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An investigation of the absolute proper motions of the XPM catalogue

P. N. Fedorov,[1★] V. S. Akhmetov,[1★] V. V. Bobylev[2★] and A. T. Bajkova[2★]
[1] *Institute of Astronomy of Kharkiv National University, Sums'ka 35, 61022 Kharkiv, Ukraine*
[2] *Central Astronomical Observatory at Pulkovo of RAS, Pulkovskoye Chaussee 65/1, 196140, St Petersburg, Russia*

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ABSTRACT

XPM-1.0 is the regular version of the XPM catalogue. In comparison with XPM, this astrometric catalogue of about 280 millions stars covering the entire sky from $-90°$ to $+90°$ in declination and in the magnitude range $10 < B < 22$ mag is somewhat improved. The general procedural steps were followed as for XPM, but some of these were performed on a more sophisticated level. The XPM-1.0 catalogue contains the star positions, the proper motions and the Two-Micron All-Sky Survey (2MASS) and United States Naval Observatory (USNO) photometry of about 280 million sources. We present some investigations of the absolute proper motions of the XPM-1.0 catalogue and also important information for users of the catalogue. Unlike the previous version, XPM-1.0 contains proper motions over the whole sky without gaps. In fields covering the zone of avoidance or those that contain fewer than 25 galaxies, quasi-absolute calibration was performed. The proper motion errors vary from 3 to 10 mas yr^{-1}, depending on a specific field. The zero-point of the absolute proper motion frame (the absolute calibration) was specified with more than one million galaxies from 2MASS and USNO-A2.0. The mean formal error of absolute calibration is less than 1 mas yr^{-1}.

Key words: catalogues – astrometry – reference systems.

1 INTRODUCTION

In this paper, we describe some steps still to be taken towards the main goal, which is to create the most comprehensive catalogue of the absolute proper motions of stars, XPM (Fedorov, Myznikov & Akhmetov 2009, hereafter Paper I), using the extragalactic reference frame defined by faint galaxies.

As is well known, there are few catalogues of the absolute proper motions of stars, while there are no catalogues that cover the whole celestial sphere. The Southern hemisphere is especially poor of data, as there is only one catalogue of absolute proper motions for the region south of $-45°$, the Southern Proper Motion 1 catalogue (SPM1; Platais et al. 1998). This covers an area of approximately 720 deg^2 near the South Pole. The limiting apparent stellar magnitude does not exceed 18 mag in all the catalogues. The catalogues are all based on photographic observations made in the 20th century. The most well-known of these are the GPM (Rybka & Yatsenko 1997, I/285 CDS), the PUL2 (Bobylev, Bronnikova & Shakht 2004, I/285 CDS) for the faint star programme (KSZ), the NPM1 (Klemola, Jones & Hanson 1987, III/199 CDS) for the Lick Northern Proper Motion programme and the SPM2 (Platais et al. 1998, III/277 CDS) for the Yale Southern Proper Motion programme. The maximal number of stars (287 000) is contained in the SPM2 catalogue, while the maximal number of galaxies (≈70 000) is in the NPM1 catalogue. The GPM, PUL2 and NPM1 catalogues cover the northern sky and partially the southern sky, and the SPM2 catalogue covers about one-third of the southern sky. The random error of proper motions in these catalogues depends on stellar magnitude and varies from 3 to 10 mas yr^{-1}, while the accuracy of the absolute calibration is 2–5 mas yr^{-1}.

The above-mentioned catalogues of absolute proper motions are very important for astrometry, as they allow the local coordinate system to be implemented, which does not rotate with respect to galaxies. The global quasi-inertial coordinate system can be established through the catalogue of absolute proper motions of stars covering the whole sky. The data of these catalogues play a principal role in determining the kinematic parameters of the Galaxy, for example, in the framework of the Ogorodnikov–Miln model. It is worth noting that this model provides the most adequate parameters, on the condition that the proper motions representing the whole celestial sphere are used.

As mentioned in Paper I, the XPM catalogue contains approximately 280 million absolute proper motions of stars and covers the whole celestial sphere, excluding a narrow zone near the galactic equator within the stellar magnitude range from $11 < B < 20$ mag. The random error of its proper motions depends on stellar magnitude and lies within 3–10 mas yr^{-1}. The error of absolute calibration in the Northern hemisphere is approximately 0.3 mas yr^{-1}, and of

★E-mail: pnf@astron.kharkov.ua; akhmetov@astron.kharkov.ua; vbobylev@gao.spb.ru; anisabajkova@rambler.ru

the order of 1 mas yr^{-1} in the Southern hemisphere. The creation of this catalogue is based mainly on the following three most important procedures:

(i) cross-identification, which allows us to identify and compare objects in the United States Naval Observatory (USNO)-A2.0 and Two-Micron All-Sky Survey (2MASS) catalogues;
(ii) elimination of systematic errors in the positions of USNO-A2.0 objects with the use of the median filter;
(iii) derivation of the absolute proper motions of stars.

Evidently, the cross-identification procedure is crucial in the procedures listed above, as it determines all other procedures and the resulting accuracy of the absolute proper motions. It has been noted in Paper I that the cross-identification procedure mentioned above is not, strictly speaking, actual cross-identification, but rather it is an association that can result in false identifications. This leads in turn to forming false position differences for stars and galaxies. Thus, the values of the function $F(\alpha, \delta)$ obtained with the median filter (see Paper I) will be burdened with errors, which will inevitably result in erroneous proper motions. Therefore, most of our attention must be given to the cross-identification procedure.

In the XPM-1.0 version, we used an improved version of the cross-identification procedure, compared to the previous version of XPM described in Paper I. It was only for this procedure that proper motions from the USNO-B1 catalogue (Monet et al. 2003) were involved. This has made it possible combine three catalogues, USNO-1, USNO-2.0 (Monet 1998) and 2MASS (Skrutskie et al. 2006), using a circular search window 1.5 arcsec in dimension. Moreover, the high-precision photometric data of 2MASS were used to calculate the USNO-2.0 magnitudes, which were compared to their original values when selecting the objects within the circular 1.5-arcsec search window. This is described in detail in Section 2. There is no simple test at this stage that would allow us to quantitatively estimate the improvement in the properties of the catalogue. This is, first of all because of the absence of accurate estimates for the individual positions of stars in the initial catalogues. Nevertheless, we believe that using the improved version of the cross-identification procedure results in a decrease of random errors in the position differences, in some broadening of the stellar magnitude range and also in an improvement in linking to extragalactic objects.

Consistent with the idea of creating the most comprehensive catalogue, we derive the proper motion of stars in the fields, which are not supplied by the number of galaxies sufficient for absolute calibration. If the number of galaxies in a particular field is not sufficient for absolute calibration, we do not exclude this field from consideration. Unlike the previous version of the XPM catalogue, we use a special absolute calibration procedure in these fields. To do this, the parameters of the reduction model of absolute calibration inside every field with an insufficient number of galaxies were calculated by a two-dimensional interpolation between the corresponding values from the neighbouring fields. We use the term ‘quasi-absolute calibration’ for the procedure of estimating proper motions in such fields, and we describe this qualitatively in Section 3. Thus, after the application of the procedures described above, each field of the total 1431 will eventually contain the absolute or quasi-absolute proper motions of stars.

Although the use of the median filter noticeably decreases the geometrical distortions in the positions of USNO-A2.0 objects, the photometric (magnitude-dependent) distortions in their positions remain unchanged after the median filter is applied. Therefore, we make efforts to eliminate the magnitude equation in the XPM-1.0 catalogue, mainly at the faint end of the range of stellar magnitudes. Section 4 is dedicated to the search and analysis of the magnitude equation in the catalogue.

Section 5 is dedicated to a comparison of the XPM-1.0 catalogue with UCAC-2.0 (Zacharias et al. 2004) and UCAC-3.0. The UCAC-3.0 catalogue (http://www.usno.navy.mil/usno/astrometry) is the only catalaogue that can be used to compare proper motions over the whole celestial sphere. Although such a comparison is not absolutely correct, because the UCAC-3.0 proper motions are in the International Celestial Reference System (ICRS) (Arias et al. 1995), the qualities of both catalogues can be estimated.

