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THE THIRD US NAVAL OBSERVATORY CCD ASTROGRAPH CATALOG (UCAC3)

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ABSTRACT

The third US Naval Observatory (USNO) CCD Astrograph Catalog, UCAC3, was released at the IAU General Assembly on 2009 August 10. It is the first all-sky release in this series and contains just over 100 million objects, about 95 million of them with proper motions, covering about R = 8–16 mag. Current epoch positions are obtained from the observations with the 20 cm aperture USNO Astrograph's "red lens," equipped with a 4k×4k CCD. Proper motions are derived by combining these observations with over 140 ground- and space-based catalogs, including *Hipparcos*/*Tycho* and the AC2000.2, as well as unpublished measures of over 5000 plates from other astrographs. For most of the faint stars in the southern hemisphere, the Yale/San Juan first epoch plates from the Southern Proper Motion (SPM) program (YSJ1) form the basis for proper motions. These data are supplemented by all-sky Schmidt plate survey astrometry and photometry obtained from the SuperCOSMOS project, as well as 2MASS near-IR photometry. Major differences of UCAC3 data as compared with UCAC2 include a completely new raw data reduction with improved control over systematic errors in positions, significantly improved photometry, slightly deeper limiting magnitude, coverage of the north pole region, greater completeness by inclusion of double stars, and weak detections. This of course leads to a catalog which is not as "clean" as UCAC2 and problem areas are outlined for the user in this paper. The positional accuracy of stars in UCAC3 is about 15–100 mas per coordinate, depending on magnitude, while the errors in proper motions range from 1 to 10 mas yr^{-1} depending on magnitude and observing history, with a significant improvement over UCAC2 achieved due to the re-reduced SPM data and inclusion of more astrograph plate data unavailable at the time of UCAC2.

Key words: astrometry – catalogs – reference systems – stars: kinematics and dynamics

1. INTRODUCTION

The US Naval Observatory (USNO) operated the 8 inch (0.2 m) Twin Astrograph from 1998 to 2004 for an all-sky astrometric survey. About 2/3 of the sky was observed from the Cerro Tololo Inter-American Observatory (CTIO) while the rest of the northern sky was observed from the Naval Observatory Flagstaff Station (NOFS). The average number of completed fields per year was a factor of 2.0 larger at CTIO than at NOFS. A 4k×4k CCD with 9 μm pixel size was used in a single bandpass (579–643 nm) providing a flat field of view (FOV) of just over 1 deg^2, taking advantage of only a tiny fraction of the FOV delivered by the optical system of the Twin Astrograph's "red lens." A two-fold overlap pattern of fields span the entire sky. Each field was observed with a long (about 125 s) and a short (about 25 s) exposure, thus each star should appear on at least two different CCD exposures, and stars in the mid-magnitude range (about 10–14) should have four images.

UCAC3 contains just over 100 million objects; most of these are stars. It covers the magnitude range of about R = 8–16 (Figure 1) with positional precision at mean epoch ranging from 15 to 100 mas, depending on magnitude (Figure 2). Mean position errors are shown per 1/10 mag bin with stars up to magnitude 13 excluded whenever the formal error in either one of the coordinates exceeds 100 mas. For fainter stars, no such outlier exclusion was adopted, which explains the discontinuity in Figure 2 and also shows what effect such a restriction has on the derived mean formal position errors.

The distribution of proper motions is shown in Figure 3, and the proper motions errors as a function of magnitude are presented in Figure 4. The large increase of the formal proper motion errors for stars at magnitude 8 and brighter is caused by the saturation of the CCD data with associated large, formal positional errors. The weighted mean epoch of UCAC3 data for most stars is in the range of 1980–2002 (Figure 5), depending on magnitude as consequence of the observing history of stars and the positional precisions at various epochs.

The released catalog is based on all applicable, regular survey field observations, excluding the CCD exposures taken on extragalactic link fields and most calibration fields. Observations of minor planets have been extracted and will be published separately from UCAC3. The released UCAC3 is a compiled catalog, similar to UCAC2. No individual epoch observations are given, nor are the pixel data publicly available at this point.

The Tycho-2 catalog (Høg et al. 2000) was used as the reference star catalog to obtain UCAC3 positions on the *Hipparcos* System (ESA 1997), which is the current optical realization of

[8] Contractor.
[9] Retired.
[10] Summer student.

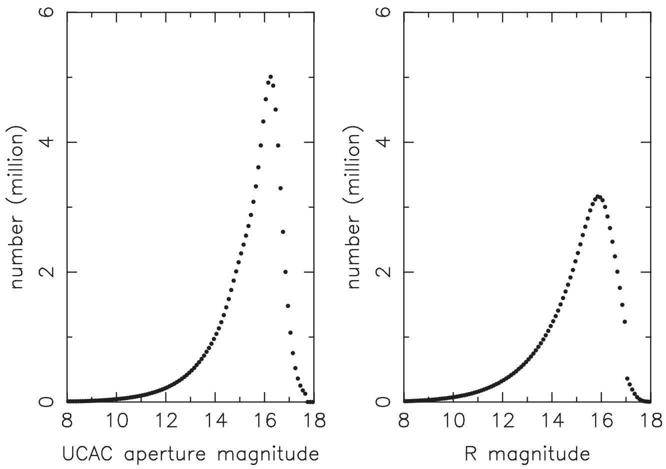

Figure 1. Distribution of UCAC3 stars as function of UCAC3 aperture magnitude (left panel) and SuperCOSMOS *R* magnitude (right panel). The limiting magnitude is close to 16.0 in both cases.

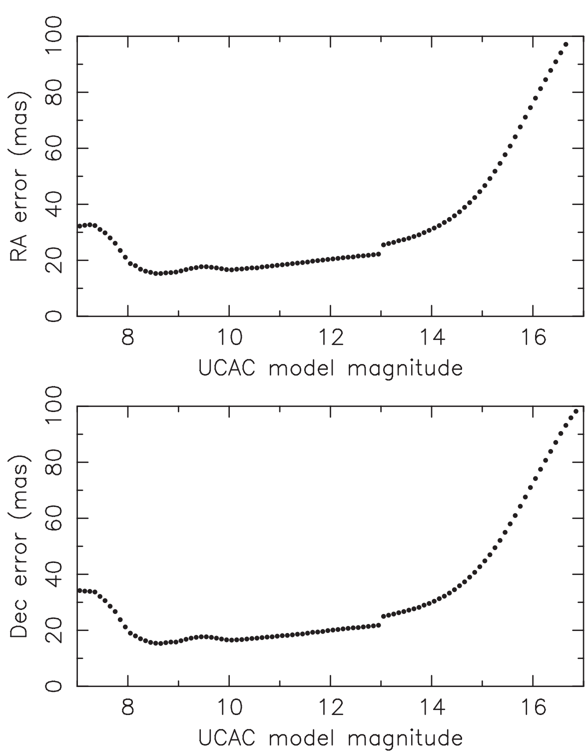

Figure 2. UCAC3 formal, mean position errors per coordinate at central epoch as function of model fit magnitude. The discontinuity at magnitude 13 is artificial due to the adopted outlier exclusion; see the text.

the International Celestial Reference Frame (ICRF). Most stars in UCAC3 have proper motions which were derived from the astrograph CCD data combined with various earlier epoch data, including all ground-based catalogs also used for the Tycho-2 project, unpublished new measurements of other astrograph plates, the Southern Proper Motion (SPM) first epoch plates, and Schmidt plate data through the SuperCOSMOS project. A final UCAC4 release is planned which will utilize the new reductions of the Northern Proper Motion (NPM) program, supplementing the SPM data, which then would allow us to derive proper motions for all UCAC stars without the use of Schmidt plate data. This goal could not be achieved for UCAC3 due to a production deadline and lack of time to complete the NPM work.

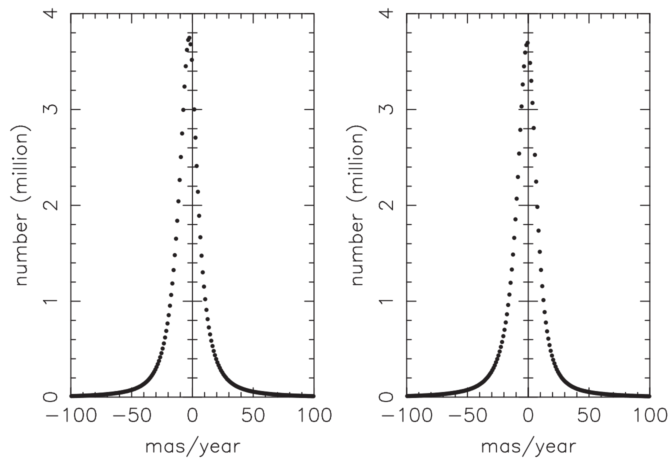

Figure 3. Distribution of the UCAC3 proper motions for the R.A. (left) and decl. (right panel) component.

