celestial Reference System positions of stars for the J2000 epoch, original absolute proper motions, as well as B, R, J, H and K magnitudes. A comparison of the proper motions obtained in this work with the data of other recent catalogues of quasars was fulfilled.

Key words: catalogues – astrometry – reference systems.

1 INTRODUCTION

The main goal of this work is to create the most comprehensive catalogue of absolute proper motions of stars using the extragalactic reference frame defined by faint galaxies. The concept of using galaxies as an inertial proper motion reference frame was initiated by Dneprovsky & Gerasimovič (1932) in Pulkovo. The results of most well-known absolute proper motion programmes using galaxies as a reference frame are presented by the following catalogues: General Compiled Catalogue of Absolute Proper Motions (GPM) (Rybka & Yatsenko 1997a), GPM1 (Rybka & Yatsenko 1997b), PUL2 (Bobylev, Bronnikova & Schakht 2004) for the faint stars programme (KSZ); NPM1 (Klemola, Jones & Hanson 1987) and NPM2 (Hanson et al. 2004) for the Lick Northern Proper Motion; and SPM2 (Platais et al. 1998), SPM3 (Girard et al. 2004) for the Yale Southern Proper Motion. We use the term 'absolute proper motions' to describe about 280 million proper motions of stars with a zero-point derived using positions of about 1.45 million galaxies as the reference frame.

As is well known, tangential velocities of galaxies (Chernin 2001) as compared to the Hubble flow are vanishingly small at distances from several Mpc. Even if their tangential motions V_t were equal in magnitude to the Hubble flow $V_t = H \times R$, the resulting proper motions should be as small as $\mu_0 = 1.5 \times 10^{-5}$ arcsec yr^{-1} for $H = 70$ km s^{-1} Mpc^{-1} (Klemola et al. 1987). It is evident that any rotation of the system of galaxies caused by their peculiar velocities is much less than μ_0. Consequently, the positions of galaxies over the time period of 100 yr may be considered to be time independent.

Thus, the absolute proper motions are tangential components of the stars' spatial velocities with respect to a quasi-inertial coordinate system, i.e. such a system that moves without rotation while its origin may have acceleration. Such coordinate systems are admissible in classical mechanics. In general relativity, such coordinate systems are admissible too, but they require some relativistic corrections (Einstein 1956; Weinberg 1972). A system of proper motions specified by any catalogue of absolute proper motions makes it possible to reproduce a quasi-inertial system of coordinates at any given time moment with an accuracy of up to the catalogue systematic errors.

Since there are large numbers of faint galaxies that look like stars in the initial images and thus can be used as astrometric reference objects, the effect of the magnitude equation for stars fainter than 15 mag can be expected to be insignificant. Unfortunately, the position data for extragalactic point sources are very scanty. For example, in the Sloan Digital Sky Survey (SDSS) data release 5 (DR5) Quasar Catalogue (available at http://www.sdss.org/dr5/products/), there are only about 78 000 quasars, and 94 000 quasars are contained in the Lyon Extragalactic Data base (http://leda.univ-lyon1.fr/), and their distribution over the sky is very inhomogeneous. Though the magnitude equation may affect extended and

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point sources differently, the use of galaxies' positions for absolute calibration seems to be reasonable from the viewpoint of minimization of the systematic errors.

Therefore, the catalogue presented in this paper is an independent realization of the extragalactic reference system in the optical range, whose rate of rotation with respect to distant extragalactic objects is less than 1 mas yr^{-1}. This paper is the first one in a series representing a catalogue of the new absolute proper motions containing 280 million objects, which we called XPM. We hope that this catalogue will be available via CDS in Strasbourg during 2010 when we will complete an investigation of the obtained proper motions and compare the proper motions with those contained in the most recent catalogues. Here, we describe the initial considerations, procedures of cross-identification, error correction, linking to extragalactic objects and deriving the absolute proper motions. Also, we briefly discuss the results of external comparison that gives the estimate of errors of the proper motions.

2 THE DATA

The Two-Micron All Sky Survey (2MASS) (Skrutskie et al. 2006) and USNO-A2.0 (Monet 1998) catalogues contain the most comprehensive data on the astrometric positions of stars. The positions of both the catalogues are nominally on the International Celestial Reference System (ICRS) (Arias et al. 1995). The mean difference of epochs between 2MASS and USNO-A2.0 is about 45 years for the Northern hemisphere and about 17 years for the Southern one. The 2MASS data contain two large data sets: the Point Source Catalogue (PSC; 470 992 970 point objects) and the Extended Source Catalogue (XSC; 1650 000 extended objects). Most of the extended objects in XSC are galaxies. Therefore, combining the 2MASS data with the earlier highly dense data sets for deriving the absolute proper motions of stars and providing the absolute zero-point of proper motion seems to be reasonable.