This version of the XPM catalogue contains approximately 280 million objects, covering the whole sky in the magnitude range $10 < B < 22$ mag. Their positions and absolute proper motions are presented, as well as the standard J, H, K, B and R magnitudes taken from 2MASS and USNO-2.0. For those stars from the XPM-1.0 catalogue that resulted from the combination of the USNO-B1, 2MASS and USNO-A2.0 catalogues, the magnitudes of USNO-B1 are also included. It should be emphasized that the XPM-1.0 catalogue is obtained using the data of two ground-based catalogues (2MASS and USNO-A2.0) and contains absolute proper motions. Positions in XPM-1.0 are given in the ICRS, as the stars from the 2MASS catalogue are given in this system.

2 CROSS-IDENTIFICATION

A preliminary investigation has shown that the XPM catalogue contains relatively many misidentified stars, especially at the faint end of the stellar magnitude range. This is not unexpected, as in fields with a high star density a circular window with a radius of 3.5 arcsec may fall on to several objects. These false identifications have led to the smearing of systematic coordinate differences on which the construction of the median filter was based, in order to eliminate the systematic errors in the USNO-A2.0 catalogue, and ultimately to errors in the absolute proper motions. In this paper, we describe a slightly different approach, which has provided a more reliable cross-identification of stars and galaxies contained in the USNO-A2.0 and 2MASS catalogues. This approach consists of decreasing the window radius to 1.5 arcsec and comparing the calculated and original catalogue magnitudes in this window. Thus, this approach greatly increases the probability of correctly identifying objects in the catalogues.

2.1 Coordinate identification

To implement this approach, first of all we have found evident systematic offsets between the positions of objects in USNO-A2.0 and 2MASS for the Southern and Northern hemispheres, separately. The systematic difference between the positions of galaxies in USNO-A2.0 and 2MASS can reach up to 2–3 arcsec, which is consistent with research on USNO-A2.0 by Assafin et al. (2001). After the exclusion of systematic coordinate offsets, we attract the proper motions of stars from the modified USNO-B1 catalogue (Barron et al. 2008).

There are two steps in the procedure for identifying stars in the circular search window with a 1.5-arcsec radius. First, we match the objects of the USNO-A2.0 and USNO-B1 catalogues, using the encoding of surveys and fields as given in the description of the USNO-B1 format. Thus, from the USNO-B1 catalogue we select a subset of objects that were used to compile the USNO-A2.0 catalogue.

Then, we reduce the positions of stars with proper motions from the USNO-B1 catalogue to the epoch of a particular field of the

USNO-A2.0. For stars with no proper motions, we use the positions from USNO-B1, which are formally given as referring to the epoch J2000, but actually they refer to the epoch equal to the average of epochs to which the surveys used refer. Unfortunately, only about 285 million out of one billion USNO-B1 objects have the proper motions, and of these, only about four million stars have proper motions exceeding 30 milliarcsec per year. For other objects in the USNO-B1 catalogue, the zero proper motions are given. The differences between the positions of these objects in both catalogues as a result of their proper motions rarely exceed 1 or 1.5 arcsec. This is because for 20–25 yr (i.e. for the difference between the mean epoch and the first epoch), the stars are displaced no more than by 1–1.5 arcsec even when their proper motions are about 60–75 milliarcsec per year. Thus, we use for the identification of objects in the search window with the radius of 1–1.5 arcsec not only stars with proper motions taken from the USNO-B1 catalogue, but also those with 'zero proper motions' taken from the same catalogue. Because in deriving the positions of the USNO-B1 objects the same surveys as for those of the USNO-A2.0 catalogue, among others, were used, it is obvious that the systematic differences between the USNO-B1 and USNO-A2.0 star positions are strongly correlated, so that their values seldom exceed 0.75 arcsec. Therefore, the uncertainties of the positions of stars in the USNO-B1 catalogue, as a result of the random and systematic errors of the positions and proper motions, are equal to 0.75–1.00 arcsec, even for epochs falling into the 1950s.

For the final cross-identification of objects in USNO-A2.0 and USNO-B1, we have used the search window with a 1.5-arcsec radius. In addition, we have compared the stellar magnitudes of the USNO-B1 and USNO-A2.0 stars in the entire range of stellar magnitudes, besides making use of the coordinate search window. Thus, we have obtained a combination of two sets in the form of a list of USNO-A2.0 and USNO-B1 objects identified in the search window with a 1.5-arcsec radius. As the next step, we identify the USNO-B1 objects from the resulting list and the 2MASS objects. As already mentioned, the positions in the USNO-B1 catalogue are formally given as referring to the epoch J2000, with the exception of stars with 'zero proper motion'. The epochs of the positions of these stars are the average epochs of those of the surveys used. As shown above, for these stars, the displacement over 25 yr does not exceed 1.5 arcsec. The differences between the coordinates of stars and galaxies in the 2MASS and USNO-B1 catalogues basically originate from the systematic and random errors of these catalogues and do not exceed 0.75 arcsec. Therefore, for the cross-identification of objects, and in the present case, too, we have used a search window with a 1.5-arcsec radius.

2.2 Photometric identification

As mentioned in Paper I, we were not able to perform a fully fledged cross-identification, so we restrict ourselves to a positional association only. However, it is clear that the coordinate criterion taken alone is not sufficient for identifying the stars, particularly those observed in the optical and near-infrared range. Therefore, it is necessary to apply an additional criterion to identify USNO-A2.0 and 2MASS objects. The photometric criterion is commonly used as such a criterion, but it is impossible to directly compare the USNO-A.2.0 and 2MASS stellar magnitudes. However, when analysing the previous version of the XPM catalogue, we have found that the photometry of the USNO-A.2.0 catalogue for the Northern hemisphere is different from that for the Southern hemisphere. For example, the average magnitudes B and R of galaxies in the Northern and Southern hemispheres differ systematically by about 2 mag, and for stars this difference is about 0.5–2 mag. Because of this, it is difficult to use the unified photometric criterion to identify the USNO-A2.0 and 2MASS objects.

To resolve this problem, it seemed to be necessary to solve two tasks. First, the magnitudes of all objects should be given in a common system, even if not in the entirely accurate photometric system. As such, the system given by the magnitudes of objects of the Northern hemisphere of the USNO-A2.0 catalogue was chosen. After this, a method for the determination of the B and R stellar magnitudes of these objects should be found, which is based on their J, H and K magnitudes from the 2MASS catalogue.

To solve the first task, we have constructed the relationships between the B and R stellar magnitudes of the previous version of the XPM catalogue and the J magnitude of the 2MASS catalogue separately for the Northern hemisphere, the photometry of which is taken as the basic one. By using similar relationships obtained in each particular USNO-A2.0 field, the B and R magnitudes of all objects in this field were reduced to the basic photometric system.

To solve the second task, we applied the method for calculating the stellar magnitudes of USNO-A2.0 using a more accurate photometry described by Sesar et al. (2006). In our case, the reference stellar magnitudes were those of the 2MASS catalogue. By using data for the entire celestial sphere, as given by the previous version of the XPM catalogue, the functions f_1 and f_2 have been determined separately for stars and galaxies from the following equations:

$$B_{\rm XPM} = J_{\rm 2MASS} + f_1(J_{\rm 2MASS} - K_{\rm 2MASS});$$

$$R_{\rm XPM} = J_{\rm 2MASS} + f_2(J_{\rm 2MASS} - K_{\rm 2MASS}).$$

To obtain a sufficiently detailed behaviour of (B–J) against (J–K) from the data of the first version of the XPM catalogue, the full range (J–K) was divided into subranges of 0.25 mag in width. The average value of (B–J) of each subrange was calculated. This dependence was approximated by a ninth power polynomial (see Fig. 1). The behaviour of the polynomial at the edges was fixed by cutting the marginal points of the (J–K) range.

