The Astronomical Journal, 139:2440–2447, 2010 June doi:10.1088/0004-6256/139/6/2440

THE PPMXL CATALOG OF POSITIONS AND PROPER MOTIONS ON THE ICRS. COMBINING USNO-B1.0 AND THE TWO MICRON ALL SKY SURVEY (2MASS)

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Received 2010 February 15; accepted 2010 April 5; published 2010 April 29

ABSTRACT

USNO-B1.0 and the Two Micron All Sky Survey (2MASS) are the most widely used all-sky surveys. However, 2MASS has no proper motions at all, and USNO-B1.0 published only relative, not absolute (i.e., on the International Celestial Reference Frame (ICRS), proper motions. We performed a new determination of mean positions and proper motions on the ICRS system by combining USNO-B1.0 and 2MASS astrometry. This catalog is called PPMXL (VO access to the catalog is possible via http://vo.uni-hd.de/ppmxl), and it aims to be completed from the brightest stars down to about $V \approx 20$ all sky. PPMXL contains about 900 million objects, some 410 million with 2MASS photometry, and is the largest collection of ICRS proper motions at present. As representative for the ICRS, we chose PPMX. The recently released UCAC3 could not be used because we found plate-dependent distortions in its proper motion system north of -20° declination. UCAC3 served as an intermediate system for $\delta \leqslant -20^\circ$. The resulting typical individual mean errors of the proper motions range from 4 mas yr^{-1} to more than 10 mas yr^{-1} depending on observational history. The mean errors of positions at epoch 2000.0 are 80–120 mas, if 2MASS astrometry could be used, 150–300 mas else. We also give correction tables to convert USNO-B1.0 observations of, e.g., minor planets to the ICRS system.

Key words: astrometry – catalogs – Galaxy: kinematics and dynamics – proper motions

Online-only material: color figures

1. INTRODUCTION

According to IAU Resolution B2 of the XXIIIrd General Assembly (1997), the *Hipparcos* catalog (ESA 1997) is the primary realization of the International Celestial Reference System (ICRS) at optical wavelengths. Its first and basic extension to higher star densities and fainter limiting magnitudes is *Tycho-2* (Høg et al. 2000), based on observations of the *Tycho* experiment on board the *ESA–Hipparcos* satellite. The early epoch observations of *Tycho-2* were taken from new reductions (Urban et al. 1998) of the observations made for the Astrographic Catalog and 143 other ground-based astrometric catalogs. *Tycho-2* contains about 2.5 million stars and is 90% complete down to $V = 11.5$. Röser et al. (2008) published the PPMX catalog of positions and proper motions of 18 million stars with limiting magnitude around 15 in a red band. The typical accuracy of the proper motions is about 2 mas yr^{-1} for 4.5 million stars with first epoch in the Astrographic Catalog and about 10 mas yr^{-1} for all other stars.

Very recently, the UCAC3 catalog (Zacharias et al. 2009, 2010) was released. UCAC3 is based on a new all-sky astrometric survey made in the years 1998–2004. The catalog contains some 100 million stars down to $r_U = 16$ mag.

The largest catalog in the optical regime is USNO-B1.0 (Monet et al. 2003) with more than one billion objects. However, USNO-B1.0 is not in the system of ICRS; it contains relative, not absolute, proper motions (see Monet et al. 2003). A comparison of USNO-B1.0 and PPMX performed in the present work yielded systematic differences (in areas of square degrees) of up to 15 mas yr^{-1} in proper motion and up to 0.6 arcsec in positions at epoch 2000.0.

The Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) is a complete sky survey in the J, H and K_s bands performed in the years 1997–2001. The Point Source Catalog of about 471 million entries is also a source of accurate astrometric positions, but contains no proper motions.

For kinematic studies in the Milky Way, a catalog of proper motions in the ICRS system and with a well-defined completeness limit is indispensable. PPMX fulfills this requirement, but with only 18 million stars it is rather small. USNO-B1.0 with inertial proper motions would be a big step forward. Since Sloan Digital Sky Survey (SDSS) observations became available, inertial proper motions have been constructed from a combination of SDSS with USNO-B1.0 using SDSS galaxies as reference (Munn et al. 2004, 2008; Gould & Kollmeier 2004). This is, of course, restricted to the SDSS part of the sky.

The fact that USNO-B1.0 is not on ICRS creates a problem for minor planet observers. Right ascensions and declinations based on USNO-B1.0, when combined with older epoch observations on ICRS, may cause biases in orbit determinations of minor planets. This is of great importance for fly-by maneuvers of interplanetary spacecraft (Chesley et al. 2009).

Combining USNO-B1.0 with 2MASS is such an obvious idea that it is already mentioned by Monet et al. (2003). In the following, we first give a schematic overview of the entire procedure (Section 2), then we describe in detail the initial steps to *coarsely* put USNO-B1.0 to the ICRS (Section 3). This is followed by a description the combination with 2MASS observations (Section 4), the details of the construction of the system of positions and proper motions on ICRS (Section 5), and we close with an overview of the properties of the catalog (Section 6). Our approach can be considered an affordable effort to put USNO-B1.0 onto ICRS and improve the individual proper motions with the inclusion of 2MASS. A sophisticated re-reduction of all the material might deliver superior results provided that a better reference catalog were available before Gaia.

2. OVERVIEW ON THE REDUCTION PROCEDURE

In this section, we give an executive summary of all the steps that lead to the construction of the catalog.

Step 1. Reconstruction of the individual observations that went into USNO-B1.0. Result: α, δ, and epoch.

Step 2. Identification of USNO-B1.0 stars in a given "field" (see the following section) with PPMX and determination of corrections $\Delta\alpha$, $\Delta\delta$ from the mean offset per field. Result: α, δ on the PPMX system on scales equal or larger than the field size.

Step 3. Cross-matching the USNO-B1.0 stars with 2MASS using a cone search with radius 2 arcsec. Result: α, δ, and epoch from 2MASS for the given USNO-B1.0 star.

Step 4. Attributing weights to each observation and weighted least-squares adjustment for each star. Result: new positions and proper motions of each star.

Step 5. The positions and proper motions of all stars with K_s-magnitudes between 12 and 13 from step 4 represent the preliminary system PS1. Cross-match the stars in PS1 with UCAC3. South of $-20°$ declination, add systematic differences UCAC3-PS1 in proper motions on a grid with 0.25×0.25 deg^2 bins with a 3×3 bin moving average filter. The proper motions of PS1 north of $-20°$ declination are left unchanged. This system is called PS2.