The USNO-A2.0 catalogue is the densest data set suitable for solving this task. It contains about 526 million positions taken from 825 POSS I fields and from 606 SRC-J and ESO-R fields, but their combination with 2MASS to obtain precise proper motions is rather problematic due to the presence of the magnitude-dependent and zone-dependent systematic errors (http://vizier.u-strasbg.fr/viz-bin/qcat?). In this paper, we use the term 'field' in the sense as it has been considered by D. Monet in READUSE.V20 for USNO-A2.0.

Another great problem in using these catalogues is the difference in spectral bands of 2MASS (near-infrared bands: 1.15, 1.65, 2.15 μm) and USNO-A2.0 (optical bands: *J*, 0.39–0.54; *R*, 0.63–0.69; *O*, 0.58–0.67 and *E*, 0.35–0.53 μm). Therefore, we cannot guarantee the cross-identification of the stars to be reliable because of a chance alignment of infrared and optical sources, especially inside highly dense star fields, and also when large epoch differences are used.

The most unexpected trouble is related to the coordinates of extended objects in 2MASS. Most of the extended objects are present in both PSC and XSC data sets, but their coordinates are systematically different in PSC and XSC (see Fig. 1). The differences reach up to 25 mas and can lead to considerable systematic errors in proper motions derived, especially in the south, where the epoch difference between 2MASS and USNO-A2.0 is relatively small (17 yr on average). We are not sure at present which coordinates of extended sources should be used for absolute calibration, so actually we derived two sets of absolute proper motions based on the PSC and XSC coordinates of extended sources.

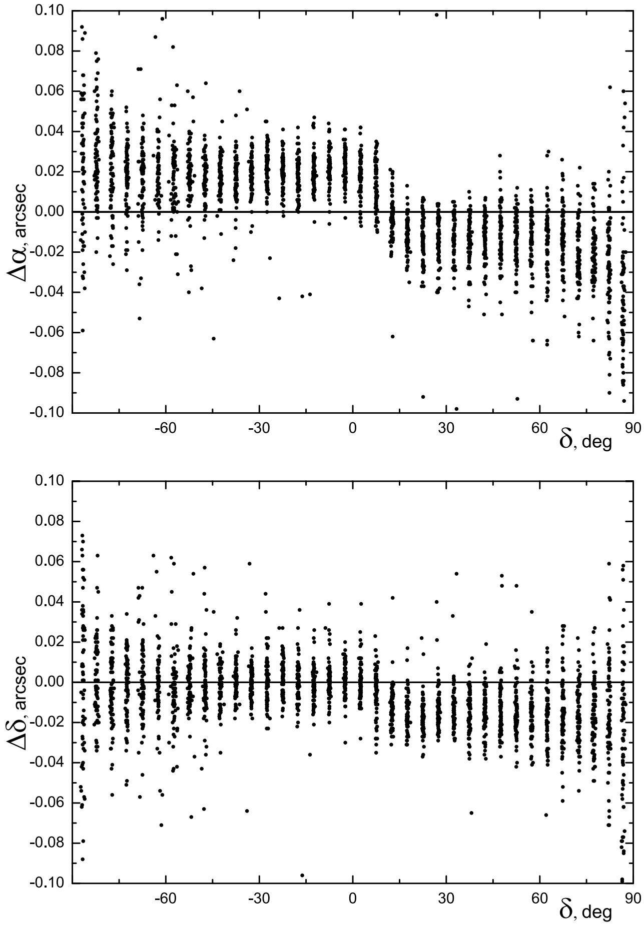

Figure 1. XSC–PSC coordinate differences for 2MASS extended sources depending on declination zone.

3 DERIVING THE ABSOLUTE PROPER MOTIONS

Here, we briefly describe the techniques for cross-identification, error correction, linking to extragalactic objects and deriving the absolute proper motions, which have been applied to individual USNO-A2.0 fields.