In the new procedure for identifying the objects, the obtained functions $f_1(J_{\rm 2MASS} - K_{\rm 2MASS})$ and $f_2({\rm J_{2MASS} - K_{2MASS}})$ were used to calculate the stellar magnitudes $B_{\rm 2MASS}$ and $R_{\rm 2MASS}$ of the 2MASS catalogue objects, which fall into the circular coordinate window. To choose between the candidates caught in the circular window, the following conditions were used:

$$B_{\rm USNO-A2.0} - B_{\rm 2MASS} < 1.00\,{\rm mag};$$

$$R_{\rm USNO-A2.0} - R_{\rm 2MASS} < 0.75\,{\rm mag}.$$

In addition, for the analysis of the signs of the colour indices (CIs) (B– R) and (J– H), we applied a procedure that allows a more reliable selection of stars. The basis for such a procedure is constituted by the simple assumption that in most cases the intensity distribution in the star's spectrum is the unimodal one. The correct identification of the stars caught in the search window is performed in accordance with this assumption in only three cases, as follows.

(i) In the first case, the CIs (B–R) and (R–J) > 0, corresponding to the monotonic increase of the intensity in the range from the blue to the infrared part of the spectrum.

(ii) In the second case, the CIs (B–R) and (R–J) < 0, corresponding to the monotonic decrease of the intensity in the same range of the spectrum.

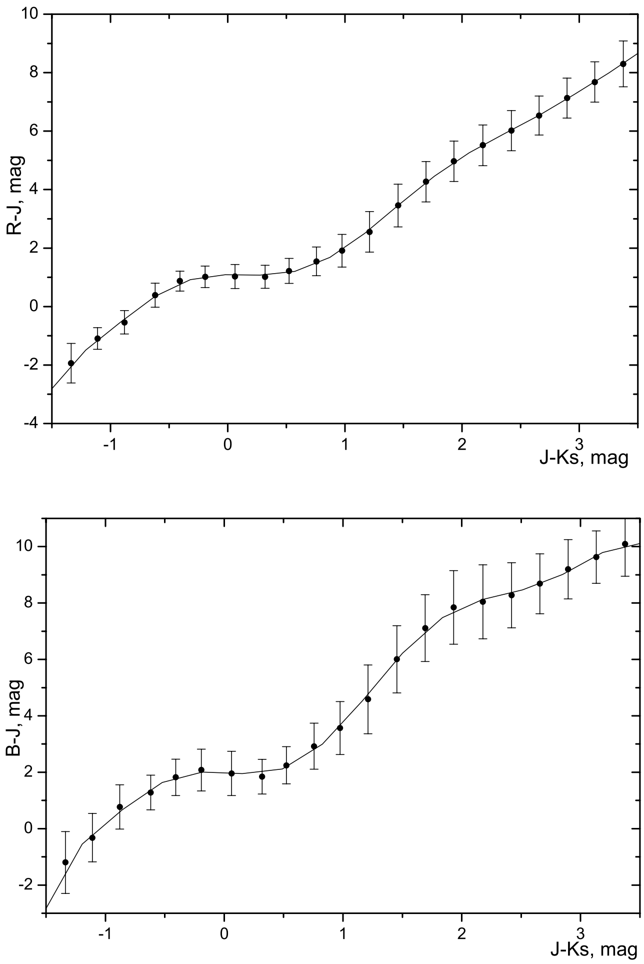

Figure 1. Fitting curves for the f_1 and f_2 functions for the calculation of *R* and *B* magnitudes and the distribution of the means and the standard deviations.

(iii) In the third case, the CI (*B*–*R*) > 0, but the CI (*J*–*H*) < 0, corresponding to the intensity maximum situated between the *B* and *H* magnitudes.

In accordance with the sign of the CI, we place either the USNO-A2.0 or the 2MASS star in the centre of the search window. This allows us not to consider those objects that may be contained in one catalogue only because of their intensity distribution in the spectrum (i.e. either in the optical or in the infrared catalogue). It should be noted that we are not aiming to improve the photometry of the USNO-A2.0 catalogue. Our goal is to be able to compare the original USNO-A2.0 magnitudes with the magnitude values calculated using the photometry of the 2MASS catalogue, in addition to identifying objects in the coordinate window. Finally, in the highly dense fields containing more than 500 000 objects, the cross-identification between the USNO-A.2.0 and 2MASS objects was carried out without using the proper motion of USNO-B1, but using the photometric cross-identification. This is because when performing the identification of objects in the field with the object number not exceeding 500 000, the rate of the identified USNO-B1 and 2MASS objects is more than 90 per cent, whereas in denser fields this rate dropped to 45–50 per cent.

After the cross-identification, the approximating functions $F(\alpha, \delta)$ (see Paper I) inside each field were derived using the coordinate differences of all the star pairs. In addition, the coordinate differences inside each field were approximated by rough linear relationships, which we have used for the cross-identification of galaxies.

The procedure of the cross-identification of galaxies is crucial for the absolute calibration. The reliable cross-identification of galaxies ensures a valid reduction of the observed proper motions of stars to a coordinate system that does not rotate in the space. However, among the extended sources from the Extended Source Catalogue (XSC), there are not only extragalactic objects but also objects in the Milky Way that have proper motions. Therefore, the procedures of the cross-identification for galaxies and for stars were performed separately. Obviously, after subtracting the approximating functions $F(\alpha, \delta)$ from the initial function $\Delta P(\alpha, \delta)$ (i.e. after reducing the coordinates of all the USNO-A2.0 objects to the 2MASS coordinate system), the revised coordinate differences of all stars, on average, are equal to zero. However, the revised coordinate differences of the galaxies, on average, have a value that approximately equals the average proper motion in this field, but with an opposite sign. To perform the correct identification of galaxies in a search window with a radius of about 0.8 arcsec, their revised coordinate differences were corrected using the linear relationship mentioned in the previous paragraph. Next, we identify the XSC and USNO-A2.0 objects in a circular window of 0.8-arcsec radius only, as at this step the position differences between the USNO-A2.0 and XSC galaxies are caused only by their position random errors. Theoretically, this will lead to eliminating the extended objects with non-zero proper motions from consideration.

Thus, the applied approach allows us to improve the cross-identification between the USNO-A.2.0 and 2MASS objects. Because of these procedures used for the cross-identification, the contamination rate of the spurious entries in the XPM-1.0 catalogue was decreased visibly, and the quality of linking to extragalactic objects was improved. Operations for linking to the extragalactic objects and deriving the absolute proper motions do not differ fundamentally from those described in our previous paper (Paper I).

3 QUASI-ABSOLUTE CALIBRATION

The procedure of the absolute calibration has been described in detail in our previous paper (Paper I). Here, we specify only the fields for which this procedure is not entirely correct. Because the galaxies are practically invisible in the zone of avoidance, particularly in the direction of the Galactic Centre, the absolute calibration has not been implemented in the fields that cover this zone or contain less than 25 galaxies. However, it is well known that this particular zone is of great interest for astrophysics and stellar astronomy. Moreover, XPM-1.0 contains the fields in which the distribution of galaxies is appreciably asymmetrical about the centre. If the number of galaxies in these fields was less than 100, the absolute calibration also was not performed. Therefore, we applied a procedure to these fields, which we call quasi-absolute calibration. The essence of this procedure is as follows. First, to fulfil the absolute calibration in every field with a sufficient number of galaxies, we determined the parameters of the reduction model $\phi(\alpha, \delta) = \Delta P_{\rm gal}(\alpha, \delta) - F(\alpha, \delta)$ (see Paper I) from the coordinate differences of the galaxies. Evidently, the function $\phi(\alpha, \delta)$ represents a distribution of the mean proper motion of stars in the field in question taken with an opposite sign. To derive quasi-absolute proper motions in the field where the absolute calibration is impossible, we obtained the parameters of