Step 6. Cross-matching the stars in PS2 with PPMX and adding systematic differences PPMX-PS2 in proper motions on a grid with 1×1 deg^2 bins with a 3×3 bin moving average filter. This is called PS3 and completes the proper motion system of PPMXL.

Step 7. Putting stars without 2MASS observations onto the system PS3. Make a least-squares adjustment (as in step 4) giving all 2MASS observations weight zero. Compare the proper motions of all stars in PS2 with the proper motions obtained in this step and add the systematic differences to a non-2MASS star on a grid with 0.25×0.25 deg^2 bins with a 3×3 bin moving average filter.

Step 8. Putting the system of position 2000.0 onto the ICRS. Cross-match the stars in PS2 with PPMX and determine the differences in position at epoch 2000.0. Add systematic differences PPMX-PS2 in positions on a grid with 1×1 deg^2 bins with a 3×3 bin moving average filter. Proceed analogously to step 7 for the positions of non-2MASS stars.

3. INITIAL STEPS

USNO-B1.0 is an impressive piece of work. The individual positions and proper motions are derived from up to five original observations. For each star, USNO-B1.0 not only publishes positions for the epoch 2000.0 and proper motions, but also gives additional information that enables us to re-construct *all* the original observations, i.e., offsets in the x-coordinate (negative right ascension) and the y-coordinate (declination) together with field and survey identifiers which allow us to recover the observational epoch. For the different surveys used for the construction of USNO-B1.0, see Monet et al. (2003). Altogether USNO-B1.0 is divided into 7435 fields, and Table 3 of Monet et al. (2003) gives the necessary information to reconstruct all the individual observations that went into USNO-B1.0. The epochs for the fields can be found mostly in http://www.nofs.navy.mil/data/fchpix/. Additional epoch information was provided by Dave Monet. Epochs and corrections for all fields contributing to PPMXL can now be found at http://vo.uni-hd.de/usnob/res/usnob/pc/form.

As astrometric reference USNO-B1.0 uses Lick Observatory Northern Proper Motion program (NPM) and Yale/San Juan Southern Proper Motion program (SPM), which has the advantage of giving a dense grid of reference stars on each field, but the disadvantage that the mean epoch of SPM and NPM is about 1975. Also, the mean motion between the Schmidt plates of USNO-B1.0 and the SPM and NPM was set to zero in the least-squares adjustment.

Given the situation above, the re-constructed individual right ascensions and declinations could not be combined immediately with 2MASS, because they are on different reference systems. To overcome this, we made the following assumption: as a dense reference catalog had been used in each field (roughly corresponding to a Schmidt plate), the offset of a field (at the field epoch) from ICRS can be described to zeroth order by $\Delta\alpha$, $\Delta\delta$, the mean deviations in right ascension and declination (at epoch) from a suitable reference catalog on ICRS. Since USNO-B1.0 gives all stars from *Tycho-2* with their *Tycho-2* entries, these cannot be used directly as a reference. Instead, we used the stars in PPMX fainter than the *Tycho-2* limits and cross-identified them with USNO-B1.0. Although the fainter part of PPMX is based partly on the same surveys this approach is justified because PPMX as a whole is already on ICRS whereas USNO-B1.0 is not.

It turned out that this simple but straightforward approach yielded remarkably good results north of $-20°$ declination, proving that the plate reductions using SPM and NPM were highly successful in these areas of the sky. This completes steps 1 and 2 from the previous section.

In step 3, USNO-B1.0 was cross-matched with 2MASS using a cone search with radius 2 arcsec. The cross-matches were performed with in a PostgreSQLA database using the q3c indexing scheme (Koposov & Bartunov 2006). Double identifications are allowed; consequences thereof are discussed in Section 6.1. After these steps, USNO-B1.0 observations could be combined with the 2MASS observations. The construction of the final system, however, has been deferred to after the least-squares adjustment of mean positions and proper motions.

4. LEAST-SQUARES ADJUSTMENT OF MEAN POSITIONS AND PROPER MOTIONS

Before entering a least-squares adjustment, individual weights $w_i = \sigma_{u.w.}^2/{\sigma_i}^2$ must be attributed to the observations of a star at epoch T_i (step 4). The a priori error of unit weight $\sigma_{u.w.}$ is arbitrarily set to 1 mas. The assignment of σ_i is always discussible. We attributed $\sigma_i = 230$ mas for each individual observation from USNO-B1.0. Munn et al. (2004) give $\sigma_i = 120$ mas for a USNO-B1.0 position. Monet et al. (2003), however, note that they found systematic offsets of up to 250 mas USNO-B1.0 positions when compared with the SDSS EDR. Our weight corresponding to $\sigma_i = 230$ mas is therefore a reasonable estimate. This weight has been chosen independent of the magnitude of the star. If we assume that the accuracy of individual observations in each survey in USNO-B1.0 deteriorates proportionally, then the resulting proper motion itself is not affected; however, the covariance matrix is. A deeper investigation of magnitude-dependent effects on individual accuracies in USNO-B1.0 was beyond this work.

The astrometric accuracy of 2MASS is 80 mas (1σ) relative to the *Hipparcos* reference frame for $K_s < 14$, and increases to 250 mas at $K_s = 16$ (Skrutskie et al. 2006). We used these values for the σ_i of a 2MASS observation.

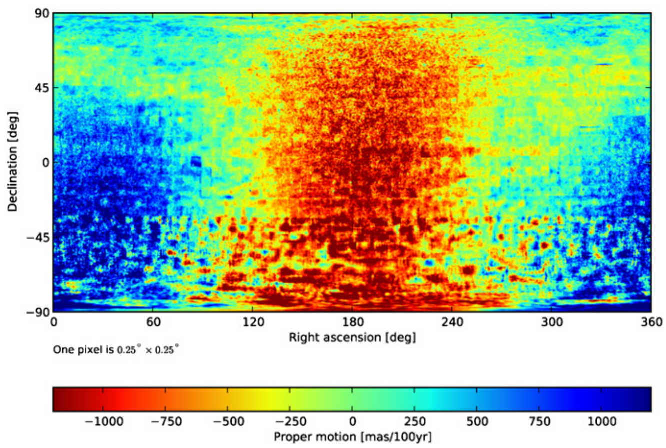

Figure 1. Proper motions in right ascension $\mu_\alpha \cos\delta$ of the preliminary system PS1 plotted over right ascension and declination. The plate structure of the underlying survey is clearly visible south of $\delta = -20°$. Unless otherwise stated, all the plots of this kind as a function of right ascension and declination refer to a grid with 0.°25 × 0.°25 bins, and the quantities plotted are the averages from a 3 × 3 bin moving average filter.