3.1 Cross-identification

Unfortunately, it was impossible to use magnitudes of both catalogues for cross-identification because of a significant difference in their passbands, and therefore we had to do it using only coordinates of objects. It should be noted that such cross-identification is usually named positional association and is not necessarily an exact identification.

Each field of USNO-A2.0 is about 5° × 5° in dimensions and has a constant observation epoch value. Because of a very large difference of stellar density at the different galactic latitudes, we used a two-step cross-identification procedure with a circular window of adjustable size. At the first stage, a circular window of 3.5 arcsec in radius was used in each field. After that, the procedure of error correction was applied. At the more precise second stage, we first calculated an approximate mean offset between the corrected USNO-A2.0 and PSC positions of stars, and then we used various windows with sizes varying from 0.1 to 15 arcsec with a step of

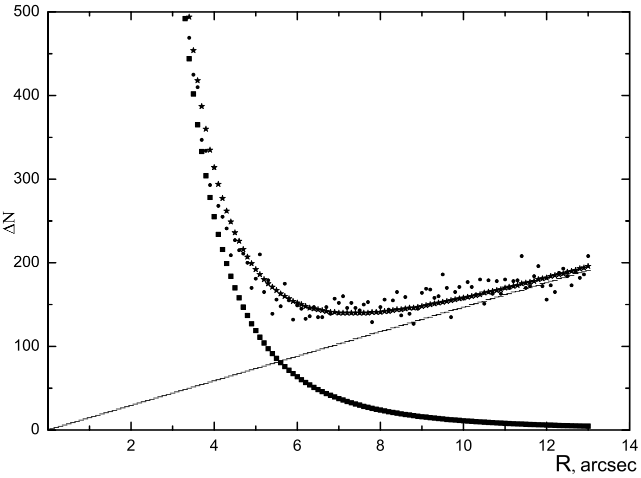

Figure 2. The increment of a number of stars as a function of the ring radius.

0.1 arcsec, and counted the increment of a number of stars dN (circular dots), which fell into the annular zones with radii R and $R + \mathrm{d}R$.

This increment shown in Fig. 2 as a function of the ring radius can be represented by a sum of two functions (asterisks). One of them is the density distribution function of angular distances for the nearest neighbours in each field (black squares). For the random (Poisson) distribution of star positions, the distribution function can be computed (Bahcall & Soneira 1981). The second one is the function of a uniform density distribution of stars over the field, which is directly proportional to the window radius (thin line). The optimal window size was specified with the intersection point of these functions. This intersection point corresponds to such a radius where the probability of misidentification reaches the probability of omitting a star with a considerable proper motion. The value of the computed window radius varies from 3.5 to 15 arcsec, depending on a particular field. Thus, the maximal value of proper motion varied from about 80 mas yr^{-1} in dense fields up to 350 mas yr^{-1} in low-density fields. This algorithm cannot guarantee a correct identification for all objects, but we believe that the overwhelming majority of objects have been identified correctly.

3.2 Error corrections

After the first step of cross-identification, the coordinate differences 2MASS minus USNO-A2.0 for the identified stars were analysed inside each field in order to find out possible geometric distortions induced by both the USNO-A2.0 and 2MASS systematic errors.

It should be noted here that, in fact, we do not need to know the actual systematic errors of both catalogues. Only coordinate differences are important. In reality, the coordinate differences of both catalogues for a particular field can be described by the following relation:

$$\Delta P = \Delta T \mu + f(\alpha, \delta),$$

where ΔP is the position difference between USNO-A2.0 and 2MASS produced by the proper motion μ_α or μ_δ during the time interval ΔT, as well as produced by the difference $f(\alpha, \delta)$ between systematic errors of both catalogues.

We believe that a saw-edged and stepped behaviour of positional errors is an intrinsic feature of USNO-A2.0, caused by specific properties of the Precision Measuring Machine (PMM) measuring device (Fedorov & Myznikov 2006). This is a characteristic feature of many current catalogues, which have also been created using telescopes with small fields of view. We regard that proper motions of stars should not demonstrate such an unnatural behaviour (Fig. 3) inside a relatively small field $\sim 5^\circ \times 5^\circ$. They must show a smooth behaviour, but the sharp, saw-edged and stepped behaviour within a small field is an artefact introduced by characteristic features of the facility used for creating USNO-A2.0 and 2MASS.

