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The XPM Catalogue. Absolute proper motions of 280 million stars

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ABSTRACT
We combined data from the 2MASS (Two Micron All Sky Survey) 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 center, in the magnitude range $12^m <$ B $< 19^m$. The proper motions were derived from the 2MASS Point Sources and USNO-A2.0 Catalogues positions with the 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 calculation of proper motions. The mean formal error of absolute calibration is less than 1 mas/yr. The XPM Catalogue will be available via CDS in Strasbourg during 2010. The generated catalogue contains the ICRS 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: Astrometry, catalogues, reference system.

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 and Gerasimovič, 1932) in Pulkovo. The results of most well-known absolute proper motion programs using galaxies as reference frame are presented by the following catalogues: GPM (Rybka and Yatsenko, 1997a), GPM1 (Rybka and Yatsenko, 1997b), PUL2 (Bobylev, 2004) for the faint stars program (KSZ); NPM1 (Klemola et al., 1987) and NPM2 (Hanson et al., 2004) for the Lick Northern Proper Motion; SPM2 (Platais et al., 1998), SPM3 (Girard et al., 2004) for the Yale Sourthern 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 becoming vanishingly small already at distances from several Mps. 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 for H=70 km sec^{-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 years 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 the classical mechanics. In the 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^m can be expected to be insignificant. Unfortunately, the position data for extragalactic point sources are very scanty. For example, in the SDSS DR5 Quasar Catalog (available at http://www.sdss.org/dr5/products/), there are only about

78000 quasars, and 94000 quasars are contained in the Lion Extragalactic Database (http://leda.univ-lyon1.fr/), and their distribution over the sky is very inhomogeneous. Though the magnitude equation may effect on extended and point sources differently, using 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 the rate of rotation with respect to distant extragalactic objects is less 1mas/yr. 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 investigate 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 discuss briefly the results of external comparison that gives the estimate of errors of the proper motions.

2 THE DATA

Catalogues 2MASS (Skrutskie et al., 2006) and USNO-A2.0 (Monet et al., 1998) contain the most comprehensive data on the astrometric positions of stars. The positions of both catalogs 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 Catalog (PSC - 470,992,970 point objects) and the Extended Source Catalog (XSC - 1,650,000 extended objects). Most of extended objects in XSC are galaxies. Therefore, combining of the 2MASS data with the more early 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 combining with 2MASS to obtain precise proper motions is rather problematic due to the presence of the magnitude-dependent and zone-dependent systematic errors (Fedorov+, 2005; http://vizier.u-strasbg.fr/viz-bin/qcat?). In this paper we use 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 micron) 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 micron). Therefore, we cannot guarantee the cross-identification of 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 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 years on the 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.

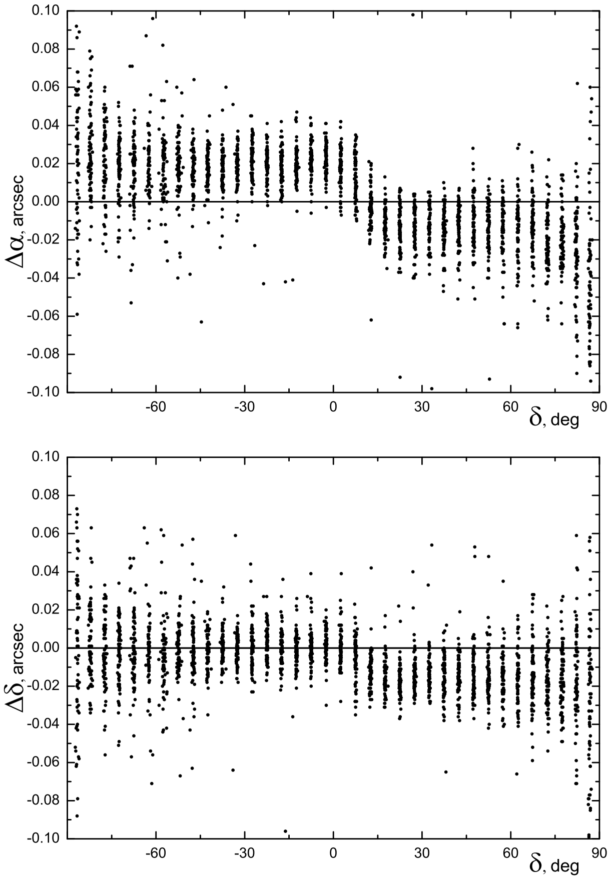

Figure 1. XSC-PSC coordinate differences for 2MASS extended sources depending on declination zone.