(A color version of this figure is available in the online journal.)

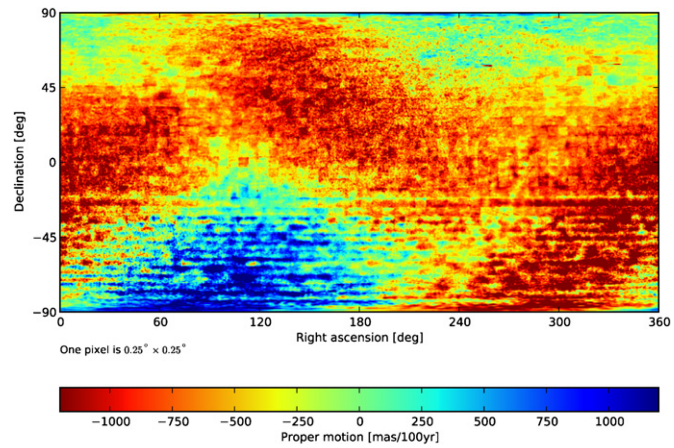

Figure 2. Same as Figure 1 but for the proper motions in declination μ_δ. Again the system is distorted south of $\delta = -20°$.

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The number of observations per star for the least-squares adjustment varies from two (one early and one late epoch) to six (up to five epochs from the USNO-B1.0 and one from 2MASS) Given the notations above, we determine the resulting covariance matrix of the unknowns as

$$w = \sum_{i=1,n} w_i, \qquad w\overline{T} = \sum_{i=1,n} w_i T_i,$$
$$w_{p.m.} = \sum_{i=1,n} w_i (T_i - \overline{T})^2, \tag{1}$$

where $\overline{T}$ is the mean epoch, w is the weight of the mean position, and $w_{p.m.}$ is the weight of the resulting proper motion. Because of the few degrees of freedom ($\leqslant 6$ observations for two unknowns) in each least-squares adjustment we did not determine an a posteriori error of unit weight for individual stars. Hence, $\sigma_p = w^{-1/2}$ and $\sigma_{p.m.} = w_{p.m.}^{-1/2}$ are the mean errors of position and proper motion per coordinate, respectively.

The mean positions $\overline{x}$ and proper motions μ for each object are computed as

$$\overline{x} = \frac{\sum_{i=1,n} w_i x_i}{\sum_{i=1,n} w_i}, \qquad \mu = \frac{\sum_{i=1,n} w_i x_i (T_i - \overline{T})}{\sum_{i=1,n} w_i (T_i - \overline{T})^2}. \tag{2}$$

Automatic tests for unduly large scatter among the measurements (based on the χ^2 sum) and automatic elimination of outliers (based on appropriately normalized individual residuals) were implemented. All stars having χ^2 sums beyond a certain significance limit, but still not showing obvious outliers, were marked as "problem cases" and got a "P" flag in the catalog.

5. THE SYSTEM OF POSITIONS AND PROPER MOTIONS

With the coarse systematic corrections described in Section 3 and the least-squares solution, a *preliminary catalog* of positions and proper motions was constructed with only the final systematic corrections missing.

5.1. The Proper Motion System

To link a proper motion system of a sky survey (catalog) to the ICRS, two distinct approaches are possible. Either the "proper motions" of extragalactic objects are forced to vanish (this is the method adopted by Munn et al. 2004 or Gould & Kollmeier 2004 in their reduction of SDSS proper motions) or the optical representation of the ICRS, the *Hipparcos* catalog, is extended to fainter magnitudes. We chose the second alternative, as we did not try to identify point-source-like extragalactic objects in USNO-B1.0. Also, at low galactic latitudes this method can hardly work.

The *Hipparcos* catalog itself is, of course, unsuited for the link because of its low spatial density and its bright stars. The next obvious choice, *Tycho-2*, is unsuitable as well for reasons laid out in Section 3. This leaves the fainter part of the PPMX for the construction of the link between the USNO-B1.0 proper motions and the ICRS.

Before we come to this comparison, let us note that the proper motion system can be checked, to a certain degree, independent of a comparison with a reference catalog. The proper motions in an inertial reference system must, except for their peculiar motions, on average only reflect the physical motions of the stars in our Galaxy, i.e., the reflex of solar motion and the rotation of the Galaxy. Systematics parallel to the axes of right ascension or declination must not appear, nor should features be seen representing the plate lay-out of a photographic survey. In step 5, the stars in the preliminary catalog with 2MASS K_s-magnitudes between 12 and 13 have been chosen to represent the preliminary system (PS1). Doing so, we get a fair overlap with the faint stars in PPMX. The magnitudes in the visual range from USNO-B1.0 are not suited, because the magnitude system is very inhomogeneous from plate to plate.

Figures 1 and 2 show the proper motions of the PS1 in the right ascension, declination plane in bins of 0.°25 × 0.°25 averaged via a 3 × 3 bin moving average filter. Surprisingly, the proper motion system is remarkably smooth north of −20° declination. Only minor plate-dependent effects can be seen. This is a hint that the authors of USNO-B1.0 achieved very satisfactory results in their plate reductions in this portion of the sky. However, south of −20° declination, plate-dependent distortions of the proper motion system are obvious and need to be corrected for.

In 2009 August, UCAC3 was released. UCAC3 contains some 100 million stars and therefore goes deeper than PPMX, and, in principle, could be used for the correction of PS1. To characterize the UCAC3 system (U3S) of proper motions, we chose stars with $14 < m_{r_U} < 15$ from UCAC3. This is well

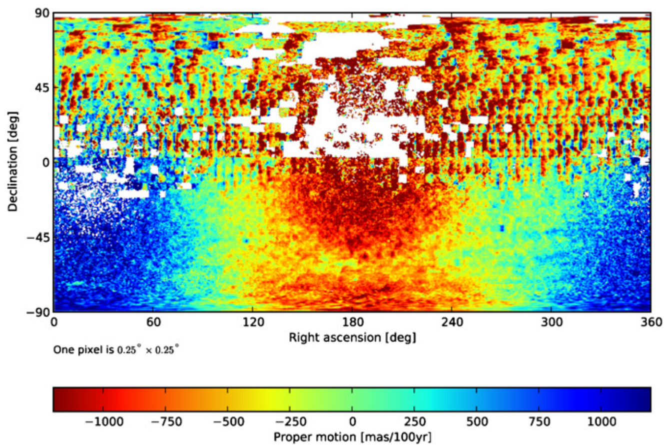

Figure 3. Proper motions in right ascension $\mu_\alpha \cos\delta$ of UCAC3 in the magnitude range r_U 14–15 plotted over right ascension and declination. Empty areas stand for regions where no proper motions in this magnitude range are available in UCAC3. The proper motions of UCAC3 north of $\delta = -20°$ show strong plate dependent systematic distortions and cannot be used for Galactic kinematics. However, the system south of $\delta = -20°$ is very well defined.