3.3 Linking to extragalactic objects and deriving the absolute proper motions

In modern usage, the term ‘absolute calibration’ denotes the procedure of reducing the observed proper motions of stars to a coordinate system that does not rotate in space. In our case, the direction of axes of such a coordinate system is determined by *spherical coordinates* of about 1.45 million extragalactic objects of 2MASS distributed over the whole celestial sphere. This is the principal difference from traditional methods of absolute calibration, which use the coordinates of extragalactic objects *measured* from photographic or CCD images as the fixed fiducial points.

To correct systematic errors of USNO-A2.0, the spherical coordinates α and δ were converted into tangential coordinates, and systematic coordinate differences of stars with magnitudes of 15–17 mag were fitted with a function $F(\xi, \eta)$ inside each field. This function is a combination of a low-power polynomial $a\xi_i + b\eta_i + c$, which describes the mean proper motion of the stars, and a ‘high-frequency’ stepping function $\varphi(\xi, \eta)$, produced by the systematic errors of USNO-A2.0. In order to find this function, we used the two-dimensional median filter, since it provides an opportunity to define a function $F(\xi, \eta)$, which almost retains the behaviour of the initial function ΔP at the points of discontinuity.

Since we do not exactly know which part of the systematic differences is introduced by the actual motions of stars, we subtract the approximating function $F(\xi, \eta)$ from the initial function ΔP, so that the mean systematic coordinate differences of stars between USNO-A2.0 and 2MASS turn out to equal zero, i.e.

$$\langle \Delta P_{\mathrm{star}}(\xi_i, \eta_i) - F(\xi_i, \eta_i) \rangle = 0,$$

and thus we reduce the coordinates of all the USNO-A2.0 stars into the coordinate system defined by the 2MASS positions of stars in any particular field.

To provide the reference to extragalactic objects, we postulate zero proper motions for galaxies and search the 2MASS extended sources among the USNO-A2.0 objects inside each field. The number N of identified extragalactic objects inside every field varies from a few tens at low galactic latitudes to several thousands at high galactic latitudes. If the number of galaxies in a particular field is less than nine, this field is excluded from consideration.

Since positions of galaxies in each field have distortions identical to those of stars, we subtracted the approximating function $F(\xi, \eta)$ from the systematic coordinate differences of galaxies, and consequently derived coordinate differences of galaxies, which are released from the saw-edged and stepped distortions. Most of the extended sources are galaxies with zero proper motion and the differences between their 2MASS and USNO-A2.0 coordinates just reflect the actual star motions with the opposite sign at this stage. These differences inside each field were approximated by a simple linear reduction model:

$$\Delta P_{\mathrm{gal}}(\xi_i, \eta_i) - F(\xi_i, \eta_i) = a\xi_i + b\eta_i + c, \quad (1)$$

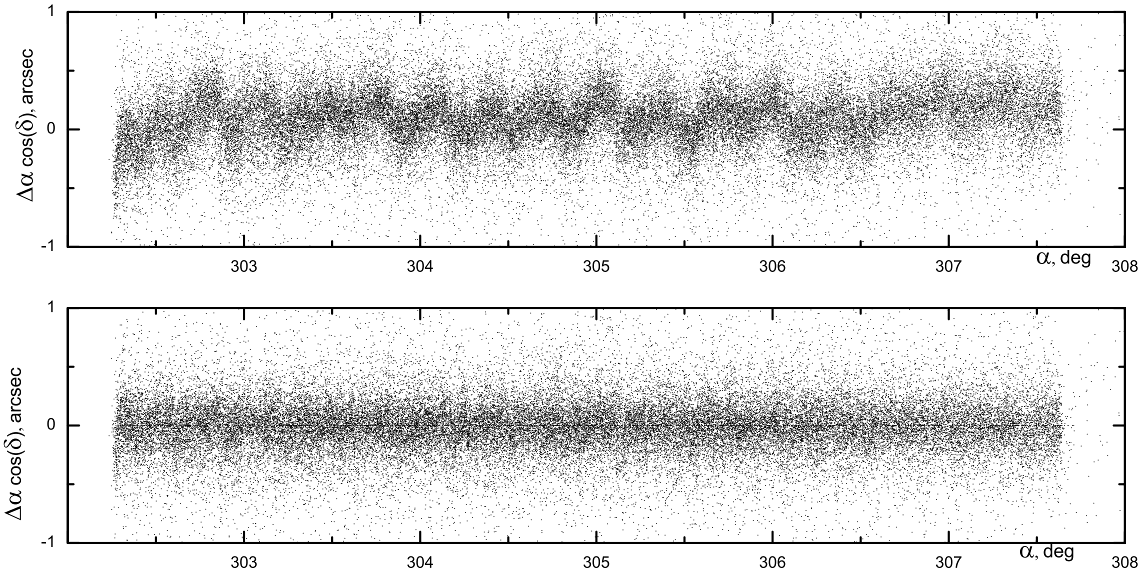

Figure 3. The typical coordinate differences between USNO-A2.0 and 2MASS before and after correction.

which reflects a general drift of the stellar system inside a field, its extension – contraction and rotation. The parameters of this model were determined with the least squares procedure.