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

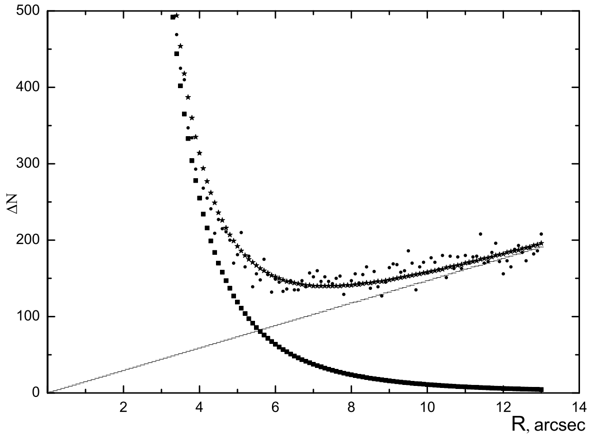

Figure 2. The increment of a number of stars as a function of the ring radius.

such cross-identification is usually named positional association and is not necessarily an exact identification.

Each field of USNO-A2.0 is about 5 x 5 degrees in dimensions and has constant observation epoch value. Because of a very large difference of stellar density at the different galactic latitudes, we used a 2-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 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 $R + dR$.

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 neighbors in each field (black square). For the random (Poisson) distribution of star positions, distribution function can be computed (Bahcall and 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 when a probability of missidentification reaches the probability of omitting a star with a considerable proper motion. The value of computed window radius varies from 3.5 arcsec up to 15 arcsec, depending on a particular field. Thus, the maximal value of proper motion varied from about 80 mas/yr in dense fields up to 350 mas/yr in low-density fields. This algorithm can not guarantee correct identification for all objects, but we believe that the overwhelming majority of objects had 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 analyzed 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:

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

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 behavior of positional errors is an intrinsic feature of USNO-A2.0, caused by specific properties of PMM measuring device (Fedorov and Myznikov, 2006). This is a characteristic feature of many current catalogues, which have also been created using the telescopes with small fields of view. We regard that proper motions of stars should be not demonstrate such an unnatural behavior (fig.3) inside a relatively small field $\sim 5 \times 5$ deg. They must show a smooth behavior, but the sharp, saw-edged and stepped behavior within a small field are artifacts 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

It modern usage the term “absolute calibration” denotes a procedure of reducing the observed proper motions of stars to a coordinate system that does not rotate in space. In our case, direction of axes of such 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 the magnitudes of 15^m-17^m 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 behavior of the initial function ΔP at the points of discontinuity.

Since we do not know, which exactly part of 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 a mean systematic coordinate differences of stars between USNO-A2.0 and 2MASS turn out to equal zero, i.e.