(A color version of this figure is available in the online journal.)

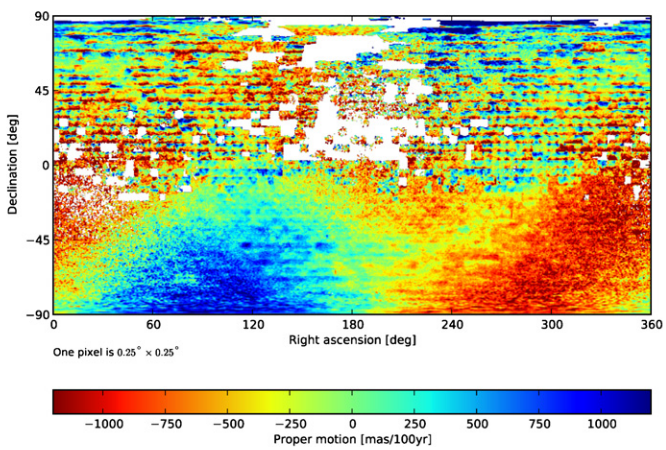

Figure 4. Same as Figure 3 but for the proper motions in declination μ_δ. Again UCAC3 proper motions should not be used north of $\delta = -20°$.

(A color version of this figure is available in the online journal.)

away from both the bright *Tycho-2* stars and the magnitude limit of UCAC3.

Figures 3 and 4 show the proper motions of the U3S in bins of 0.°25 × 0.°25 averaged via a 3 × 3 bin moving average filter. White pixels show areas where UCAC3 ($14 < r_U < 15$) contains only stars without proper motions. These areas presumably largely coincide with those without first epochs in the UCAC3 project. We interpreted proper motion zero and negative errors on it (found for about 9 million stars) as signifying null values in the corresponding columns of UCAC3.

While the proper motion system is well determined south of −20° declination, it clearly shows unphysical effects in both coordinates north of −20°, where pattern-dependent proper motions occur with amplitudes exceeding ±12 mas yr^{-1}. According to N. Zacharias (2009, private communication) the source of the systematic effects comes from the Schmidt plates used for the first-epoch positions, whereas in the south ($\delta < -20°$) the plates from the SPM could be used. These systematic errors in UCAC3 north of $\delta = -20°$ are so large that UCAC3 cannot be considered to be on the ICRS system, and the reader is advised to take care when using it for kinematic investigations of our galaxy.

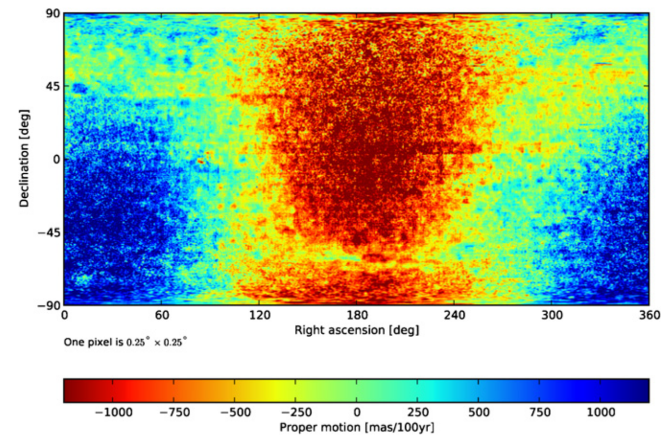

Figure 5. Proper motions in right ascension $\mu_\alpha \cos\delta$ of the system of PPMXL represented by stars with 2MASS K_s-magnitudes between 12 and 13.

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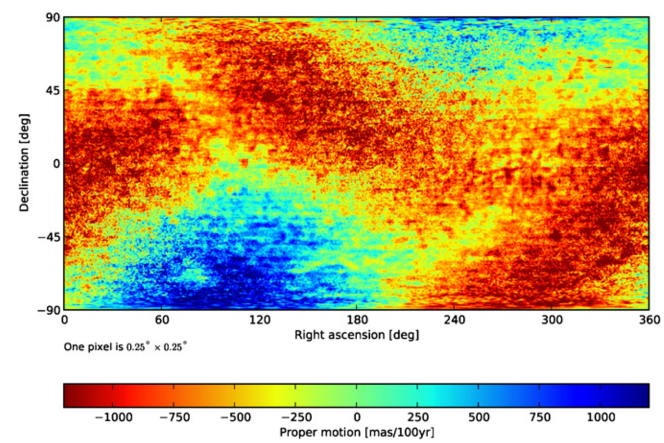

Figure 6. Proper motions in declination μ_δ of the system of PPMXL represented by stars with 2MASS K_s-magnitudes between 12 and 13.

(A color version of this figure is available in the online journal.)

To summarize the situation, it happens that we have proper motion systems north and south of $\delta = -20°$ which do not show conspicuous plate-dependent structure. This enabled us to construct an intermediate system as a combination of both, i.e., the proper motions of the PS1 are left unchanged north of $\delta = -20°$, and differences U3S − PS1 are applied south of $\delta = -20°$ on a grid with 0.25 × 0.25 deg^2 bins with a 3 × 3 bin moving average filter. The resulting system is called PS2. This completes step 5.

The absence of plate-dependent distortions alone does not place a proper motion system onto the ICRS; the link to the *Hipparcos* system is mandatory. In step 6, we chose PPMX as representative for *Hipparcos*, and we added systematic differences PPMX-PS2 to PS2 on a grid with 1 × 1 deg^2 bins with a 3 × 3 bin moving average filter. This lay-out was chosen to have enough PPMX stars for the link. Their number varies between 1000 and 5000, with a few areas containing only 500 stars per bin. This link completes the proper motion system of PPMXL. The resulting system PS3 is shown in Figures 5 and 6. The link to PPMX introduced a negative systematic in Figure 5 compared to Figure 1 at +40° declination. This depression is already inherent in *Tycho-2* as shown by Röser et al. (2008).