In order to obtain corrected USNO-A2.0 coordinates, we apply this model to reduce all objects (stars and galaxies) of the USNO-A2.0 field into the coordinate system defined by positions of the 2MASS extended sources.

The proper motions of stars were derived at the final stage by just dividing the coordinate differences of 2MASS minus corrected USNO-A2.0 by the epoch difference for every star:

$$\mu_i = \frac{\Delta P_{\rm star}(\xi_i, \eta_i) - F(\xi_i, \eta_i) - (a\xi_i + b\eta_i + c)}{\Delta T_i}.$$

The epoch difference for each star was determined by the following relation:

$$\Delta T_i = T_{\rm 2MASS} - \frac{1}{2}\left(T^R_{\rm USNO} + T^J_{\rm USNO}\right),$$

where $T_{\rm 2MASS}$, $T^R{}_{\rm USNO}$ and $T^J{}_{\rm USNO}$ are epochs of observations of the 2MASS, USNO-A2.0 (*R*) and USNO-A2.0 (*J*) stars, respectively.

These corrected USNO-A2.0 coordinates were used at the second stage of the cross-identification procedure.

4 EXTERNAL ERROR AND ERROR OF ABSOLUTE CALIBRATION

As follows from the algorithm of calculating the absolute proper motions of stars, they depend on the accuracy of the definition of a non-rotating coordinate system, which is determined by the accuracy of extragalactic objects' positions. Uncertainty in the definition of axes arises due to the presence of two sets of positions of extragalactic objects in the 2MASS catalogue. This leads to different values of parameters of the linear reduction model $a\xi_i + b\eta_i + c$. Since systematic differences between the PSC and XSC coordinates of extragalactic objects reach 25 mas, systematic differences in the absolute proper motions of stars derived with the use of the PSC and XSC will vary from 0.6 mas yr^{-1} in the Northern hemisphere to 1.5 mas yr^{-1} in the Southern one.

In order to estimate the external errors of the proper motions derived, we identified about 12 000 quasars from the DR5 and LEDA data sets among our stars, and analysed their formal proper motions (see Figs 4 and 5, right-hand panels). Unfortunately, we cannot use the whole sphere because of a specific distribution of quasars over the sky (Fig. 5, left-hand panel).

We obtained a zero mean value for the formal proper motions as was expected, while the rms value turned out to be 3–8 mas yr^{-1}, depending on the magnitude. These values provide the estimate of the external error of proper motions for the Northern hemisphere. In order to inspect the internal error of proper motions, we use variance of the initial catalogue positions as the measure of accuracy of the astrometric reduction. The relation (1) is the basis for deriving the estimates for random accuracy of proper motions of stars. To do this, it will suffice to assume that the errors of the USNO-A2.0 coordinates after reducing to the 2MASS system, as well as the 2MASS coordinate errors, are of a random character and distributed normally:

$$\epsilon_{\Delta P_{\rm star}} \in N\left(0, \sigma^2_{\Delta P_{\rm star}}\right)$$

$$\epsilon_{\Delta P_{\rm Gal}} \in N\left(0, \sigma^2_{\Delta P_{\rm Gal}}\right).$$

Then, the formal error of proper motions can be determined from the following relation:

$$\epsilon^2_\mu = \frac{\sigma^2_{\Delta P_{\rm star}}}{\Delta T^2} + \frac{\sigma^2_{\Delta P_{\rm Gal}}}{\Delta T^2 N},$$

where the two terms correspond to the principal constituents of a total error of proper motion. The first term characterizes a random error of proper motions of stars caused by the errors of their positions in the catalogues used, while the second one is the error of absolute calibration, that is, the accuracy of reducing the observed proper motions of stars to the frame of reference, determined within a certain field by positions of the 2MASS extragalactic objects.