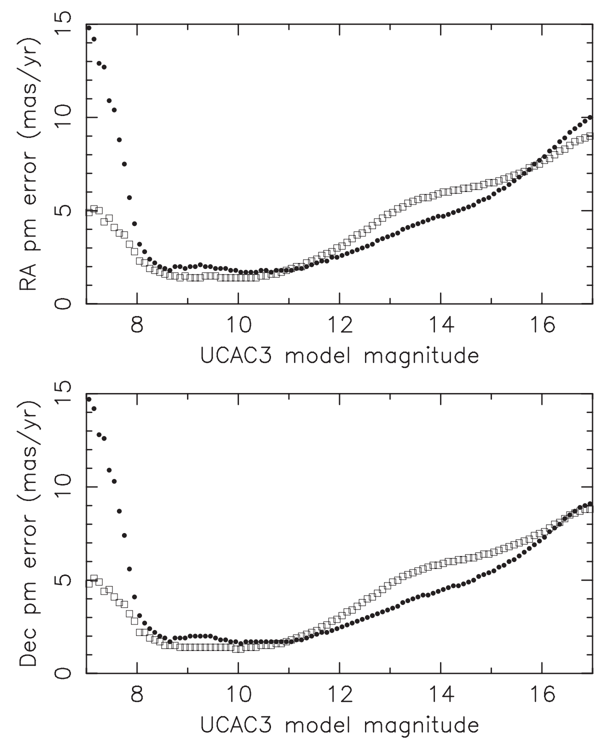

Figure 4. Formal, standard errors of UCAC3 proper motions as a function of magnitude, separately for each coordinate. The filled dots are for stars in the declination range of $-90°$ to $-20°$, dominated by the SPM first epoch data. The open squares are for the rest of the sky dominated by the SuperCOSMOS first epoch data.

The Two Micron All Sky Survey, 2MASS (Skrutskie et al. 2006) was extensively used to analyze systematic errors of UCAC3 data and to supplement the UCAC3 catalog with near IR photometry. Optical *B*, *R*, *I* magnitudes were copied from the SuperCOSMOS source catalog (photographic photometry) into UCAC3 for the benefit of the users. The number of UCAC3 objects matched with various catalogs is presented in Table 1.

For more details about the observational data and earlier reductions, the reader is referred to the UCAC1 (Zacharias et al. 2000) and UCAC2 (Zacharias et al. 2004) papers. Contrary to those papers, which each describe one of the earlier releases in detail, the UCAC3 effort will be documented in a series of papers. This paper gives the introduction aiming at the user of

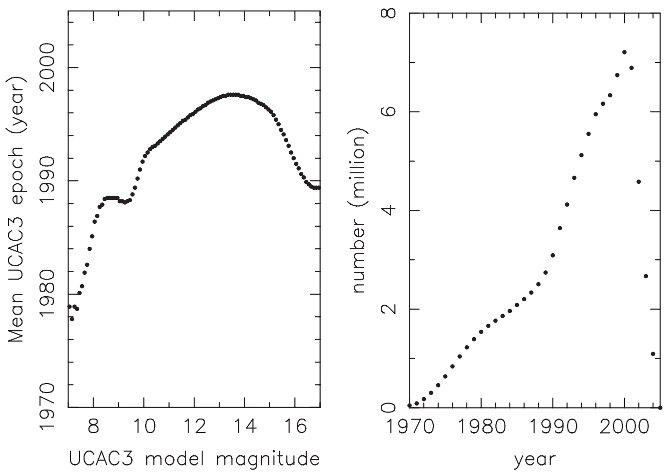

Figure 5. Distribution of the mean epoch of all UCAC3 stars as a function of magnitude (left panel) and as histogram (right panel).

Table 1
Number of Stars in UCAC3 Common with Other Catalogs or Data Sets

Number of Stars	Catalog Flag	Catalog or Data Set Name
65,392	1	*Hipparcos*
2,386,607	2	Tycho-2
4,098,873	3	AC2000[a]
270,823	4	AGK2 Bonn
960,074	5	AGK2 Hamburg
4,320,925	6	Hamburg Zone Astrograph
2,970,383	7	USNO Black Birch Astrograph, Yellow lens
1,043,857	8	Lick Observatory 50 cm Astrograph
85,563,642	9	SuperCOSMOS data
51,112,855	10	SPM Yale/San-Juan catalog (YSJ1)
51,297	. . .	High proper motion stars from external catalogs[b]
98,114,307	. . .	2MASS[c]
100,766,420	. . .	Total number of entries in UCAC3

Notes.
[a] Urban et al. (2001).
[b] Identified by MPOS star number (last column in catalog data records, also see the text) over 140,000,000.
[c] Identified by separate 2MASS star identifier flag.

the UCAC3 catalog, describing the released data, limitations, and comparisons to other catalogs. Technical details of the reduction process will be outlined in a paper about the new pixel processing (Zacharias 2010) and a separate paper on the astrometric reductions leading to the mean positions at the CCD observing epoch (Finch et al. 2010). Preliminary results of these were already presented at a recent meeting (Finch et al. 2009). The SPM data re-reduction will be described elsewhere (T. M. Girard et al. 2010, in preparation). Papers about double stars discovered in UCAC3 and confirmed with speckle observing, mining UCAC3 data for new high proper motion (HPM) stars, and the extragalactic reference frame link of UCAC are in preparation.

2. UCAC3 VERSUS UCAC2

Here we summarize the main differences of UCAC3 data as compared to the previous release, with more details provided in the following sections.

Pixel reduction. A completely new raw data reduction was performed for UCAC3, applying flats, and improved darks resulting in a deeper limiting magnitude.

Centroiding, double stars. New image profile model functions were used, including double star fit models.

Completeness. UCAC3 is all-sky with improved completeness; however, this resulted in more false entries than UCAC2 had.

Photometry. UCAC3 gives vastly improved photometry from the CCD data re-processing.

Early epoch data. Many more astrograph plates (see below) were scanned at USNO and used to derive proper motions for UCAC3 stars. A complete re-processing of the SPM data was performed, while the rest of the sky has only SuperCOSMOS early epoch data for faint stars.

3. CCD DATA AND PROCESSING

3.1. Pixel Data

All of the 4.5 TB of compressed, raw pixel data were re-processed for the UCAC3 release. For the first time, flats were applied to the pixel data. An improved scheme for darks was employed which resulted in lower background noise and a slightly deeper limiting magnitude.

Extensive research to better model the observed stellar image profiles was undertaken, including investigating asymmetric model functions to account for the skewed image shapes caused by poor charge transfer efficiency of the UCAC detector. The final reductions are based on a symmetric Lorentz profile model which matches the observed profile better than a Gaussian profile with the same number of parameters. Details will be presented in a separate paper.

New code was developed to detect blended images of double stars and to perform least-squares image profile fits using double star models, fitting both components at the same time. Many such pairs, mainly in the 2–10 arcsec separation range are now being handled properly. However, many of those pairs could only be matched to a single, blended image in earlier epoch data to derive proper motions. Flags in the catalog indicate the level of double star processing. Detected pairs in UCAC data were compared to existing double star data, and samples of potential new discoveries put on the USNO 26 inch speckle observing program. Results will be presented in a separate paper.

Contrary to UCAC2, the issue of completeness was pushed as much as possible for UCAC3, which thus naturally contains many more false detections than UCAC2 did. Even single image detections from the CCD data were propagated into the final catalog if they match up with any one of the other catalogs and are above a conservative detection threshold. For this matching, the large catalogs, 2MASS and SuperCOSMOS, were restricted to the anticipated UCAC3 limiting magnitudes plus some margin before performing the position-based match. This avoids accidental mismatches with very faint objects. Unconfirmed, faint, single images from UCAC observations are not included in the final catalog. Overexposed stars were propagated to the final catalog for reason of completeness. For those stars, and other problematic images, the image center fit often failed, which is indicated in the number of "used images" in UCAC3. If this number is zero, no fit position could be obtained; instead, the provided position is only approximate, based on the centroid (first moments) of the light distribution in the pixel data.