So far, we only discussed the proper motion system of PPMXL for stars having 2MASS observations. To ensure that objects in PPMXL beyond the 2MASS limits are on the same

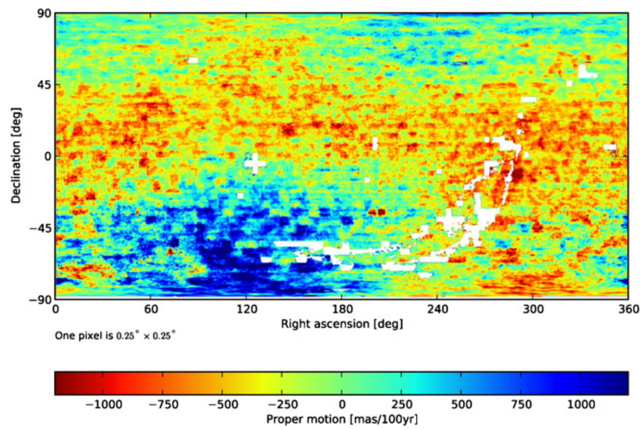

Figure 7. Proper motions in declination μ_δ of faint stars in PPMXL ($18 < I < 19$). Qualitatively, the faint stars show a similar pattern as the bright ones ($12 < K_s < 13$) in Figure 6. However, plate-dependent distortions are not negligible. Empty areas stand for regions where the stars in PPMXL have no I-band observations in this magnitude range.

(A color version of this figure is available in the online journal.)

proper motion system, we made a least-squares adjustment giving weight zero to 2MASS observations (step 7). Then, we compared this proper motion system with PS3 and applied the resulting corrections on a grid with 0.25×0.25 deg^2 bins with a 3×3 bin moving average filter. In other words, for the stars in PS3 we derived positions and proper motions with and without including 2MASS observations and, so, corrected the stars that happen to have no 2MASS observations.

It is well known that magnitude- and color-dependent systematic errors occur in astrometric observations, be they photographic, taken with CCDs or even with photoelectric meridian circles. In the case of USNO-B1.0 or PPMXL, they are hard to be detected, as there is no independent reference on ICRS at fainter magnitudes, e.g., at "blue" or "red" magnitudes between 19 and 20. Also, these stars have kinematics different from the bright stars in solar reflex and galactic motion. So, to a certain extent it is difficult at present to distinguish between systematic errors and different kinematics. There is only one thing one can check: the plate structure of the underlying surveys *must not* be seen. As an example, we show in Figure 7 the proper motion system of PPMXL in the I band of USNO-B1.0 in magnitudes $18 < I < 19$. We chose the I band here as representative, because the I-magnitudes are more homogeneous over the full sky than are the "blue" or "red" magnitudes.

Qualitatively, the faint stars show a similar pattern as the bright ones ($12 < K_s < 13$) in Figure 6. However, plate-dependent distortions *still* are not negligible. Empty areas display regions where the stars in PPMXL have no I-band observations in the range $18 < I < 19$. We attribute this to inhomogeneities in the USNO-B1.0 I-band photometry, which leads to an apparent underdensities or missing stars compared to other fields.

In conclusion, the proper motions system at *the faintest* magnitudes is more uncertain than at *bright* ones. A remedy could come from a sophisticated new reduction of all the survey plates where care is taken to study and avoid all magnitude- and color-dependent effects. With Gaia at the horizon, this effort probably is not warranted.

5.2. The System of Positions at 2000.0 (Step 8)

Unlike the proper motions, the positions of PPMXL at J2000.0 can only be referred to the ICRS by comparison with a catalog which is on ICRS. The obvious choice would be UCAC3. However, UCAC3 does not publish the original observations made in the years 1998–2004 with the CCD camera on the USNO astrograph from CTIO and Flagstaff. In the published catalog, the positions at 2000.0 are given, which result from applying proper motions to the original positions. In the following, we show that the positional system of UCAC3 at 2000.0 is already corrupted by the systematically distorted proper motions even over the few years between observation and 2000.0. Indeed, this can best be seen in Figure 8 for the declination system. In Section 5.1, we showed the UCAC3 proper motions in declination (see Figure 4). If we average the proper motions over right ascension and let them pass through a high-pass filter (variations on scales larger than 10° are suppressed), we get on the northern sky $0^\circ < \delta < 90^\circ$ a wave-like behavior with an amplitude of more than 5 mas yr^{-1}, a period of 5° and phase 0 at the equator. A similar behavior is seen on the southern hemisphere but with a much smaller amplitude of only 1 mas yr^{-1}. This is illustrated in the upper left panel of Figure 8. The upper right panel shows the same plot (proper motions in declination) for PPMXL. On the northern hemisphere, the difference is striking, whereas the coincidence south of $\delta < -20^\circ$ is very good, as it should, because the system of PPMXL is strongly linked to UCAC3 in this area. This becomes much clearer in the plot in the lower left, where we show the proper motion differences PPMXL − UCAC3 for 30 million stars in common.

The lower right panel of Figure 8 shows the differences in positions at epoch 2000.0 between PPMXL and UCAC3. Here, we find again a 5° wave with an amplitude increasing from the equator to the north pole (from 15 mas to 30 mas). We note that the difference in proper motions (lower left panel) and the difference in declination (lower right panel) between PPMXL and UCAC3 are in anti-correlation; the explanation is given below.

At epoch 2000.0, the following equations hold (individually as well as averaged over right ascension). Here, the subscript U stands for UCAC3 and P for PPMXL:

$$\delta_{U,2000} = \delta_{U,\mathrm{orig}} + \mu_{\delta,U} \times (2000.0 - T_{U,\mathrm{orig}}) \tag{3}$$

$$\delta_{P,2000} = \delta_{P,\mathrm{orig}} + \mu_{\delta,P} \times (2000.0 - T_{P,\mathrm{orig}}). \tag{4}$$

Subtracting both equations

$$\begin{aligned}\delta_{P,2000} - \delta_{U,2000} = \delta_{P,\mathrm{orig}} &- \delta_{U,\mathrm{orig}} + \mu_{\delta,P} \\ &\times (2000.0 - T_{P,\mathrm{orig}}) - \mu_{\delta,U} \\ &\times (2000.0 - T_{U,\mathrm{orig}}).\end{aligned} \tag{5}$$

Note that in this magnitude range, $\delta_{P,\mathrm{orig}}$ essentially coincides with the 2MASS declination, because 2MASS has the highest weight and is almost at epoch 2000.0. The difference $\delta_{P,\mathrm{orig}} - \delta_{U,\mathrm{orig}}$ hence gives the difference between an original 2MASS position and an original UCAC3 position where no proper motions (i.e., old epochs) are involved. Both are reduced with *Tycho-2*, are almost coeval, and the mean difference should be zero, at least not showing 5° waves. Also, having filtered out the large scale effects, $\mu_{\delta,P}$ is negligibly small (smaller than 1 mas yr^{-1}, Figure 8 (upper right panel)), so we get

$$\delta_{P,2000} - \delta_{U,2000} \approx -\mu_{\delta,U} \times (2000.0 - T_{U,\mathrm{orig}}). \tag{6}$$