After the systematic errors are excluded, the root-mean-squared deviation of the coordinate differences 2MASS minus USNO-A2.0 is about 150–200 mas, and the rms error of proper motions varies from 4 to 10 mas yr^{-1}, depending on the specific field. These data were obtained from the inner convergence and do not contradict the estimates of the external accuracy of proper motions. Similarly, the root-mean-squared deviation of the coordinate differences of

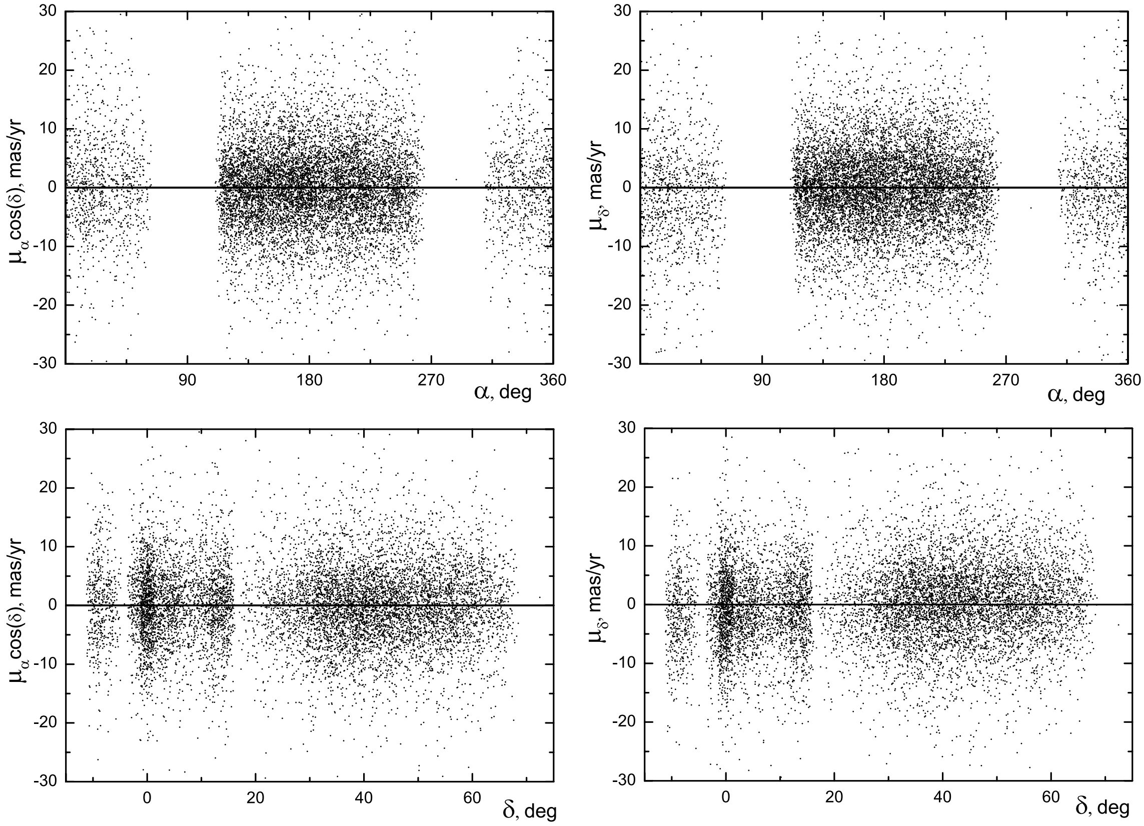

Figure 4. Scatter of formal proper motions for the DR5 quasars versus RA and Dec.