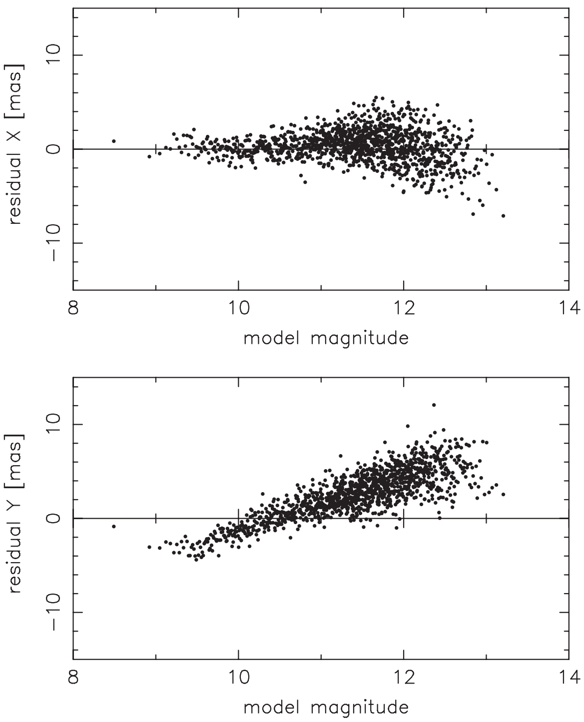

Figure 6. Residuals of UCAC frames taken at CTIO with the telescope on the West side of the pier, reduced with Tycho-2 reference stars, final reductions. Each dot represents the mean over 5000 residuals.

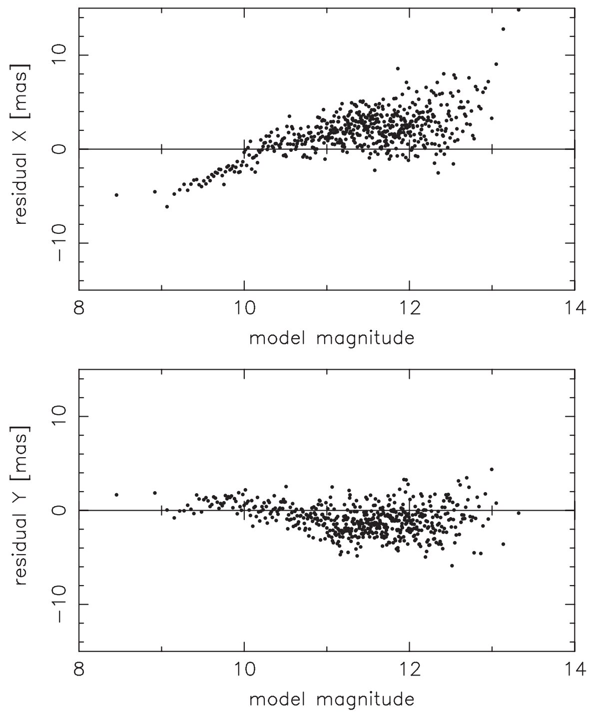

Figure 7. Residuals of UCAC frames taken at NOFS with the telescope on the East side of the pier, reduced with Tycho-2 reference stars, final reductions. Each dot represents the mean over 5000 residuals.

3.2. Photometry

UCAC3 gives two observed magnitudes, based on the volume of the image profile model fitted, and a true aperture photometry, respectively. Extinction coefficients are derived for each exposure with respect to Tycho-2 stars adopting a linear model with $B-V$ color. Thus, a photometric zero point was determined for each CCD exposure and applied to the instrumental magnitudes to arrive at our bandpass magnitudes based on the available Tycho-2 stars in a given field. An estimate of the photometric quality of a night is made from the average extinction coefficients of all CCD frames taken that night and compared to other nights' results. Magnitudes obtained from nights flagged as non-photometric are excluded in the calculation of a mean magnitude for each star. If all images are excluded, a "best guess" for the zero point of the magnitude scale on each CCD frame is made and a mean magnitude for such stars is derived over all available CCD frames and the error of the magnitude is set to -1 in those cases. Normally, for each individual star, two photometric errors have been derived. The model error is based on the signal-to-noise ratio of the images of a star, while the scatter error is determined from the distribution of the individual magnitudes per star from different frames. The larger of these is then published in the UCAC3 catalog.

It is expected that the photometry of the UCAC3 CCD data is vastly improved over UCAC2, which was on the 0.3 mag level. However, no detailed investigation into the precision or accuracy of photometric errors in UCAC3 has been made so far. For well exposed stars, 5%–10% photometric accuracy is expected. The UCAC observing program was never envisioned to provide reliable photometry. No photometric standard stars were observed to derive photometric constants for any observing night, and all UCAC observations were performed in a single bandpass.

3.3. Positions

Positions in UCAC3 are on the International Celestial Reference System (ICRS) as realized by the Tycho-2 catalog, which was used as reference star catalog in a conventional, frame-by-frame, astrometric reduction after various corrections were applied. Residuals of the final reductions are shown in Figures 6 and 7 for the CTIO and NOFS data, respectively. Remaining systematic errors are on the 5 mas level. It is possible that these are inherent in the Tycho-2 data, see discussion below. The x-coordinate is along right ascension (R.A.), while y is along declination (decl.).

Fortunately, the 2MASS observations were made at roughly the same epoch as UCAC observations, and the 2MASS catalog was extensively used to derive systematic error corrections in UCAC data. Complex look-up tables were generated empirically to correct for purely geometric field distortions (depending only on the x, y coordinates of stars on CCD frames) as well as coma-like terms involving magnitude and x, y coordinates. These types of systematic errors can be attributed to be in the UCAC data due to the correlation with x, y pixel coordinates. However, a pure magnitude equation (systematic positional error as a function of brightness) could either be in UCAC or 2MASS data. Thus, the overall pure magnitude equation corrections of the UCAC data were derived from the "flip" calibration data alone. These calibration fields have been observed throughout the UCAC project with the telescope being on one side of the pier (East or West) then on the other. These flip observations provide pairs of CCD exposures which are rotated by 180° with respect to each other, revealing the magnitude equation offsets independent of external catalog data. The assumption here of course is that the magnitude equation stays constant over the set of East/West exposures and other systematic errors like coma terms have been removed.

No corrections as a function of color were applied. Differential color refraction effects are typically below 5 mas due to the narrow UCAC bandpass. For a detailed discussion of the astrometric reductions leading to UCAC3, the reader is referred to the separate paper by Finch et al. (2010).

4. PROPER MOTIONS

4.1. New Data and Processing

For UCAC3, the complete set of the second *Astronomische Gesellschaft Katalog* (AGK2) plates, taken around 1930, could be utilized from scans made on the StarScan machine (Zacharias et al. 2008). This set comprises about 1950 plates taken at the Bonn and Hamburg observatories, covering the sky north of $\delta = -2^{\circ}\!.5$ and blue magnitude range 5–12. Only a partial set of the AGK2 data was available for UCAC2. Over 1.2 million stars (see Table 1) could be measured this time, while "only" about 186,000 stars were measured, reduced, and published in the original AGK2/AGK3 project from a several decade long effort, when "computers" were humans.

In addition, a total of about 2000 Hamburg Zone Astrograph (ZA), 900 USNO Black Birch Astrograph (yellow lens, BY), and 300 Lick Astrograph (LA) plates were scanned on StarScan and reduced with *Hipparcos* reference stars to provide accurate early epoch positions for stars down to $V = 14$ (ZA, BY) and $V = 16$ (LA). However, all those plates together cover only about 1/3 of the sky, targeting fields around ICRF extragalactic sources and special fields observed for other programs.

A complete new reduction of the SPM data was performed applying the modified StarScan (Zacharias et al. 2008) pipeline reduction code to the Precision Measuring Machine (PMM; Monet & Levine 2001) pixel data. The resulting global-plate x, y center coordinates were processed by the Yale University reduction pipeline to correct for systematic errors as function of magnitude, utilizing all grating images of those data (T. M. Girard et al. 2010, in preparation). The new processing of these data improved the proper motions of UCAC3 stars fainter than about 14th magnitude and covered by the SPM2 by about a factor of 2 with respect to the UCAC2 release.

Unfortunately, the corresponding NPM reductions did not progress fast enough for the UCAC3 schedule and will be utilized at a later time for UCAC4. The SuperCOSMOS data (Hambly et al. 2001b) based on Schmidt survey plates provided early epoch positions to derive proper motions of faint UCAC3 stars all-sky. For each catalog used in the proper motion calculation, an estimated systematic error floor was added to the internal errors (Table 2). Individual CCD mean position errors (small number statistics from scatter of a few observations per star) were already clipped to a minimum of 10 mas prior to this step. SuperCOSMOS data were not excluded in areas covered by SPM; however, the SPM data with their significantly lower errors dominate the proper motion solution, if available.

4.2. HPM Stars

An effort has been made to tag previously known HPM stars in the UCAC3 catalog utilizing published proper motion catalogs and surveys. While we have made an effort to identify most previously known HPM stars with $\mu \geqslant 0\farcs15\ \mathrm{yr}^{-1}$, the list is not complete. In all but a few cases, data for these known proper motion stars were retrieved using the VizieR online data tool at the Strasbourg Astronomical Data Center (CDS). For the few cases where data were not available through CDS, the data were retrieved through the corresponding published literature.