For $\delta > 0^\circ$, we find that the position difference at 2000.0 is in phase with the UCAC3 proper motions as long as (2000.0 −

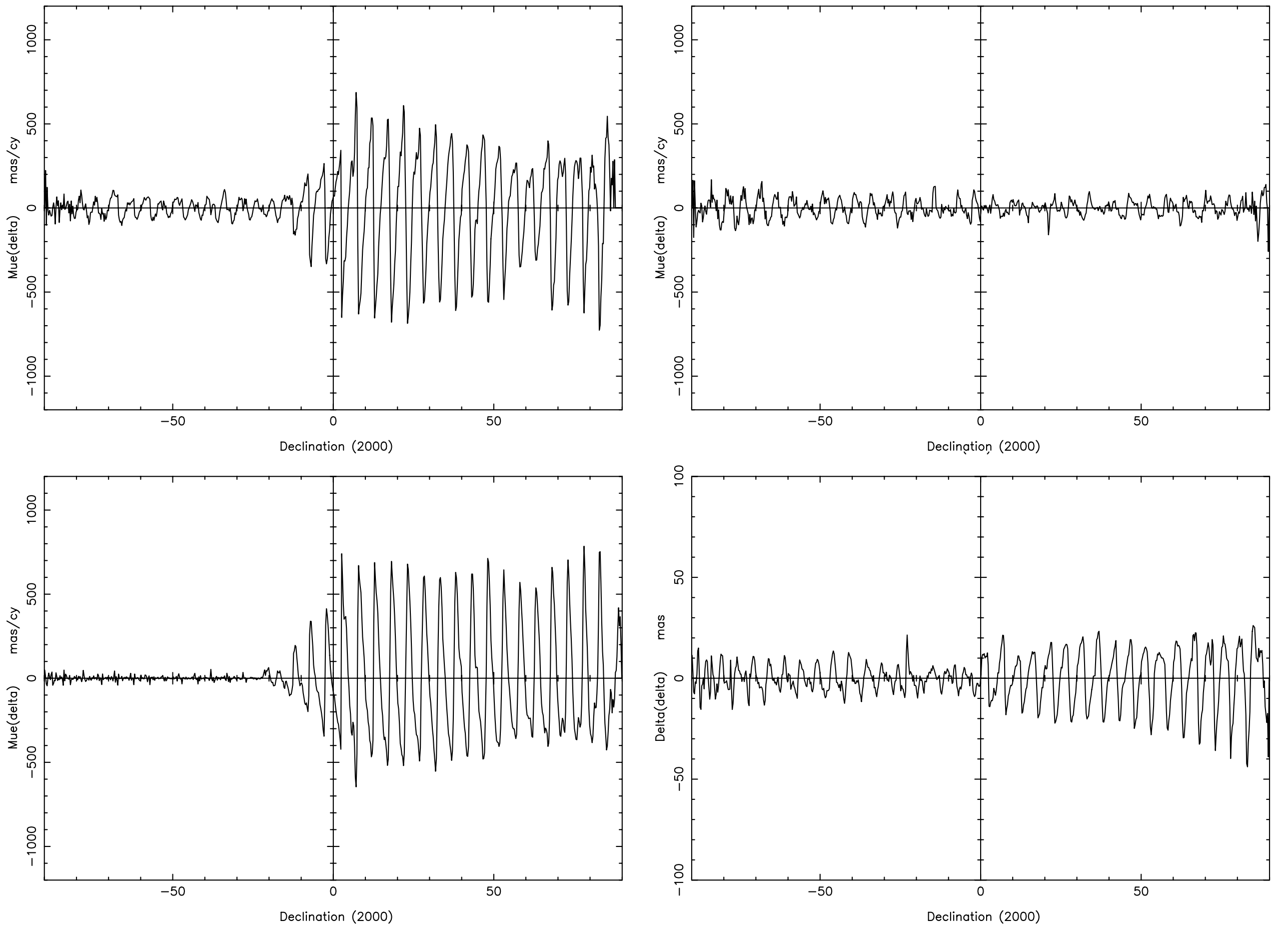

Figure 8. Influence of the distorted UCAC3 proper motions in declination onto the systematic accuracy of the compiled UCAC3 position at epoch 2000.0. Large-scale (>10°) variations have been filtered out by a high-pass (in frequency) filter. Top left: the UCAC3 proper motions. Top right: the PPMXL proper motions. Bottom left: the difference in proper motions PPMXL-UCAC. Bottom right: the difference in declination 2000.0 in the sense PPMXL-UCAC. Units for proper motions are mas per 100 yr, and mas for the difference in declination; for explanation see the text.

$T_{U,\mathrm{orig}}) < 0$ and in anti-phase otherwise. For the northern sky, $(2000.0 - T_{U,\mathrm{orig}})$ is negative because UCAC3 was observed from 2002 to 2004 from equator to pole, exactly what we observe in Figure 8. The increase in amplitude from equator to pole even reveals that the observations at the pole came later than at the equator. Although position differences of 15–30 mas are small, modern UCAC3 observations, accurate at epoch to 15–70 mas (Zacharias et al. 2004), are considerably deteriorated systematically in only a few years. In consequence, we could not use UCAC3 as a reference catalog on ICRS for the position at epoch 2000.0.

The system PS2 of PPMXL consists of the proper motion system and the position system at J2000.0. As in the final step of the construction of the proper motion system (step 7), we chose PPMX as representative of the positional system at epoch 2000.0, so we added systematic differences PPMX-PS2 at epoch 2000.0 to PS2 on a grid with 1×1 deg^2 bins with a 3×3 bin moving average filter to achieve the final positional system of PPMXL at 2000.0. In the case of stars having no 2MASS observations, we proceeded analogously to the proper motion system. This completes step 8.

6. THE FINAL CATALOG

USNO-B1.0 contains more than a billion entries: stars and galaxies, and a number of artifacts. Barron et al. (2008) have detected spurious entries in USNO-B1.0 that are caused by diffraction spikes and circular reflection halos around bright stars in the original imaging data. These defects, numbering some 24 million or 2.3%, were removed using the data provided by Barron et al. (2008).

The final version of PPMXL contains some 900 million stars. We kept an entry from USNO-B1.0 whenever the maximum epoch difference between the observations was larger than 10 years. This somewhat arbitrary choice was guided by the idea to formally derive proper motions even if a star has only observations from 2MASS and the second epoch POSS, whereas no observations from the first epoch POSS are available. Because of this short epoch difference, these stars have large mean errors of proper motions, and they have to be used with care.