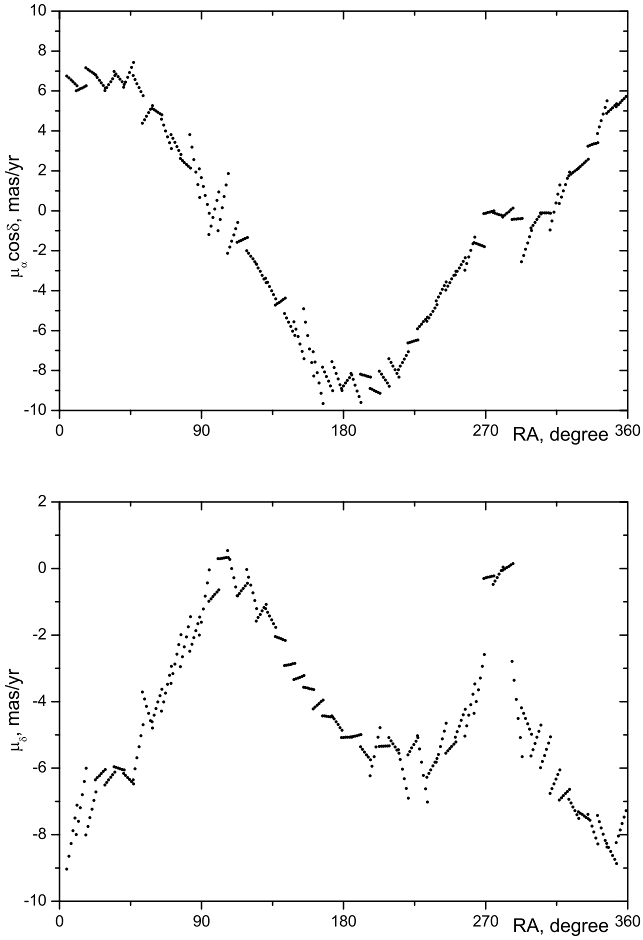

Figure 2. Mean proper motions as functions of the coordinates in fields having declinations approximately from $-7\overset{\circ}{.}5$ to $-2\overset{\circ}{.}5$ and located in the band of right ascensions from 0° to 360°. Each field is represented by six points of averaged proper motion.

the reduction model for this field by interpolation of the $\phi(\alpha, \delta)$ values from a surrounding area of the 2 × 2 field, having applied several iterations.

In this case, we assume that the motion of stars in the sky can be described by a continuously differentiable function. For example, in the one-dimensional case, the fields that contain no galaxies are seen in Fig. 2 near RA = 270°. The mean proper motion in these fields is significantly different from that of the neighbouring fields. Therefore, we obtained the mean proper motion for the fields that contain no galaxies by interpolation of the corresponding values from the neighbouring fields. The 67 fields (45 in the Southern hemisphere and 22 in the Northern hemisphere) in which the quasi-absolute calibration procedure had been carried out were marked by a special flag in the catalogue. This approach also allows us (see Fig. 2) to inspect visually the absolute calibration validity. The rest of the procedures for these fields, in principle, do not differ from those described previously. Unfortunately, it is not possible to test the method at this stage, so we are planning to do this in our future investigations. To approximately estimate the uncertainty of the quasi-absolute calibration, we used a value that does not exceed a half-difference of the mean proper motions from the neighbouring fields.

4 MAGNITUDE EQUATION

It is commonly understood that the term 'magnitude equation' refers to the unwanted correlation between the measured position of the star image and its magnitude. The main causes of this phenomenon are assumed to be optical misalignment, optical aberrations and the inevitable errors of the telescope guidance system. These lead to the asymmetry of the stellar profile and dissimilar to a point spread function. Combined with the non-linear response of the emulsion, these lead to the differing profiles of images of stars with different magnitudes. As a result, there is a systematic bias of the measured centres of stellar images depending on the apparent brightness. The magnitude equation in the proper motions of the XPM catalogue is a result of the difference of the magnitude equations present in the positions of the USNO-A2.0 and 2MASS catalogues. There is no information about the magnitude equation in the 2MASS catalogue. However, we hope that if it were available, the magnitude equation would be not very large, because the observations were made with CCD detectors. Concerning the magnitude equation of the 2MASS catalogue, it is reasonable to assume that it is caused by charge transfer efficiency (CTE) effects and can induce a systematic error of the position centroid CCD; however, we hope that this is not very significant.

The USNO-A2.0 catalogue had been compiled on the basis of three photographic surveys: the first Palomar Observatory Sky Survey (POSS-I), European Southern Observatory (ESO)/Science and Engineering Research Council (SERC) *J* and ESO/SERC *R*. As is well known, the POSS-I survey covers the whole northern sky and the part of the southern sky from 0° to −30° in declination. Our experience based on work with scanned images of the photographic plates of the POSS-I survey indicates that the magnitude equation present in the O and E plates in the range of Tycho-2 stellar magnitudes is negligible (Fedorov & Myznikov 2006).

In the Southern hemisphere, the surveys were made with two Schmidt telescopes. One of these was located in Australia ($\varphi = -31°27'$, $\lambda = 149°07'$). With this telescope 606 blue plates in the declination range from −20° to −90° were taken during 1975–1987 with the blue filter GG 395 (3950–5400 Å). The corresponding plates with the filter RG 630 (6300–6900 Å) were taken during 1978–1990 with the Schmidt telescope of the La Silla Observatory in Chile ($\varphi = -29°15'$, $\lambda = 70°44'$).

Thus, it is clear that the magnitude equation present in each of these surveys originates from causes that are intrinsic to a specific survey only, and ideally it should be studied separately. However, there is no such possibility, because the USNO-A2.0 catalogue contains the averaged coordinate values assigned to the mean epoch of the blue and red plates. For the Northern hemisphere and for part of the Southern hemisphere (up to $-17\overset{\circ}{.}5$ in declination), the observations were made with the red and blue filters during one night with the same telescope, and the mean epochs of the red and blue plates are essentially identical. For the Southern hemisphere, the observations were made under different conditions, with different telescopes and with different filters. Obviously, the magnitude equations present in these two parts of the catalogue should be different. Therefore, the magnitude equation should be examined in each specific field in order to most reliably eliminate it.

4.1 Influence of the magnitude equation on the absolute calibration

For an arbitrary field of the XPM-1.0 catalogue, the proper motion of any star, depending on the coordinates, may be represented by the expression:

$$\mu(\alpha,\,\delta)_i = \mu_{\rm true}(\alpha,\,\delta)_i + \varphi(\alpha,\,\delta)_i + f[m_i(\alpha,\,\delta)].$$

Here, $\mu_{\rm true}(\alpha,\,\delta)_i$ is the true proper motion of any arbitrary star, $\varphi(\alpha,\,\delta)_i$ is the coordinate systematic error caused by systematic coordinate errors in both catalogues, being inherent to all objects in the field given, and $f[m_i(\alpha,\,\delta)]$ is the systematic photometric error caused because of different displacements of the photometric centres of stars with various stellar magnitudes (i.e. the magnitude equation). The bright stars are shifted from the true centre more than the faint stars. As a result, a fictitious proper motion arises with a greater value for the bright stars than for the faint stars. When the coordinate dependence of the proper motions of the field stars is approximated by a linear relationship, we obtain the coordinate dependence of the mean true proper motion of stars distorted by the mean coordinate error and the mean photometric error:

$$\langle\mu^{\rm S}(\alpha,\,\delta)\rangle = \langle\mu^{\rm S}_{\rm true}(\alpha,\,\delta)\rangle + \langle\varphi^{\rm S}(\alpha,\,\delta)\rangle + \langle f[m^{\rm S}(\alpha,\,\delta)]\rangle.$$

The absolute calibration of the proper motions of stars involves the use of the formal mean proper motions of galaxies:

$$\langle\mu^{\rm G}(\alpha,\,\delta)\rangle = \langle\varphi^{\rm G}(\alpha,\,\delta)\rangle + \langle f[m^{\rm G}(\alpha,\,\delta)]\rangle.$$

Because the true proper motions of galaxies are equal to zero and the coordinate mean errors $\langle\varphi^{\rm S}(\alpha,\,\delta)\rangle$ end $\langle\varphi^{\rm G}\,(\alpha,\,\delta)\rangle$ differ only randomly as a result of a random sampling, the procedure for the absolute calibration is the following:

$$\langle\mu^{\rm ABS}(\alpha,\,\delta)\rangle = \langle\mu^{\rm S}(\alpha,\,\delta)\rangle - \langle\mu^{\rm G}(\alpha,\,\delta)\rangle;$$

$$\langle\mu^{\rm ABS}(\alpha,\,\delta)\rangle = \langle\mu^{\rm S}_{\rm true}(\alpha,\,\delta)\rangle + \langle f[m^{\rm S}(\alpha,\,\delta) - \langle f[m^{\rm G}(\alpha,\,\delta)]\rangle.$$