Table 2
Adopted Systematic Errors Which are Added (rms) to Internal, Random Errors of Star Positions to Obtain Realistic Weights before Calculating Proper Motions

Error (mas)	Catalog Name
1	*Hipparcos*
10	Tycho-2
70	AC2000.2
30	AGK2 Bonn
30	AGK2 Hamburg
20	ZA
20	BY
15	Lick Astrograph
100	SuperCOSMOS
10	SPM
5	UCAC mean CCD position
80	All others

The proper motion data given in the UCAC3 catalog for these previously known HPM stars come from the catalogs themselves and are not computed as other proper motions are in the UCAC3 catalog.

A list of HPM stars was compiled and each UCAC CCD frame searched for possible images of those stars. Those images were extracted from the regular pipeline processing of UCAC3 to avoid confusion and mismatches with other catalogs. A total of 51,297 HPM stars could be identified in UCAC3 data; they are identified by the *MPOS* numbers larger than 140 million.

The mean positions of the HPM stars are based on UCAC CCD observations; however, no attempt was made to identify these stars in early epoch catalogs to derive new proper motions. More details and a list of references can be found in the readme file of UCAC3 and the upcoming paper about new HPM stars and common proper motion pairs found in UCAC3 data (Finch et al. 2010).

5. CTIO–NOFS OVERLAP REGION

A region of the sky around $\delta = +20^{\circ}$ was observed at CTIO and then repeated from NOFS within about three months (see UCAC2 paper). Based on these 1410 CCD frames, separate mean positions were generated from the data of each site, utilizing the final version of the systematic error corrections, which are different for location and telescope orientation. For the observing at CTIO, the telescope was on the West side of the pier, while at NOFS it was on the East. Figure 8 shows the position differences between the CTIO and NOFS based data as function of magnitude. Large differences are found only for bright, overexposed stars in the declination coordinate, as expected. These are residual systematic errors from bleeding columns of stars too bright for precise UCAC astrometry. All other systematic position differences are small, typically 5 mas, showing excellent consistency between the different data sets of CCD observing (at vastly different zenith distances) and processing. The data shown in Figure 8 is not inconsistent with Figures 6 and 7 because of the different area of the sky sampled. Residuals with respect to Tycho-2 reference stars vary with declination zone. Figures 6 and 7 show the summary over all applicable frames taken at CTIO and NOFS, respectively, while Figure 8 covers only a small area in the sky.

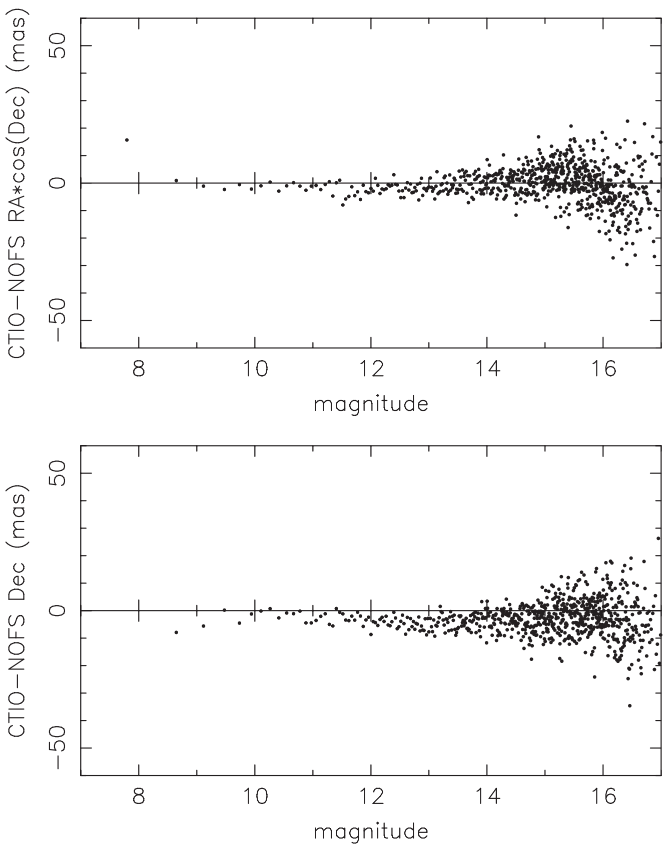

Figure 8. Position differences of the same area in the sky as observed from CTIO and then from NOFS. Results are based on 1410 CCD frames taken within about 3 months. The telescope orientation is flipped by 180° between the two data sets, with different systematic error corrections applied according to the final pipeline processing. Each dot represents the mean over 250 stars.

6. COMPARISONS WITH OTHER CATALOGS

For the following comparisons with the UCAC3 release data, only stars with unique, single matches to the following catalogs were used. A match radius of 1.5 arcsec was adopted for positions at the desired common match epoch, by applying proper motions as specified below.

6.1. SuperCOSMOS

There are several star catalog solutions based on the same all-sky Schmidt plate surveys and different plate measures. SuperCOSMOS (Hambly et al. 2001a) proper motions were applied to the SuperCOSMOS Source Catalog positions to generate positions at the epoch of UCAC data. Relatively small systematic position differences are found. Figure 9 shows some examples of such systematic position differences as a function of magnitude (UCAC model mag), R.A. and decl. The Schmidt plate pattern is clearly seen in the differences as a function of declination; however, overall typical systematic errors are only on the 100 mas level, less than what earlier had been found in USNO-B data, typically 200 mas, sometimes exceeding 300 mas (Zacharias et al. 2006). Similar results were obtained from minor planet orbit determinations based on UCAC2 and USNO-B reference stars (Chesley et al. 2009), and a re-processing of USNO-B is in progress. The error contribution from the UCAC data is negligible for these comparisons, thus we see mostly the absolute position errors of these Schmidt plate data when comparing to UCAC. These results led to the decision to use SuperCOSMOS data to derive proper motions of UCAC3 instead of the current USNO-B catalog.

6.2. UCAC2

Figures 10–20 illustrate the systematic differences between this UCAC3 data release and the previous UCAC2 version regarding magnitude, positions, and proper motions. Out of the 48.3 million entries in UCAC2, close to 1 million could not be matched up with a UCAC3 entry uniquely. We cannot exclude the possibility that UCAC3 is actually missing a significant number of bona fide stars; however, equally well the majority of those not matched objects could be invalid entries in UCAC2. Also see Section 8 for a discussion of UCAC3 problems and issues. Due to the large volume of data, the comparison was split up between the northern and southern hemisphere.

For the stars in common, we see a very small scatter but complex, large, systematic difference in the photometry (Figure 10). This confirms reported errors in UCAC2 photometry of typically 0.3 mag, which hopefully are resolved for the better in UCAC3.

The rms position differences between UCAC2 and UCAC3 at the standard epoch of 2000.0 are shown in Figures 11 and 12 for the southern and northern hemisphere, respectively. The floor level for the well exposed stars (10–14 mag) is around 15 mas for the southern hemisphere data, consistent with a 1σ formal error of each catalog in this magnitude range. The northern hemisphere data have an added rms component beyond 12th magnitude, which can be explained by the systematic differences as function of magnitude as shown in Figures 13 and 14. There are clear differences between the southern and northern hemisphere data; however, typical systematic UCAC2−UCAC3 position differences are only 5–15 mas for the entire 8–16 mag range.

Similarly Figures 15–18 display the UCAC2−UCAC3 position differences as function of right ascension and declination. The mean offset is dominated by the majority of the faint stars from the offset as function of magnitude (see Figures 13 and 14). In general, differences in the south are smaller than in the north. The parabola-shape differences for the R.A. component as function of R.A. in the north is surprising. There is also a saw-tooth pattern visible. These were likely introduced into UCAC3 through the use of SuperCOSMOS data propagating into the positions at epoch 2000 through proper motion errors.

The large saw-tooth pattern in the declination differences as function of decl. in the north (Figure 18, bottom panel) is similarly caused by the difference between the previous (UCAC2) Yellow-Sky (NPM based) and the UCAC3 SuperCOSMOS data, based on Schmidt plates. This is likely an effect inherent in the proper motion differences between the two sets of early epoch data for the faint stars. The UCAC sky survey in the declination range from 0° to 50° was undertaken between about 2000 and 2003, going north, thus with increasing epoch difference relative to the standard epoch of 2000.0, at which this position comparison is performed. This pattern is a combination of position errors and propagation from proper motion errors.