At its bright end, PPMXL is merged with PPMX according to the following scheme. The stars of PPMX were searched in PPMXL using a cone with 1.5 arcsec radius. When no match was found, the resp. PPMX star was added to the catalog. This mainly happened in the case of bright stars. When a match has been found, the PPMX star is selected if the mean error of its proper motion is smaller than that of the PPMXL star, and vice versa. If a PPMX star is added to the catalog, all PPMXL matches within 1.5 arcsec are deleted.

The photometric information from USNO-B1.0 is retained, as is the NIR photometry from 2MASS if available. The data can be queried in the VO and from http://vo.uni-hd.de/ppmxl, where a text dump is available for download as well. The catalog is also available at CDS Strasbourg.

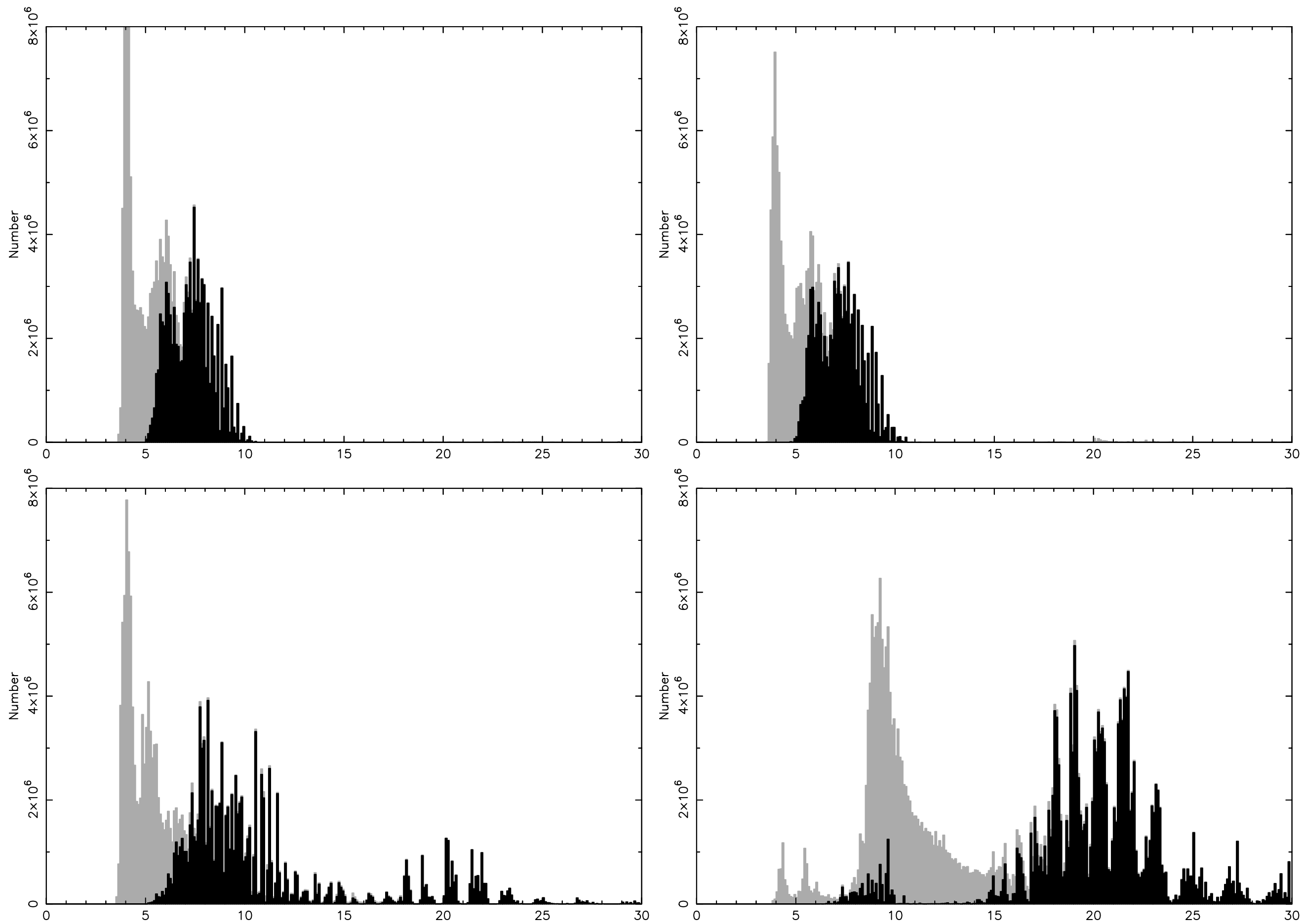

Figure 9. Distribution of the formal mean error of a proper motion component (here $\mu_\alpha \cos\delta$) in units of mas yr^{-1}. Shown are the four quarters of the sky. Top left: $+90° > \delta \geqslant +30°$. Top right: $+30° > \delta \geqslant 0°$. Bottom left: $0° > \delta \geqslant -30°$. Bottom right: $-30° > \delta > -90°$. The envelope is the distribution of all stars; stars shaded in gray are those having 2MASS observations, and stars in black do not have 2MASS observations.

6.1. Properties

PPMXL contains 910,468,710 entries, including stars, galaxies, and bogus entries. Of these, 412,410,368 are in 2MASS, i.e., 2MASS is used to determine proper motions and the J, H, K_s magnitudes are given in the catalog. In total, 6,268,118 stars are taken from PPMX, so PPMXL aims to be complete from the brightest stars down to about 20th magnitude in V.

The covariance matrix obtained in the least-squares adjustment in Section 4 gives (per coordinate and per star) the mean epoch, the mean error of position at mean epoch, and the mean error of proper motions. All these quantities are published in the catalog.

Mean errors of the positions at the reference epoch 2000.0 can be computed star by star. On average, the mean errors of position 2000.0 are between 80 and 120 mas if 2MASS astrometry is available, and range from 150 mas to 300 mas else.

The statistics of the mean errors of the proper motions resembles the observational history rather than the poorer signal to noise at fainter magnitudes. In Figure 9, we present the distributions of the mean errors of the proper motions in four declination zones. The following can be drawn from this figure. Including the measurements from 2MASS yields a considerable improvement, both because of its good accuracy and its recent epoch. The latter effect is most pronounced on the southern sky. At $\delta < -30°$, the proper motions without 2MASS are of poor quality, because the first epoch is much later than in the other zones, and hence the epoch difference is rather small. 2MASS improves the situation, but a contemporary (2010) survey such as the Sky Mapper Southern Sky survey (Keller et al. 2007) will give a considerable improvement.