Many stars with different proper motions and different magnitudes are contained in each range of coordinates (right ascensions and declinations). However, the faint stars make the largest contribution to the value of

$$\langle f[m^{\rm S}(\alpha,\,\delta)]\rangle = \frac{1}{N}\sum f[m^{\rm S}_i(\alpha,\,\delta)],$$

as these are the most numerous in each subrange. In other words, we may say that the average value of the magnitude equation in the field will be approximately equal to the magnitude equation value for the mean stellar magnitude of this field. This means that the contribution of the average magnitude equation to the coordinate dependence of the average proper motion is practically zero. Similarly, the faint galaxies, for which the magnitude equation is practically also equal to zero, make the main contribution to the value of

$$\langle f[m^{\rm G}(\alpha,\,\delta)]\rangle = \frac{1}{N}\sum f[m^{\rm G}_i(\alpha,\,\delta)].$$

Thus, we can conclude that the magnitude equation almost does not influence the process of absolute calibration, and remains unchanged in the absolute proper motions of the XPM-1.0 catalogue.

4.2 Magnitude equation in the faint part

To study the magnitude equation in the faint range of stellar magnitudes, we have used quasars. The profiles of their images are very close to the stellar profiles, which usually constitute the basis for a correction of the magnitude equation. Because the proper motions of quasars are equal to zero, it should be reasonable to interpret any magnitude dependence of their formal proper motions as the magnitude equation. As quasars were not used for the absolute calibration by the derivation of proper motions of the XPM-1.0 catalogue, their absolute proper motions were derived exactly in the same way as for stars. Therefore, their own formal proper motion may well be used to verify the existence of the magnitude equation in the faint end of the range of stellar magnitudes. Unfortunately, at present the most complete catalogue of quasar positions, the Sloan Digital Sky Survey Data Release 5 (DR5; Schneider et al. 2007), covers only a part of the celestial sphere. Therefore, it is not possible to investigate the magnitude equation throughout the XPM-1.0 catalogue. Approximately 12 000 quasars from the DR5 were found in the XPM-1.0 catalogue.

The formal proper motions of quasars as functions of the stellar magnitude are shown in Fig. 3. It is obvious that there is no dependence, and the mean values of the formal proper motions are 0.12 and −0.24 mas yr^{-1} of μ_α cos δ and μ_δ, respectively. The standard deviations of μ_α cos δ and μ_δ are estimated to be approximately 3.8–7.4 mas yr^{-1}. Thus, we may conclude that in the right ascension and declination areas of the XPM-1.0 catalogue, intersecting with the DR5, the magnitude equation is absent in the ranges from about 15–20 stellar magnitudes. Fig. 4 shows the formal proper motions of galaxies (taken as the residual discrepancies in the coordinates of galaxies divided through the epoch differences) versus the stellar magnitudes considered in the same overlapping zones. As seen from the figures, there is no distinction between these relationships,

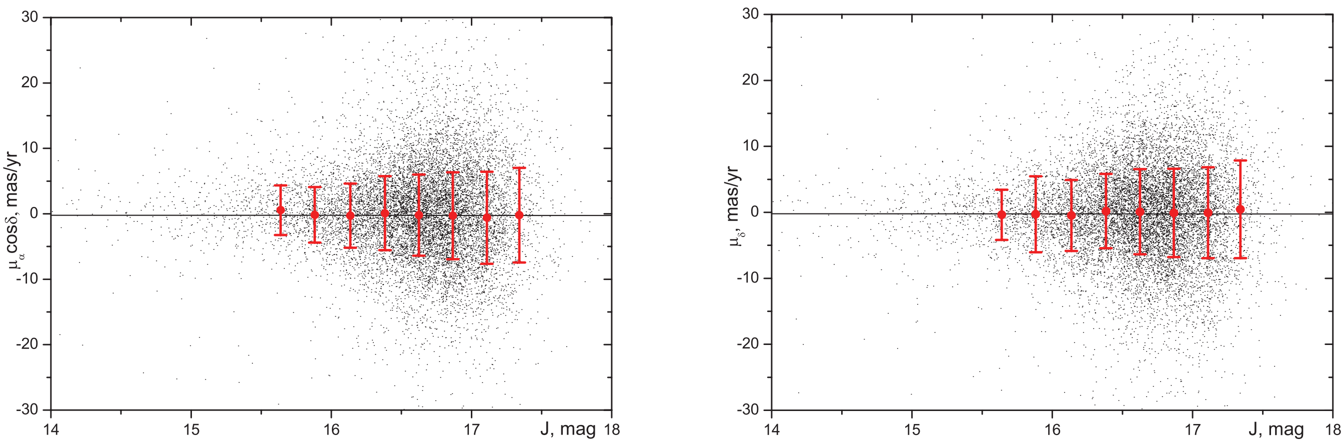

Figure 3. Scatter of individual formal proper motions μ_α cos δ (left) and μ_δ (right) DR5 quasars as a function of magnitude J. The red solid circles and lines show the mean values and standard deviations.

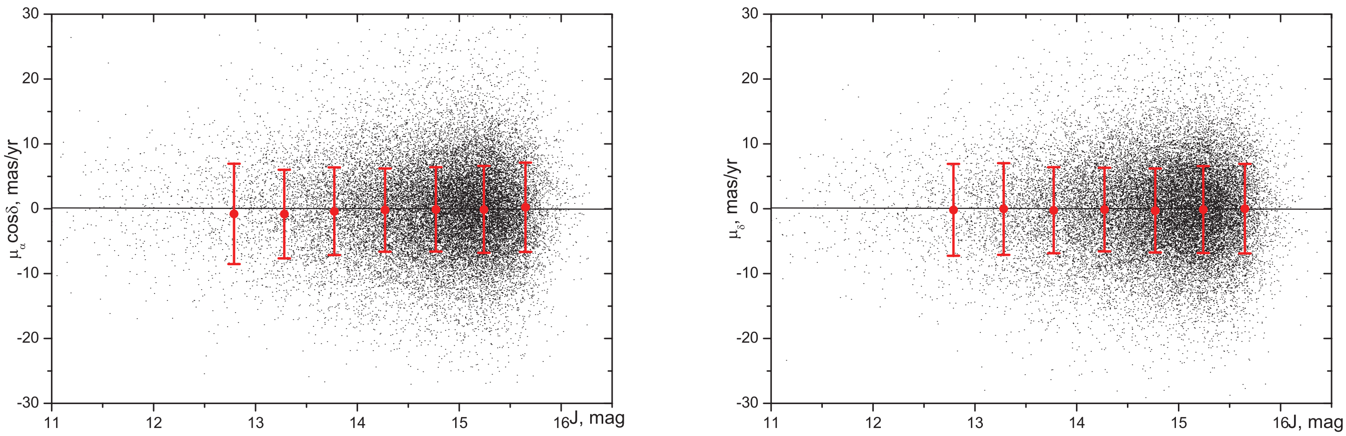

Figure 4. Scatter of individual formal proper motions $\mu_\alpha \cos\ \delta$ (left) and μ_δ (right) galaxies as a function of magnitude J. The red solid circles and lines show the mean values and standard deviations.

so that we can use the galaxies in each USNO-A2.0 field for the elimination of the magnitude equation in the faint end of the range of stellar magnitudes.