To understand this better, we look at the proper motion differences between UCAC2 and UCAC3 as shown in Figures 19 and 20 for the south and north, respectively. Averaging over all stars the mean magnitude is about 15.5, at which we see almost +5 mas yr^{-1} (UCAC2−UCAC3) proper motion difference in the R.A. component. The data at +50° declination were taken around 2003 and moved back by three years of proper motion to the comparison epoch 2000. Thus, the 5 mas yr^{-1} proper

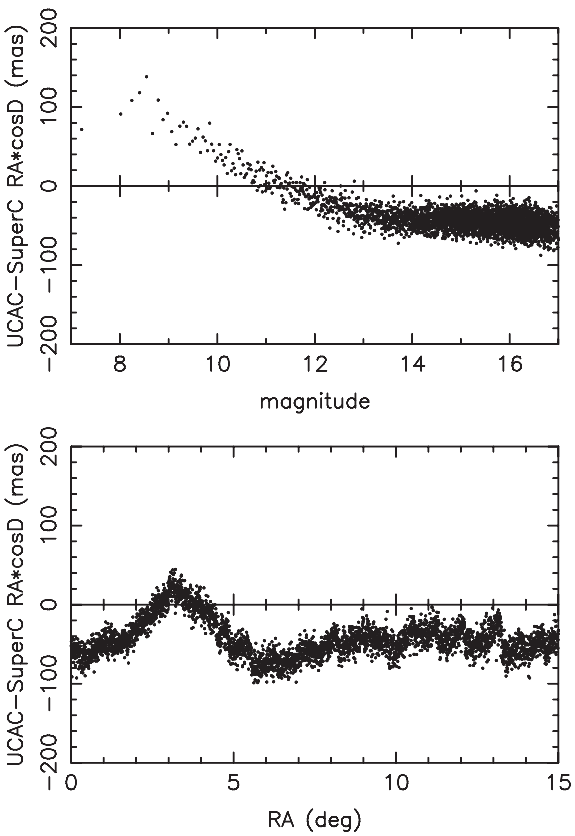

Figure 9. Position differences UCAC3−SuperCOSMOS at epoch of UCAC by applying SuperCOSMOS proper motions. These data are for a slice along all declinations for R.A. = 0–1 hr plotted as a function of UCAC3 model magnitude (top), R.A. and decl. Each dot represents the mean over 400 stars.

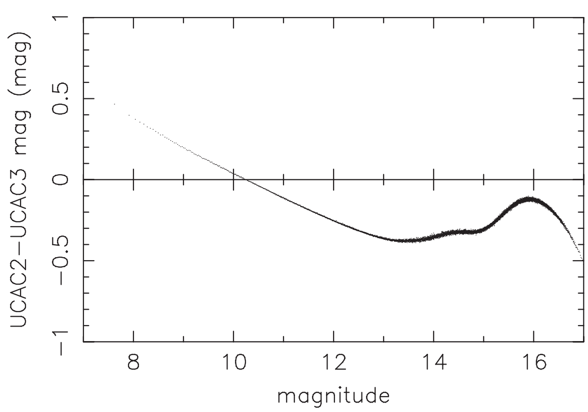

Figure 10. Magnitude differences UCAC2−UCAC3 (model fit) as function of UCAC3 magnitude. The data shown are for the northern hemisphere, the south looks very similar.

motion error results in a position offset of 15 mas with respect to data taken around 2000 (thus near the equator). This is close to what we are seeing in the R.A. difference plot of Figure 18 (top panel). Similarly, with opposite sign, Figure 20 suggests a -3 mas yr^{-1} difference in declination proper motion which translates into a position offset of +9 mas in the 2003 data. This is very similar to the average increase of the declination offset as seen in Figure 18 (bottom panel), which goes from about +6 to +15 mas over the 0° to +50° decl. range plus the modulation of the saw-tooth pattern added on top of this average trend.

The period of this saw-tooth pattern is very close to 5°. Both the NPM plate pattern as well as the second Palomar Observatory Schmidt Survey (POSS) adopted a 5° spacing between fields, while the first POSS adopted a 6° pattern. The SuperCOSMOS data used for UCAC3 are based on the POSS

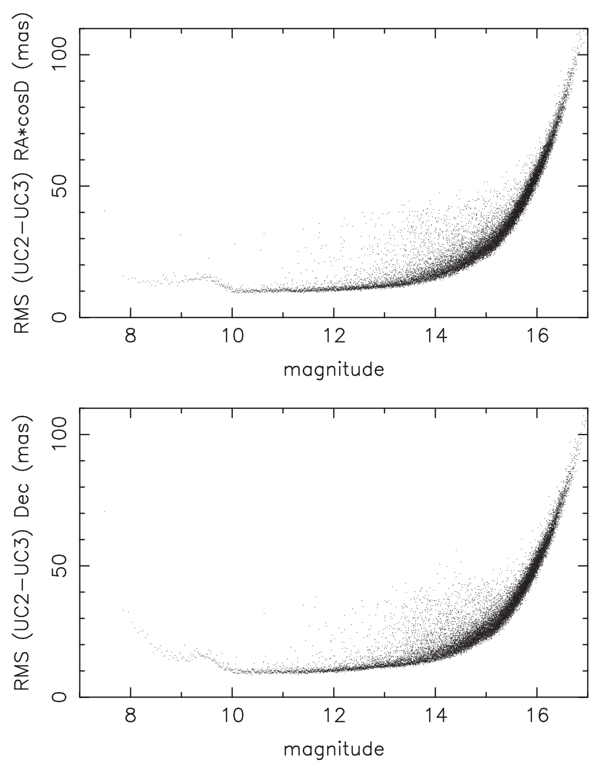

Figure 11. rms position differences UCAC2−UCAC3 at epoch 2000.0 for stars on the southern hemisphere. The upper diagram shows results for the R.A. component and the lower for decl.

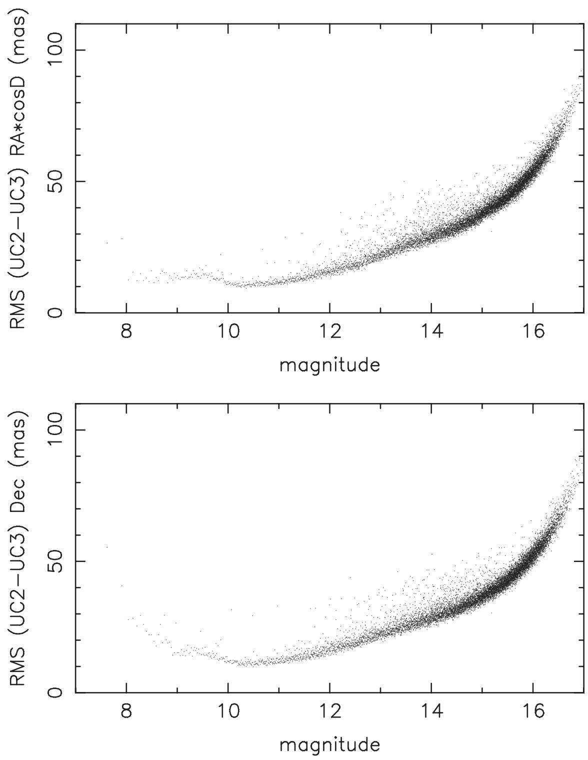

Figure 12. Similarly as the previous figure for the northern hemisphere.

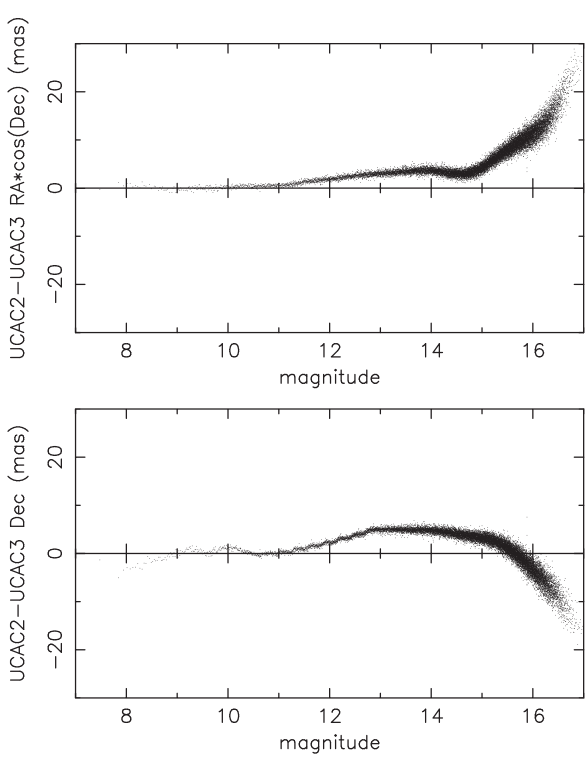

Figure 13. Position differences UCAC2−UCAC3 at epoch 2000.0 as function of magnitude for stars on the southern hemisphere.