$$< \Delta P_{star}(\xi_i, \eta_i) - F(\xi_i, \eta_i) >= 0$$

and thus we reduce the coordinates of all the USNO-A2.0

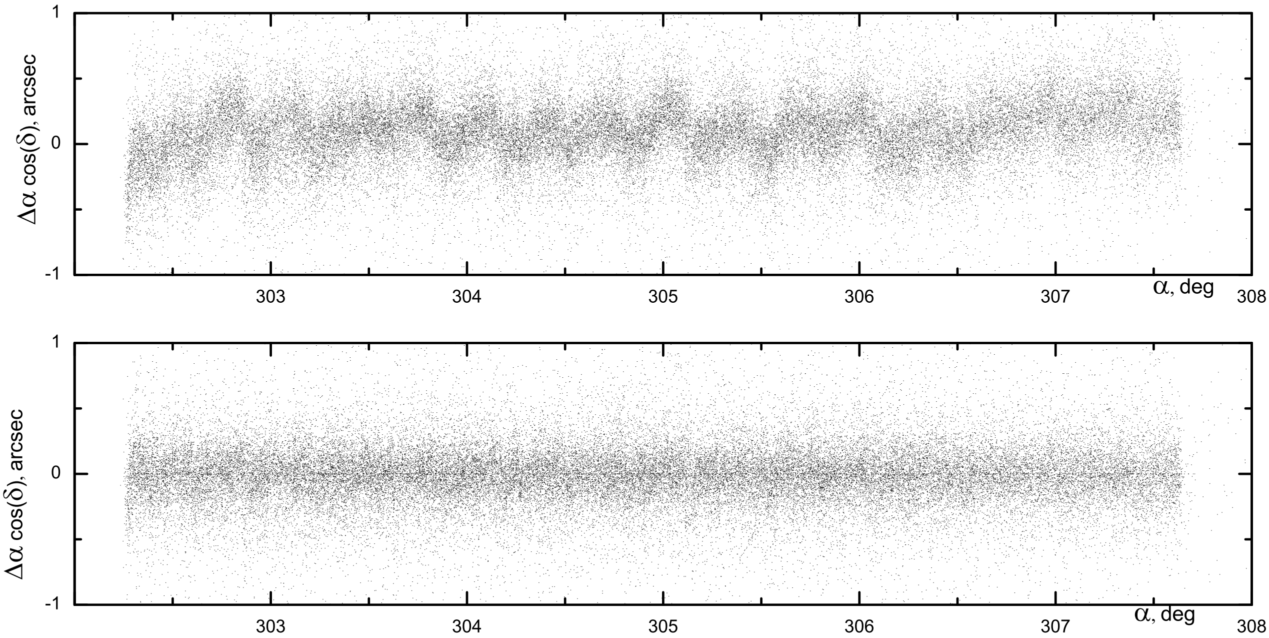

Figure 3. The typical coordinate differences between USNO-A2.0 and 2MASS before and after correction

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 the zero proper motions for galaxies and search the 2MASS extended sources among the USNO-A2.0 objects inside each field. A number N of the identified extragalactic objects inside every field varies from a few tens at low galactic latitudes up to several thousands at high galactic latitudes. If a number of galaxies in a particular field is less than 9, 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 extended sources are galaxies with the 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:

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

, which reflects a general drift of stellar system inside a field, its extension - contraction and rotation. The values of parameters 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:

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

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

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

where T_{2MASS}, T^R_{USNO} and T^J_{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 definition of a non-rotating coordinate system, which is determined by the accuracy of extragalactic objects positions. Uncertainty in 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 in the northern hemisphere to 1.5 mas/yr in the southern one.

In order to estimate the external errors of the proper motions derived, we identified about 12000 quasars from DR5 and LEDA data sets among our stars, and analyzed their formal proper motions (see Fig.4, and Fig.5 right). Unfortunately, we cannot use the whole sphere because of a specific distribution of quasars over the sky (Fig.5 left).