4.3 Analysis of the magnitude equation in the bright star range of the XPM-1.0 catalogue

To study the magnitude equation in the bright end of the range of stellar magnitudes, we used the Tycho-2 and UCAC-2.0 catalogues (Høg et al. 2000; Zacharias et al. 2004). We assume that there are no magnitude equations in the Tycho-2 and UCAC-2.0 catalogues. In theory, the difference between the proper motions of stars from these catalogues and of those from the XPM-1.0 catalogue can be represented as

$$\mu^{\mathrm{ABS}}(\alpha, \delta, m) - \mu^{\mathrm{kat}}(\alpha, \delta) = \mu^{\mathrm{ABS}}_{\mathrm{true}}(\alpha, \delta) - \mu^{\mathrm{kat}}_{\mathrm{true}}(\alpha, \delta) + \Delta\mu(m) + \Delta\mu_0(\alpha_{\mathrm{field}}, \delta_{\mathrm{field}}). \quad (1)$$

Here, $\Delta\mu(m)$ depends on the magnitude, but does not depend on the coordinates, and $\Delta\mu_0(\alpha_{\mathrm{field}}, \delta_{\mathrm{field}})$ does not depend on the magnitude but depends only on the coordinates of a particular field and presumably is caused by the differences of proper motion systems of both the XPM and Tycho-2 catalogues. If we construct the dependence of the proper motion differences versus the magnitude in every field

$$\mu^{\mathrm{ABS}}(\alpha, \delta, m) - \mu^{\mathrm{kat}}(\alpha, \delta) = \Delta\mu(m) + \Delta\mu_0(\alpha_{\mathrm{field}}, \delta_{\mathrm{field}}),$$

we can determine the form of the dependence in the range of the Tycho-2 and UCAC-2.0 stellar magnitudes only. As can be seen, by using the proper motions of the Tycho-2 and UCAC-2.0 stars, the magnitude equation in the XPM-1.0 catalogue may be determined up to a constant only. Thus, the elimination of the magnitude equation using the Tycho-2 proper motions means that the system of the proper motions of the XPM-1.0 catalogue ceases to be an independent realization in the bright part, being linked to the system of proper motions of Hipparcos (Perryman et al. 1997; Kovalevsky et al. 1997) via of Tycho-2 catalogue stars. Therefore, we have left the magnitude equation in the bright part of the XPM-1.0 catalogue for a while unchanged.

5 COMPARISON OF XPM-1.0 WITH OTHER CATALOGUES OF PROPER MOTIONS

After considering the magnitude equation of the XPM-1.0 catalogue, we have compared it with other catalogues with the aim of finding out whether the absolute proper motions of stars are consistent with the relative proper motions of stars obtained in the Hipparcos/Tycho-2 system. Today, there are several catalogues of the proper motions of stars, but by no means all of these can be used for this comparison. Some of these catalogues contain the absolute proper motions and cover the Northern or Southern hemisphere only, such as NPM1 (Klemola et al. 1987) and SPM2 (Platais et al. 1998). Although other catalogues cover partially or almost the entire celestial sphere, they contain, however, the relative proper motions of stars only (Girard et al. 2004; Hanson et al. 2004; Zacharias et al. 2004; Monet et al. 2003). *Prima facie*, the USNO-B1 and UCAC-2.0 and -3.0 catalogues are the most suitable for this purpose.

The USNO-B1.0 catalogue, covering the entire sky up to 21 mag, and containing positions, proper motions and other data, provides an astrometric accuracy of 0.2 arcsec at the epoch J2000. The proper motions given in the catalogue are relative. As noted earlier, despite the fact that the positions of about one billion stars are given in the catalogue, the proper motions are given for 285 million objects only. The proper motions for the remaining approximately 760 million stars in the catalogue are equal to zero. This fact greatly complicates the identification of stars in the catalogues and the direct comparison of their proper motions. In addition, the catalogue contains a great many (tens of millions) artefacts (Barron et al. 2008). These facts compelled us to abandon the use of the USNO-B1.0 catalogue for comparison with XPM-1.0.

UCAC-2.0 is a previous version of catalogue UCAC-3.0. The UCAC-3.0 catalogue is a dense astrometric catalogue of high precision, containing 100 766 420 stars, covering the entire sky. The errors of its positions are from 15 to 20 milliarcsec for the stars in the range from 10 to 14 R mag and about 70 milliarcsec for other stars up to 16 mag. The errors of proper motions of bright stars (up to 12 mag) are in the range of 1–3 milliarcsec per year. For the fainter stars (the positions of which were taken from the SPM), the typical errors are estimated to be approximately 2–3 milliarcsec yr^{-1}, and for the data taken from the early epoch of SuperCOSMOS, the typical error is 6–8 milliarcsec yr^{-1}. The positions and proper motions of stars are given in the ICRS for the epoch J2000.0. The comparison of the proper motions in star catalogues was carried out in the following two simple ways.

(i) The individual differences of proper motions of stars in the selected fields were calculated.

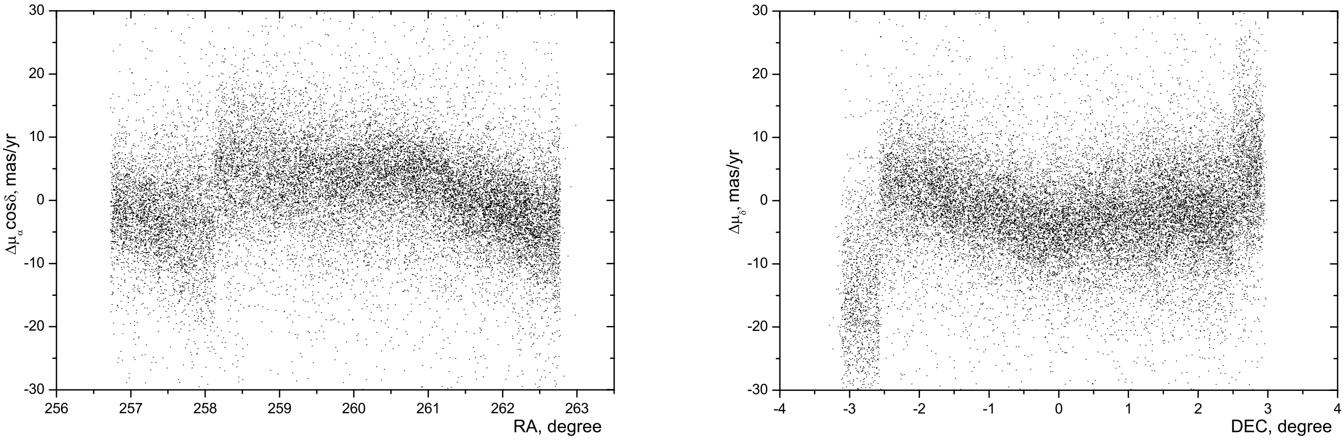

Figure 5. Individual differences of the proper motions of stars (XPM-1.0–UCAC-3.0) in the selected field as a function of RA and Dec.

(ii) The systematic differences of proper motions as well as their dispersions, depending on the magnitude, were computed.

To compare the proper motions of stars in the fields, we simply calculated the individual differences of the proper motions of stars from two catalogues, and then we studied the distribution of these differences on the field. These dependences for the individual differences of the proper motions (XPM-1.0–UCAC-3.0) are shown in Fig. 5. As seen Fig. 5, the individual differences of the proper motions of stars have an unnatural behaviour. In our opinion, the proper motions of stars should not display such an unnatural behaviour within the relatively small field of about 5×5 deg^2. A linear dependence or small quadratic non-linearity is expected, at least. Therefore, we believe that this behaviour is not real, and is most likely caused by the systematic positional errors of the catalogues. In order to confirm to which catalogue the majority of these errors belong, we constructed the dependences of the proper motions versus the coordinates for the UCAC-3.0 (Fig. 6) and XPM-1.0 (Fig. 7) catalogues separately.

As can be seen in Fig. 6, the UCAC-3.0 catalogue contains remarkable systematic errors. An analysis of the behaviour of the proper motions of UCAC-3.0 stars in various fields has shown that in certain areas of the sky, the stepwise discontinuity can reach a considerable value up to 20–30 mas yr^{-1}. Although the UCAC-3.0 catalogue has been declared accurate with very small errors on average across the sky, it appears that in most cases in fields of the sky with a size of 5×5 deg^2 (especially in the Northern hemisphere) an unnatural behaviour of proper motions is observed. This indicates, in our opinion, that the stepwise discontinuity behaviour of the proper motions in the catalogue have not been excluded. These errors in some fields may be very significant. This fact is important, because most modern observations with CCDs are performed in small-sized fields, where the reference stars can have unfortunate systematic errors.