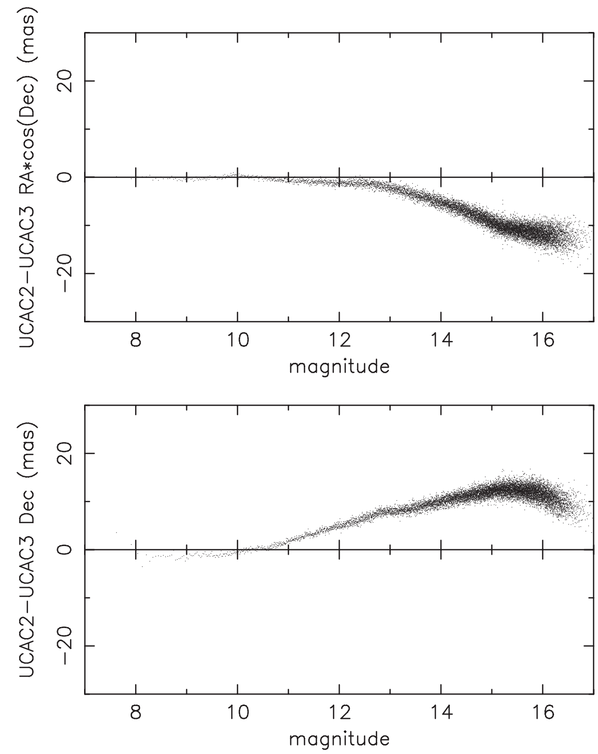

Figure 14. Similarly as the previous figure for the northern hemisphere.

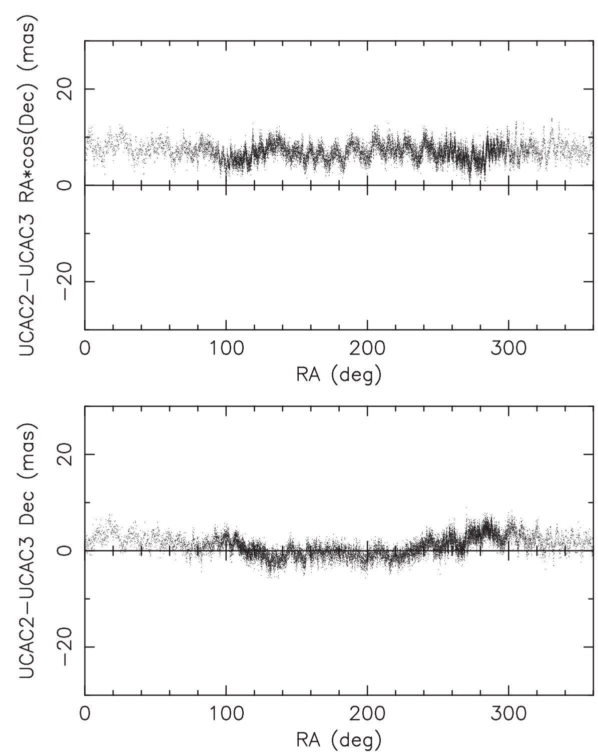

Figure 15. Position differences UCAC2−UCAC3 at epoch 2000.0 as function of right ascension for stars on the southern hemisphere.

plates, while the Yellow-Sky catalog which was used for proper motions of faint stars in UCAC2 in the northern sky is based on NPM plates. Looking only at the UCAC2−UCAC3 differences, it is not clear which data caused the saw-tooth pattern seen in Figure 17, i.e., whether this is a new problem in UCAC3 or something in UCAC2 has been fixed now.

6.3. SPM2

UCAC3 proper motions were compared with those from the SPM2 catalog (Girard et al. 1998). The SPM2 contains about 321,000 stars, individually selected and measured on the Yale University PDS machine. The plates cover a declination range of about −45 to −25°, span two epochs about 25 years apart,

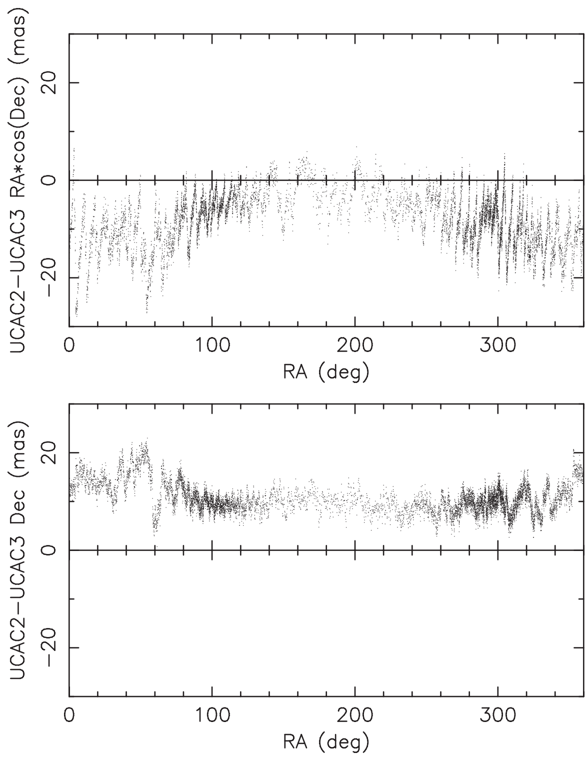

Figure 16. Similarly as the previous figure for the northern hemisphere.

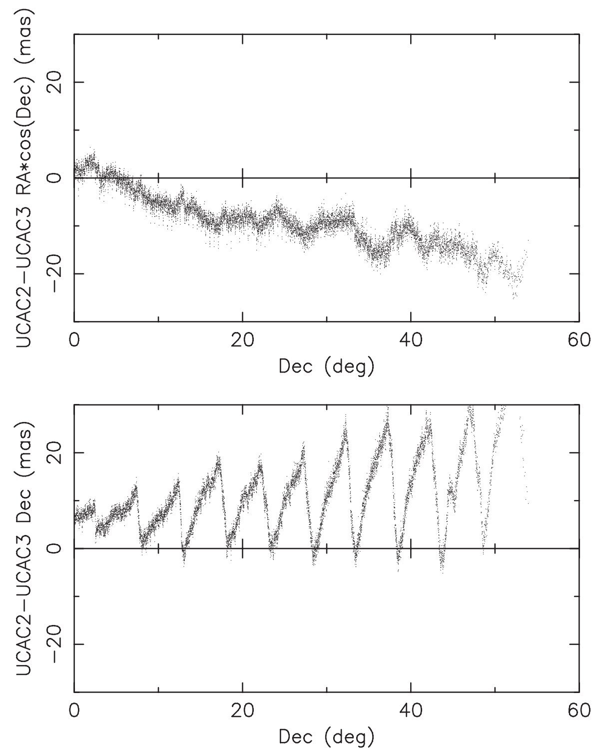

Figure 18. Similarly as the previous figure for the northern hemisphere.

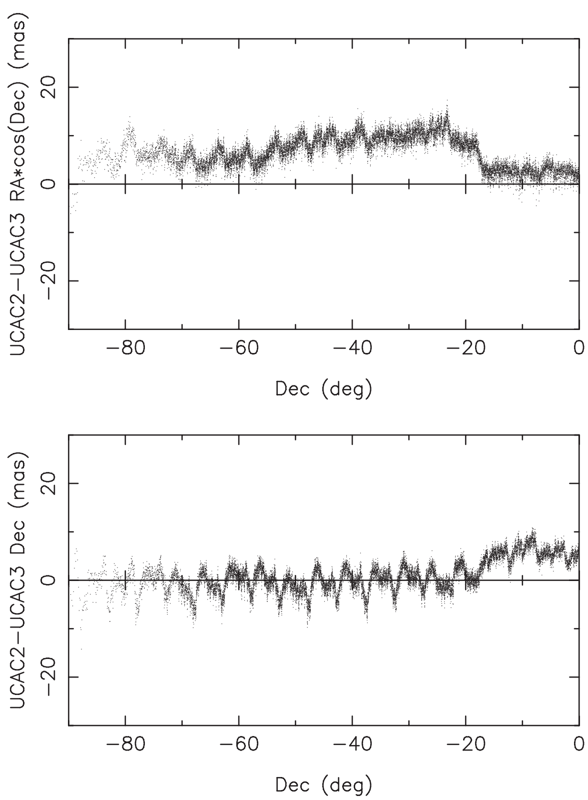

Figure 17. Position differences UCAC2−UCAC3 at epoch 2000.0 as function of declination for stars on the southern hemisphere.