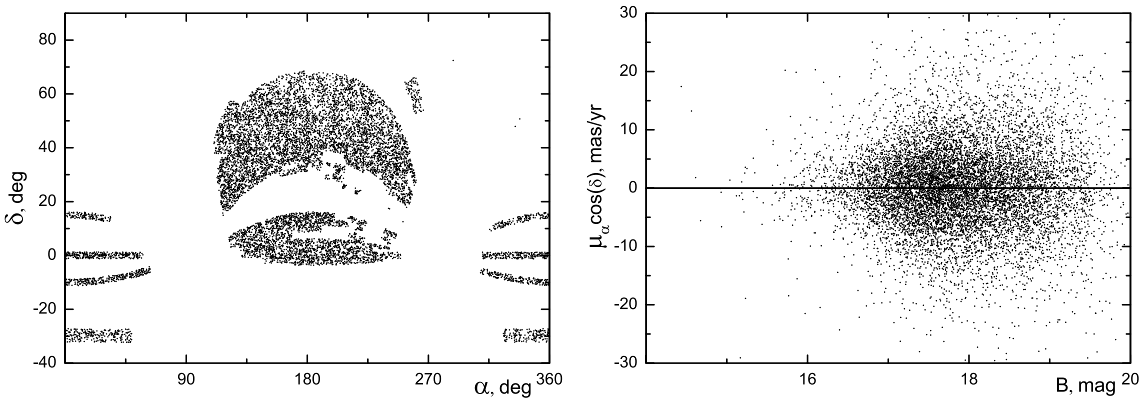

Figure 5. Distribution of the DR5 quasars' positions over the sky (left-hand panel), and scatter of formal proper motions in RA for DR5 quasars versus magnitude (right-hand panel).

extended sources is about 400–450 mas, and the mean number of galaxies inside each field is about 1000, so we expect the error of absolute calibration to be

$$\epsilon_{\rm abs} = \frac{\sigma_{\Delta P_{\rm Gal}}}{\Delta T \sqrt{N}} \sim 0.3 \ {\rm mas\,yr^{-1}}$$

in the north, and 2.5–3 times larger in the south, depending on the particular field.

5 CONCLUSIONS

As far as we know, there is no large full-sky catalogue of absolute proper motions for faint stars, though there are many tasks where they are applicable. We present a catalogue, XPM, which is an independent realization of the quasi-inertial reference frame and can be used for many astronomical studies.

In this work, we did not correct the derived proper motions for the magnitude equation, but we believe that it must be negligible at the faint edge of the magnitude range. The magnitude equation seems to be considerable for stars brighter than 15 mag. This fact hampers a comparison of proper motions of faint stars with those from the most recent catalogues, such as Tycho-2 (Hog et al. 2000), USNO-B (Monet et al. 2003), UCAC-2 (Zacharias et al. 2004) and SPM3 (Girard et al. 2004). Besides, we cannot exclude that the magnitude equation has a different effect on images of extended and point sources. Therefore, measured coordinates of extended objects may be biased with respect to the measured coordinates of stars in the 2MASS and USNO-A2.0 catalogues. This effect cannot be rigidly detected and measured, but it may cause problems in agreement of zero-points for different catalogues referenced to extragalactic objects. At the moment, we are doing a more detailed analysis of the obtained results in order to investigate the magnitude equation for bright stars and to compare the proper motions with those contained in the most recent catalogues.

REFERENCES

Arias E. F., Charlot P., Feissel M., Lestrade J.-F., 1995, A&A, 303, 604
Bahcall J. N., Soneira R. M., 1981, ApJ, 246, 122
Bobylev V. V., Bronnikova N. M., Schakht N. A., 2004, Astron. Lett., 30, 519
Chernin A. D., 2001, Phys-Usp, 44, 1099
Dneprovsky N., Gerasimovič B., 1932, Pulkovo Obs. Circ. No. 3, p. 1
Einstein A., 1956, The Meaning of Relativity. Princeton Univ. Press Princeton
Fedorov P. N., Myznikov A. A., 2006, Kin. Phys. Celest. Bodies, 22, 309
Girard T. M., Dinescu D. I., van Altena W. F., Platais I., Lopez C. E., Monet D. G., 2004, ApJ, 127, 3060
Hanson R. D., Klemola A. R., Jones B. F., Monet D. G., 2004, AJ, 128, 1430
Hog E. et al., 2000, A&A, 355, L27
Klemola A. R., Jones B. F., Hanson R. B., 1987, AJ, 94, 501
Monet D. G., 1998, BAAS, 30, 1427
Monet D. et al., 2003, AJ, 125, 984
Platais I. et al., 1998, AJ, 116, 2556
Rybka S. P., Yatsenko A. I., 1997a, Kin. Phys. Celest. Bodies, 13, 70
Rybka S. P., Yatsenko A. I., 1997b, A&AS, 121, 243
Skrutskie M. F. et al., 2006, ApJ, 131, 1163
Weinberg S., 1972, Gravitation and Cosmology: Principles and Application of the General Theory of Relativity. Wiley, New York
Zacharias N., Urban S. E., Zacharias M. I., Wycoff G. L., Hall D. M., Monet D. G., Rafferty T. J., 2004, AJ, 127, 3043

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