To obtain the systematic differences of proper motions and their dispersions depending on the magnitude, the range of stellar magnitudes was divided into sub-bands with a width of 0.05 mag. Then, in each of these sub-bands the differences of proper motions, as well as their dispersions, were calculated. The dependences of the systematic differences of proper motions between the UCAC-2.0, UCAC-3.0 and XPM-1.0 catalogues are shown in Figs 8 and 9 for the Northern and Southern hemispheres, respectively. Undoubtedly, the systematic differences of proper motion (UCAC-2.0–UCAC-3.0) for the Northern and Southern hemispheres are the most intriguing feature. The appearance of the systematic differences between the proper motions of the UCAC-2.0 and UCAC-3.0 catalogues could be a result of using early epoch SPM data (-90° to -10° Dec.) and the Schmidt plates data from the SuperCOSMOS project. As can be seen in the figures, the standard deviation for the Northern hemisphere is approximately 8 mas yr^{-1} compared with UCAC-2.0 and 14 mas yr^{-1} compared with UCAC-3.0 in the range 14–16 mag. Here, we suppose that no magnitude equation exists in the XPM-1.0

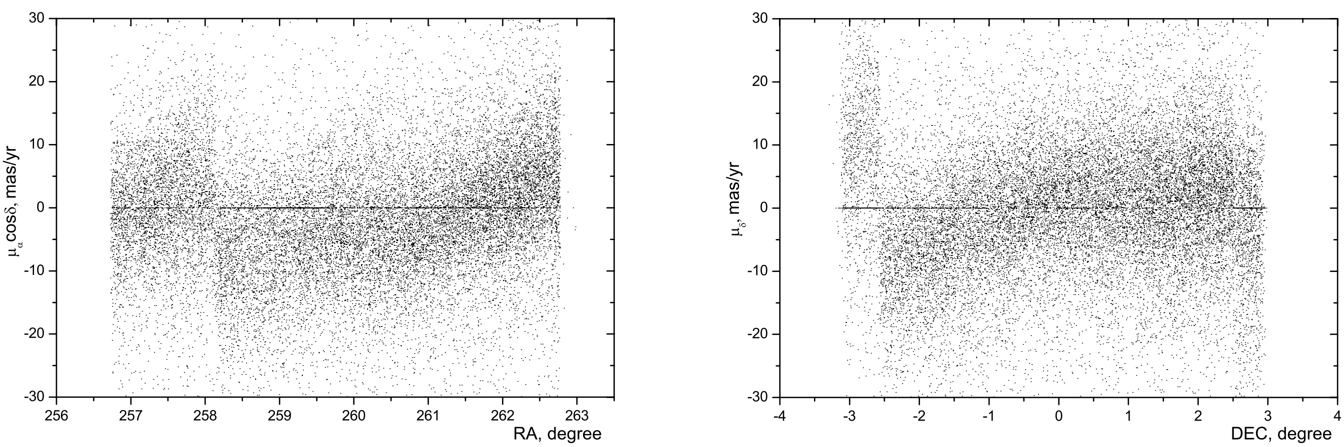

Figure 6. Proper motions of UCAC-3.0 stars in the selected field as a function of RA and Dec.

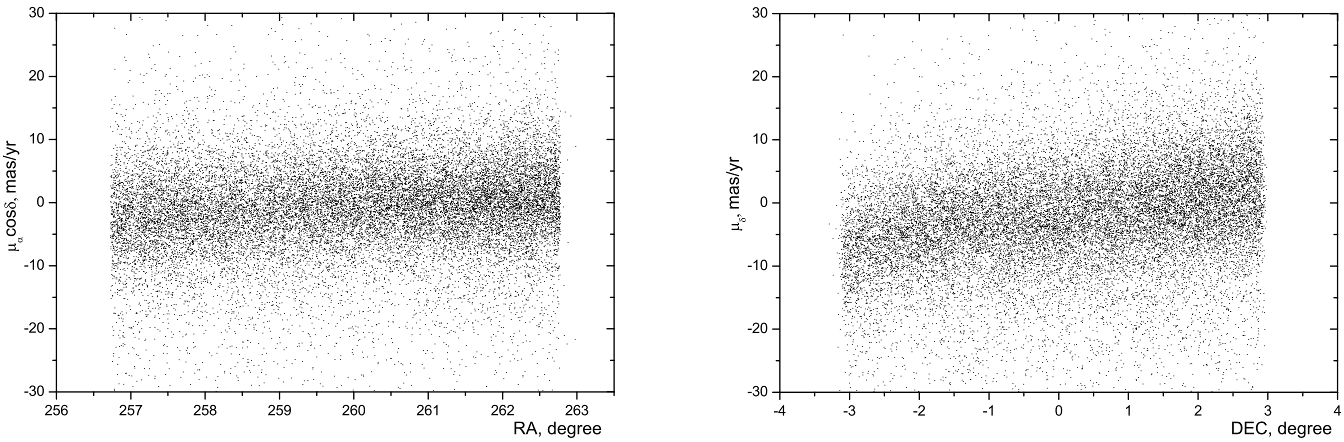

Figure 7. Proper motions of XPM-1.0 stars in the selected field as a function of RA and Dec.

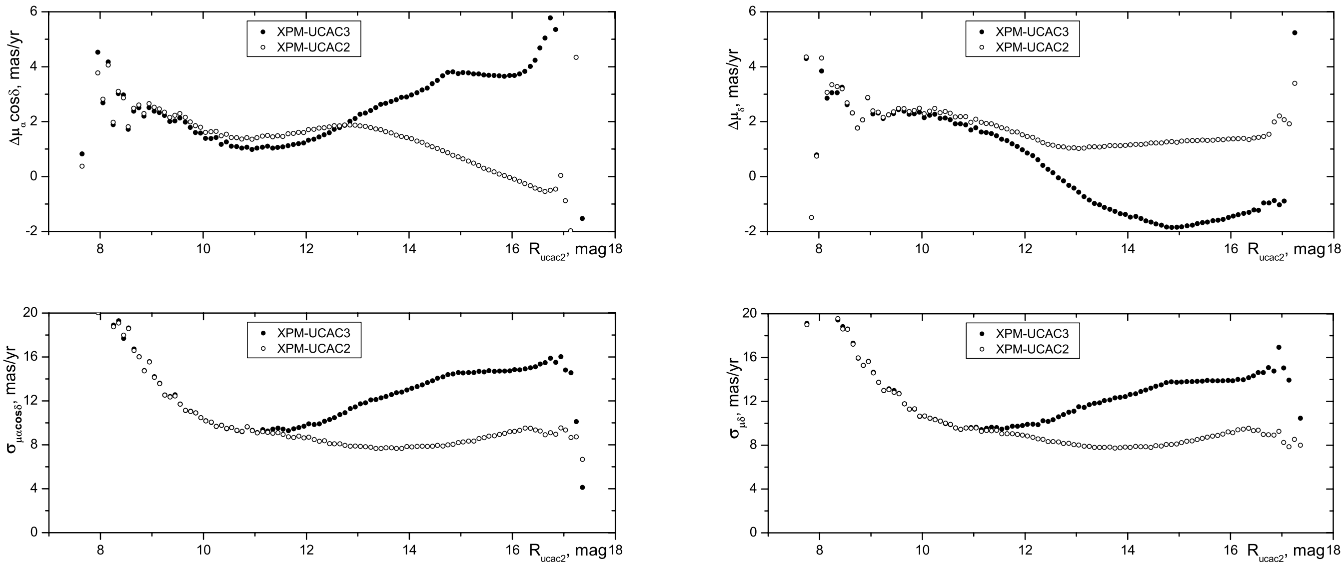

Figure 8. Systematic differences of the proper motions and their standard deviations (XPM-1.0–UCAC-3.0, XPM-1.0–UCAC-2.0) in the Northern hemisphere as a function of magnitude $R_{\mathrm{UCAC-2.0}}$.

catalogue. For the Southern hemisphere, the standard deviation is approximately 16–18 mas yr^{-1} compared with UCAC-2.0 and 15–16 mas yr^{-1} compared with UCAC-3.0. Unfortunately, the use of internal errors of proper motions in both catalogues yields a result that is not consistent with the values of the standard deviations of proper motions presented in Fig. 9. Even if we use the maximum values of the internal errors of proper motions, as stated in the catalogues (8 mas yr^{-1} for UCAC-3.0 and 10 mas yr^{-1} for XPM-1.0), the result does not exceed 13 mas yr^{-1}. Thus, a comparison between the XPM-1.0 and UCAC-2.0, UCAC-3.0 catalogues, with the aim of determining the external errors of the proper motions in the catalogues separately, shows that the internal errors in one or all of them are defined incorrectly.