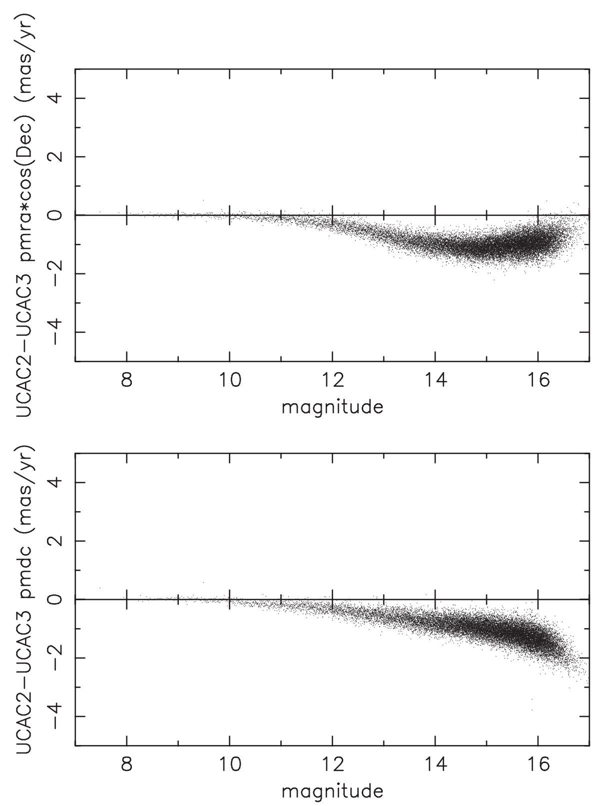

Figure 19. Proper motion differences UCAC2−UCAC3 as function of magnitude for stars on the southern hemisphere.

and reach a limiting magnitude near 18, deeper than UCAC. About 205,000 of the SPM2 stars were uniquely matched with UCAC3. The difference in proper motions (UCAC3−SPM2) for R.A. and decl. (Figures 21 and 22) show only small (about 1 mas yr^{-1}) systematic differences as a function of UCAC magnitude. Figure 23 displays the position differences UCAC3−SPM2 at the SPM2 epoch of 1991.25 by using the UCAC3 proper motions to bring the UCAC3 positions from 2000 to 1991.25. Similarly, Figure 24 shows the position differ-

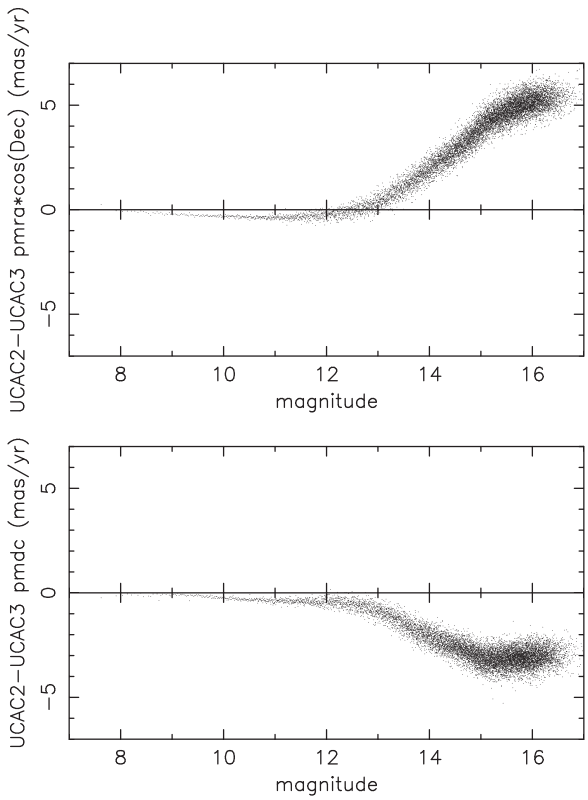

Figure 20. Similarly as the previous figure for the northern hemisphere.

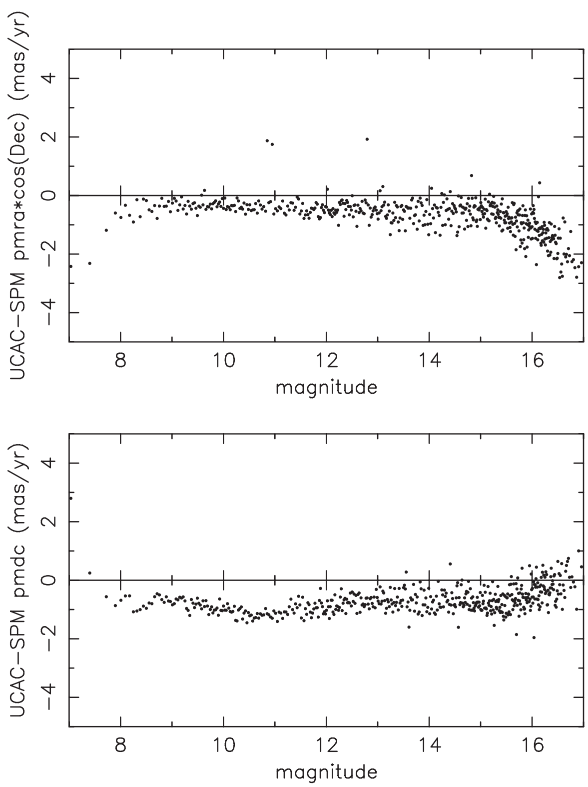

Figure 21. Proper motion differences UCAC3−SPM2. For this match of stars, the UCAC3 proper motions were used. Each dot is the mean over 400 stars.

ences at UCAC3 epoch of 2000 when applying SPM2 proper motions to SPM2 positions.

Because both data sets share the first epoch SPM positions, these plots show mainly the difference between the CCD

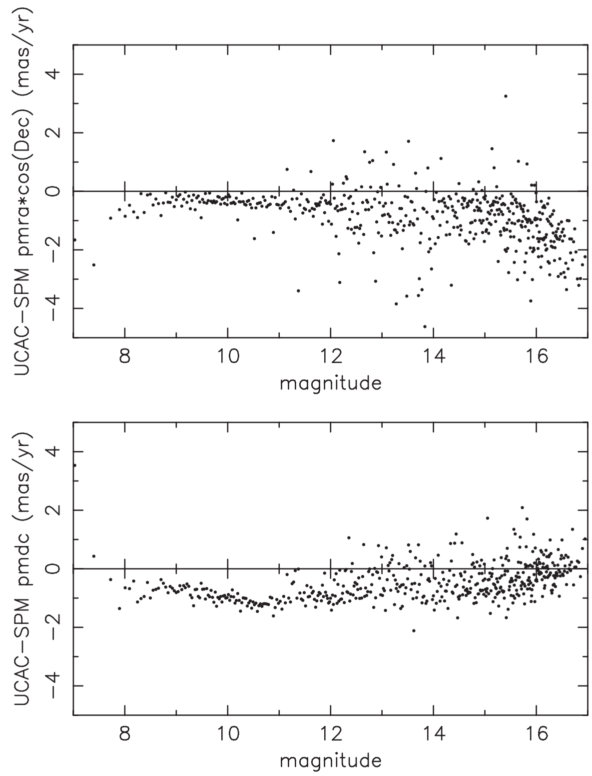

Figure 22. Proper motion differences UCAC3−SPM2. For this match of stars, the SPM2 proper motions were used. Each dot is the mean over 400 stars.

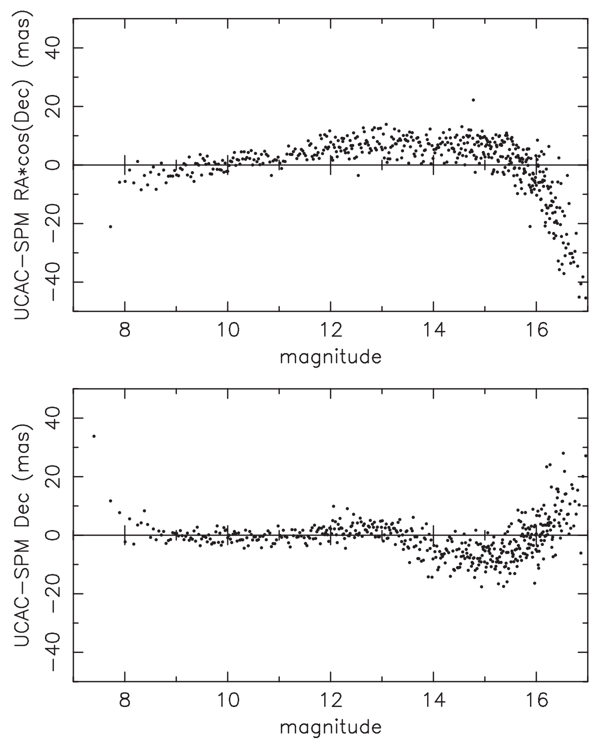

Figure 23. Position differences UCAC3−SPM2 at epoch of SPM2 (1991.25) by applying UCAC3 proper motions to the UCAC3 positions (originally at epoch 2000) as function of magnitude. Each dot is the mean over 400 stars.

observations of UCAC and the second epoch SPM observations. What we see is a mix between remaining systematic errors of UCAC3 and SPM2 which cannot be separated out at this point. However, these position differences are as small as can be hoped for, about 3–10 mas.