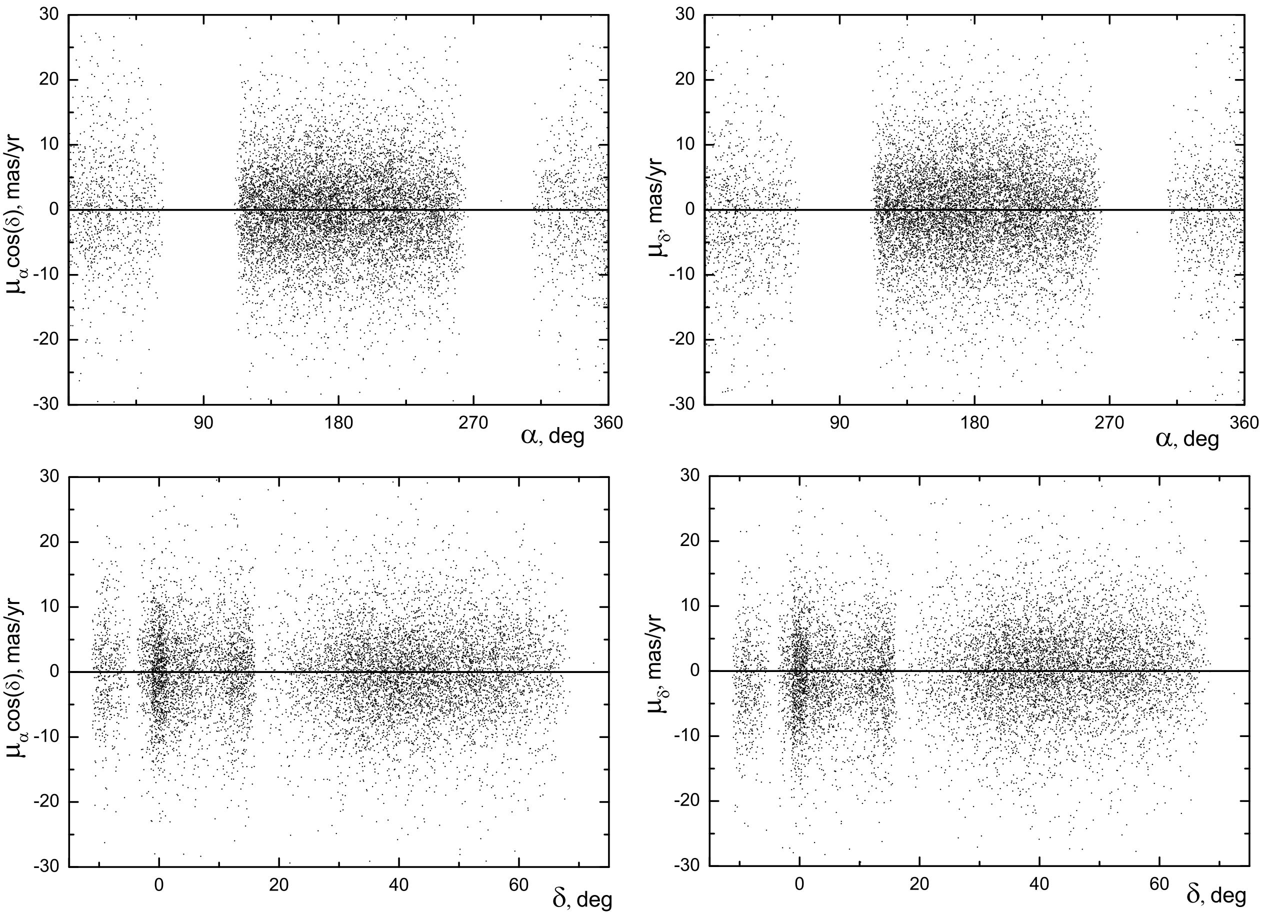

Figure 4. Scatter of formal proper motions for the DR5 quasars versus RA and Dec.

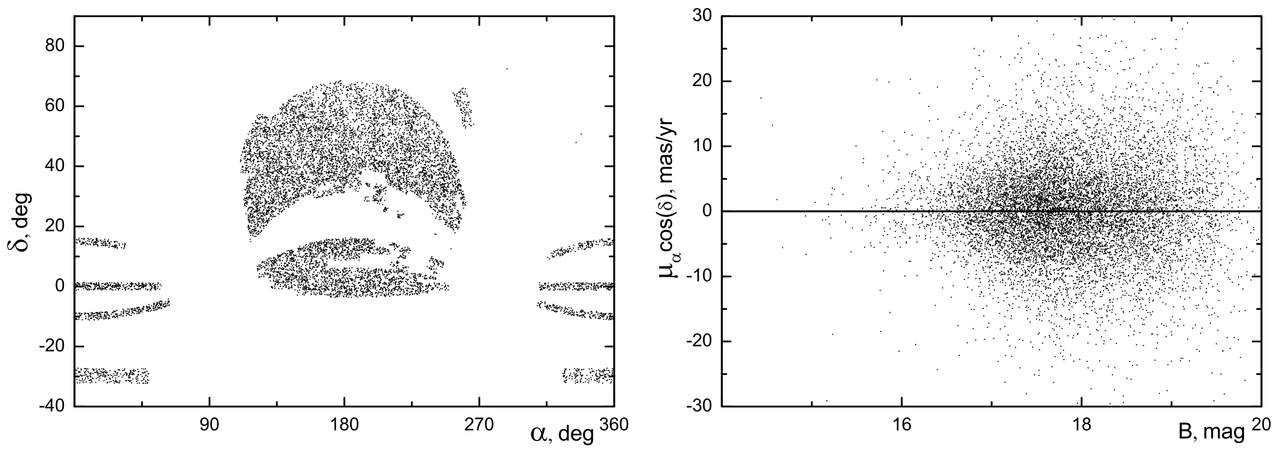

Figure 5. Distribution of the DR5 quasars positions over the sky (left), and scatter of formal proper motions in RA for DR5 quasars versus magnitude (right).

We obtained the zero mean value for the formal proper motions as was expected, while the RMS value turned out to be 3-8 mas/yr, depending on a 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:

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

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

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

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

where 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, depending on a specific field. These data were obtained from the inner convergence and do not contradict to the estimates of the external accuracy of proper motions. Similarly, the root-mean-squared deviation of the coordinate differences of extended sources is about 400-450 mas, and a mean number of galaxies inside each field is about 1000, so we expect the error of absolute calibration to be

$$\epsilon_{abs} = \frac{\sigma_{\Delta P_{Gal}}}{\Delta T \sqrt{N}} \sim 0.3 mas/yr$$

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

5 CONCLUSIONS

As far as we know, there is no large full-sky catalogues 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^m. 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 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 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.

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