PPMXL is a catalog that is nominally on the ICRS system. It is linked to the *Hipparcos* catalog, the optical representation of the ICRS, via *Tycho-2* and PPMX. A word about the inertiality of PPMXL is therefore appropriate. The uncertainty of a residual rotation of *Hipparcos* itself is 0.25 mas yr^{-1} (Kovalevsky et al. 1997). This is a global quantity; on smaller scales the uncertainty is larger. On a typical field of the sky of 1 deg^2 we find about three faint *Hipparcos* stars with an rms error of the proper motion of, say, 1.7 mas yr^{-1} each. Therefore, their "average motion" has a mean error of roughly 1 mas yr^{-1}, a figure representative of the uncertainty of the deviation of *Hipparcos* from a truly inertial system on a 1° scale. The actual value of such a deviation can be determined only with the results from Gaia or other space missions with limiting magnitude deeper than *Hipparcos* such as JMAPS and, perhaps, nano-JASMINE. Also, all-sky block-adjustment procedures applied to old and new surveys can help. The two intermediate steps from *Hipparcos* to PPMXL introduce additional systematic errors which cannot be estimated rigorously. It is therefore not unreasonable to state that the absolute proper motions given in PPMXL have an underlying systematic uncertainty of at least 1–2 mas yr^{-1}, which is small compared to the random error for the vast majority of PPMXL stars. The mean motion of an ensemble of stars, however, cannot be determined better than the 1–2 mas yr^{-1} mentioned above. These arguments, of course, hold similarly to *Tycho-2*, PPMX, and the UCAC series of catalogs.

6.2. Caveats

Stars with $n_{obs} = 2$ *or with* "P" *flags*. About 146 million stars (or 16%) have proper motions based on two observations only; and some 77 million (or 8.4%) carry the P flag defined in Section 4 denoting bad χ^2 sums of the residuals after the least-squares adjustment. Both cases concentrate toward the edges of plates and in dense regions of the southern sky.

Magnitude system. We made no attempt to recalibrate the USNO B1.0 magnitude system. There are discrepancies in the magnitude system from field to field and from early to late epoch. In principle, the magnitudes can be calibrated using the Guide Star Photometric Catalog (Bucciarelli et al. 2001).

Double entries. Cross-matching with 2MASS has been performed using a cone of 3 arcsec radius. Given the spatial resolution on the Schmidt plates underlying USNO-B1.0 only a single match between a 2MASS and a USNO-B1.0 entry should occur. However, on the northern hemisphere a single match was found in 93.6% of all cases, on the southern hemisphere in only 88.7%. There are also triple and multiple matches, but their number is smaller than 0.03% north and 0.16% south. The number of doubles and multiples strongly increases at plate boundaries and in dense regions on the southern sky (LMC, inner Galactic plane). No complete auto-cross-match has been made with PPMXL, but extrapolating the matches with 2MASS to the full 900 million objects, we estimate that about 90 million (10%) are false doubles or multiples from USNO-B1.0. Turning the cross-match around we also found double matches of 2MASS stars with a USNO-B1.0 star. This amounts to 1.5% of all cases. So, 2MASS has between 6 and 7 million doubles.

"High proper motion" stars. There is a huge number of stars with high proper motions, e.g., on the northern hemisphere about 24.5 million objects have proper motions larger than 150 mas yr^{-1}. The vast majority of them must be fakes; a practically flat proper motion distribution function between 130 and 430 mas yr^{-1} is a hint to this. Also, the LSPM-NORTH Catalog (Lépine & Shara 2005) lists only some 61,000 stars on the northern hemisphere with proper motions larger than 150 mas yr^{-1} and claims to be completed to $V = 19$. An attempt to solve the problem with these large proper motions (already inherent in USNO-B1.0) is far beyond this paper; we only note in passing that many cases occur among the above-mentioned doubles or multiples.

7. CORRECTION TABLES FOR OBSERVATIONS BASED UPON USNO-B1.0

Observers using USNO-B1.0 for the reduction of their CCD frames get positions of their targets which are not on the ICRS. Such positions can neither be used to derive inertial stellar proper motions, nor should they be used for in orbit determinations in the case of solar system bodies. According to Chesley et al. (2009), there are millions of minor planet positions based on USNO-B1.0 in recent years.

To aid in reducing these observations to ICRS, we present systematic correction tables from USNO-B1.0 to PPMXL for positions at epoch 2000.0 and for proper motions. These tables give the means of the four quantities in circles of radius $\sqrt{2}/2$ degrees around the centers of 360 by 180 spherical squares covering the sky. The application of these tables is straightforward. Suppose you have an observation (α, δ) based on USNO-B1.0 at epoch T (in years). For this α, δ, the tables give four quantities $\Delta\alpha$, $\Delta\delta$, $\Delta\mu_\alpha \cos\delta$, $\Delta\mu_\delta$ in the sense PPMXL − USNO-B1.0. Then the conversion to ICRS is given by

$$\alpha_{ICRS} = \alpha + \Delta\alpha + (\Delta\mu_\alpha \cos\delta)/\cos\delta \times (T - 2000.0) \quad (7)$$

$$\delta_{ICRS} = \delta + \Delta\delta + \Delta\mu_\delta \times (T - 2000.0). \quad (8)$$

The correction tables can be used or downloaded from http://vo.uni-hd.de/ppmxl. In applying these formulae, note that they are not rigorous near the poles, and also that a star can cross the $\alpha = 0$ border when one applies the corrections in right ascension. We will also deliver correction tables for USNO-A2.0, UCAC2 and UCAC3, and 2MASS on the same server. Note that 2MASS is an observational catalog, literally speaking with proper motions $\equiv 0$, observed in the years 1997 and 2001. So, in 2010 *systematic* offsets may already reach 150 mas (15 mas yr^{-1} × 10 yr). All the correction tables are created under the implicit assumption that PPMXL has no magnitude-dependent systematics.

Note added in proof. While this paper was being reviewed, the paper describing UCAC 3 appeared in the *Astronomical Journal* (Zacharias et al. 2010).

This research made use of the facilities of the German Astrophysical Virtual Observatory (GAVO). This publication refers to observations from the ESA-*Hipparcos* satellite. It makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. We also acknowledge the institutions that funded the sky surveys on which USNO-B1.0 is based upon.

We are grateful to Nina Kharchenko for quality checks in regions of a few open clusters. We thank Dave Monet for supplying a complete list of field epochs of USNO-B1.0.

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