In order to estimate the external errors of the proper motions of the XPM-1.0 catalogue, we intend to use the statistical method of error calculation, proposed by Wielen (1995). This method is based on the comparison of a sufficient number of independent proper motions and positions. However, because the Schmidt plates data from the SuperCOSMOS project were used to derive the UCAC-3.0 proper motions, this was not feasible.

The discovered systematic difference in proper motions could be caused by the rotation of the UCAC-2.0 and UCAC-3.0 systems and the XPM-1.0 system each relative to other. However, as a final conclusion, the XPM-1.0 catalogue should be carefully studied and the magnitude and colour equations should certainly be excluded in the whole range of stellar magnitudes.

6 PROPERTIES OF XPM-1.0

This version of the XPM catalogue contains the original absolute proper motions of about 280 million stars. Most of these absolute proper motions have been determined for the first time. As we have noted earlier, the accuracy of the absolute calibration for the Northern and Southern hemispheres is not equal. This is caused not only by the lesser mean difference of the epochs for the Southern hemisphere, but also by the different amount of galaxies contained in these hemispheres. The XSC contains about one million galaxies for the Northern hemisphere, whereas about 0.5 million galaxies are included for the Southern hemisphere. This proportion is retained for the XPM-1.0 catalogue. The XPM-1.0 positions were

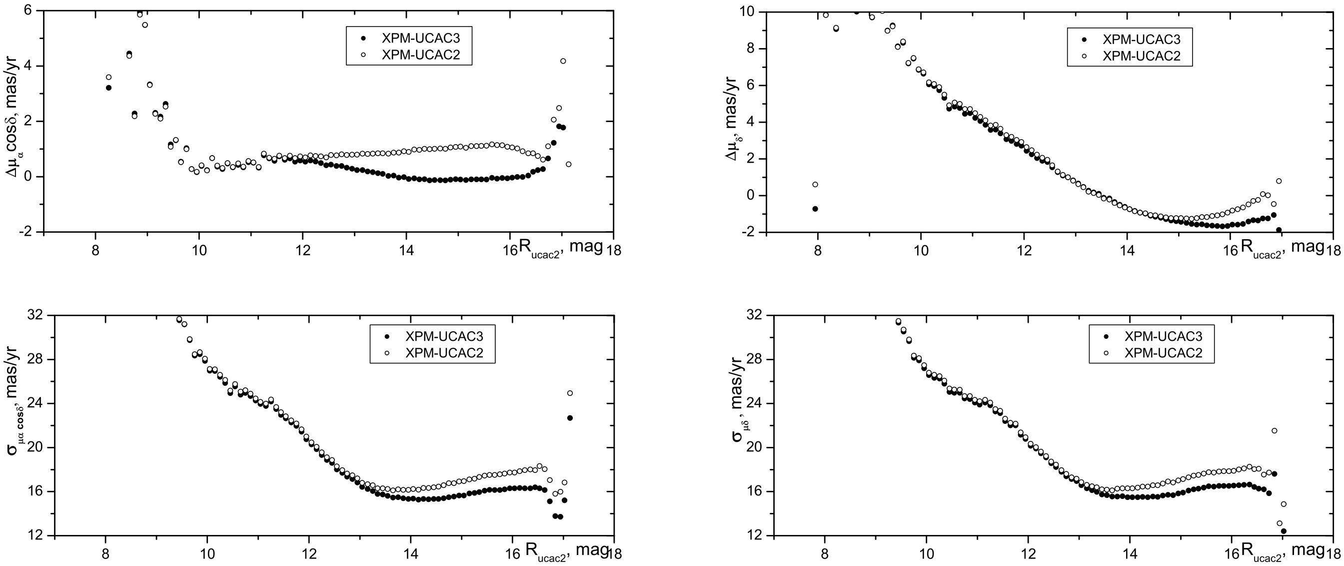

Figure 9. Systematic differences of the proper motions and their standard deviations (XPM-1.0–UCAC-3.0, XPM-1.0–UCAC-2.0) in the Southern hemisphere as a function of magnitude $R_{\mathrm{UCAC-2.0}}$.

calculated for the mean epoch of a real object as the average value of the source 2MASS position and its USNO-A2.0 position was reduced to the 2MASS system after applying the median filter. As the 2MASS positions are linked to the ICRS system, the XPM-1.0 catalogue contains the formal ICRS positions of all objects reduced to the epoch J2000 by using the proper motions. Moreover, it should be noted that for those objects that occur twice in the overlapping USNO-A2.0 fields, their positions and proper motions were obtained by a simple averaging of the positions and proper motions in the intersection. We did not classify using the discernibility criterion for stellar or non-stellar objects, as done, for example, in the GSC2.3 catalogue (Lasker et al. 2008). The flag indicating that the extended source was put into the catalogue was introduced only for XSC objects. It seems to us that the number of stars with absolute proper motions contained in the XPM-1.0 catalogue is reasonable and practically coincides with the number of stellar objects (210 million) in the GSC2.3 catalogue, which includes data for about one billion objects contained in the Schmidt plates. The XPM-1.0 catalogue covers the entire sky in the range of stellar magnitudes $10 < B < 22$ mag. Unlike the previous version, it does not have any gaps in the zone of the galactic equator. For each XPM-1.0 object, the J, H, K, B and R magnitudes and their errors are taken from the corresponding catalogues containing these quantities.

7 CONCLUSIONS

The main goal of this work is to provide an independent realization of the quasi-inertial reference frame based on the catalogue of absolute proper motions of 280 million stars, which can be used for many astronomical studies. As is well known, the zone of avoidance is of great interest for astrophysics and stellar astronomy. Therefore, for fields from this zone of avoidance, or those that contain fewer than 25 galaxies, we applied a procedure that we have called quasi-absolute calibration. The parameters of the reduction model were obtained by interpolation of the values from neighbouring fields. At this point, we performed a more thorough identification of objects in the source catalogues. This allowed us to decrease the number of false stars and to improve the quality of the absolute calibration. Besides, we have made more detailed analyses of the obtained results in order to investigate the magnitude equation and to compare the proper motions with those contained in recent catalogues. We have found a systematic difference between the proper motions in the XPM-1.0, UCAC-2.0 and UCAC-3.0 catalogues, which reaches several mas yr^{-1}. The existence of the systematic differences between the UCAC-2.0 and UCAC-3.0 catalogues is most surprising. This prevents us from obtaining an objective estimate accuracy when comparing the catalogues. It is obvious that the internal estimates of the accuracy of proper motions in the compared catalogues are too low in one or all of the catalogues, and additional research is required. Because we will undertake further studies of the proper motions at the bright end of the range of stellar magnitudes of the XPM-1.0 catalogue in order to identify and eliminate the magnitude equation, we have purposefully left the magnitude equation unchanged in the bright part of the XPM-1.0 catalogue for a while. Analysis of the behaviour of the proper motions of UCAC-3.0 stars in various fields has shown that in certain areas of the sky there are stepped discontinuities, reaching 20–30 mas yr^{-1}. This should be taken into account, because most modern observations with CCDs are performed in small-sized fields, where the reference stars can have unfortunate systematic errors.

We have almost finished preparing the XPM catalogue for release, and we hope that the final version of the XPM catalogue will be available via CDS in Strasbourg in 2010. Currently, in order to access an intermediate version of XPM-1.0, you may e-mail P. N. Fedorov (pnf@astron.kharkov.ua) or V. S. Akhmetov (akhmetov@astron.kharkov.ua).

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