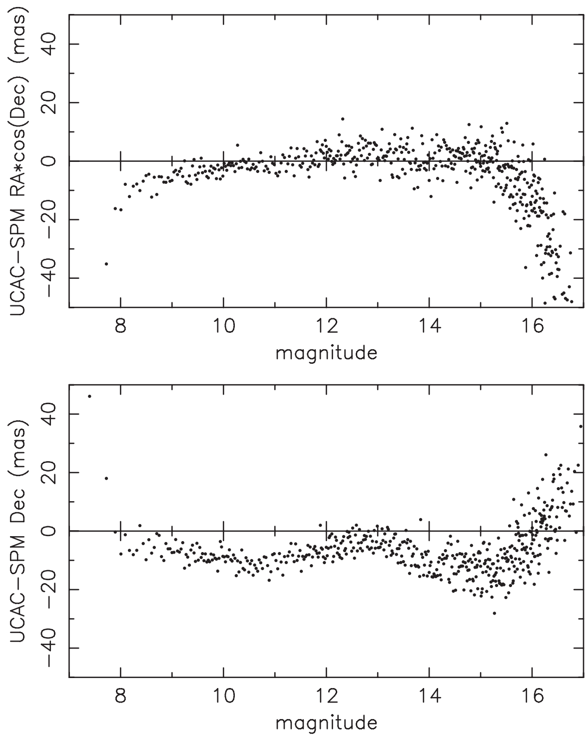

Figure 24. Position differences UCAC3−SPM2 at epoch of UCAC by applying SPM2 proper motions, as function of magnitude. Each dot is the mean over 400 stars.

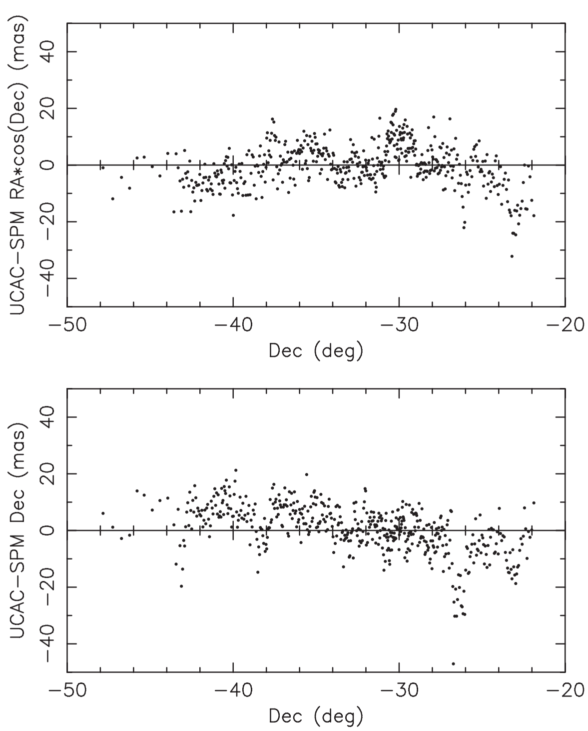

Figure 25. Position differences UCAC3−SPM2 at epoch of SPM2 (1991.25) by applying UCAC3 proper motions to the UCAC3 positions (originally at epoch 2000) as function of declination. Each dot is the mean over 400 stars.

Figures 25 and 26 similarly show the UCAC3−SPM2 position differences as a function of declination. Again, differences are small; however a saw-tooth pattern seems to be present in the declination differences. Again, the period seems to be close

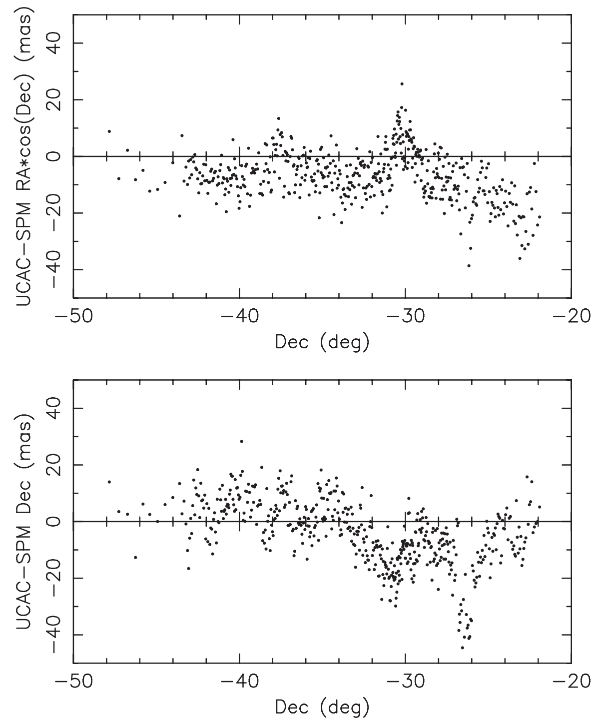

Figure 26. Position differences UCAC3−SPM2 at epoch of UCAC by applying SPM2 proper motions, as function of declination. Each dot is the mean over 400 stars.

to 5°, pointing to small residual systematic error contributions from the SPM2 data.

6.4. PM2000

The PM2000 catalog (Ducourant et al. 2006) was used in an external comparison with UCAC2 and UCAC3. The PM2000 covers the zone of about $9^{\circ}.5$–$18^{\circ}.5$ declination. Position differences are shown in Figure 27 for the epoch of 2000.0 which is very close (within about a year) of the CCD observations of UCAC. For the right ascension component, the PM2000 agrees with the UCAC2 better than with the UCAC3. The reverse is true for the declination component. All systematic differences are at or below the 10 mas level except for the R.A. component in the UCAC3−PM2000 comparison at 16th magnitude.

6.5. 2MASS

Figures 28 and 29 show position differences between UCAC3 and 2MASS as function of magnitude, for the southern and northern hemisphere, respectively. The UCAC3 proper motions are used to bring the UCAC3 positions to the 2MASS epoch (about 1998–2002) for each individual star matched uniquely. Figures 30 and 31 show the rms scatter of the corresponding data. The issue of concern here is the large position difference at the faint end for the southern hemisphere data.

For comparison, similar plots were generated using the UCAC2 data (Figures 32–35), which show clearly smaller differences than the comparison of UCAC3 with 2MASS. For both the UCAC2 and UCAC3 data sets versus 2MASS, the minimum rms scatter (70 mas) occurs at around 12th magnitude, thus with negligible error contribution from the UCAC data. However, at the fainter magnitudes, in the 14 to beyond 16 mag range, UCAC2 agrees with 2MASS significantly better than UCAC3 does.

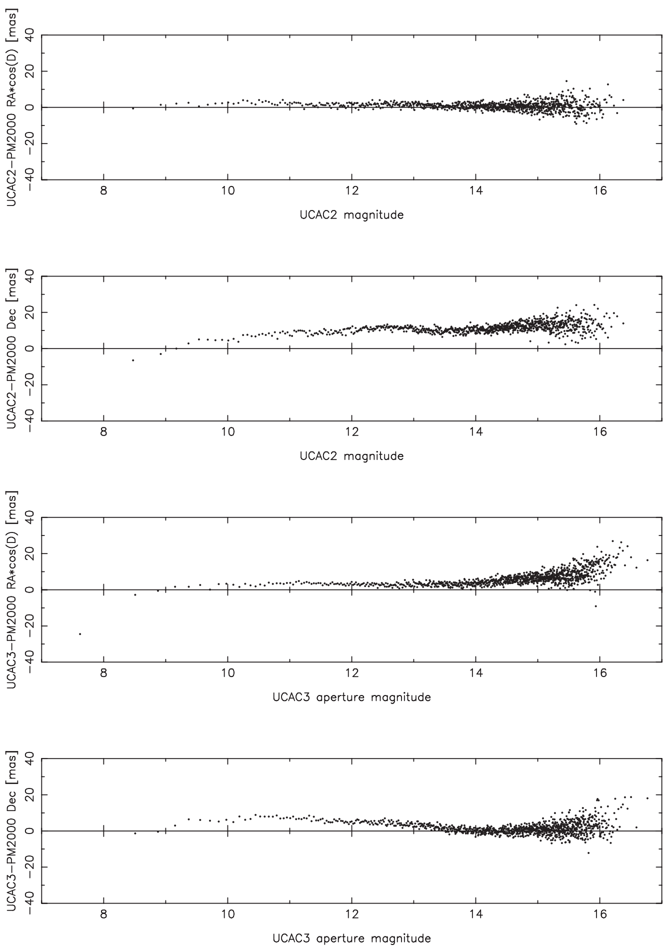

Figure 27. Position differences UCAC2−PM2000 (top panel) and UCAC3−PM2000 at epoch 2000.0 using PM2000 proper motions, as function of magnitude. These data cover about 9°.5–18°.5 declination zone. Each dot represents the mean over 2500 differences.

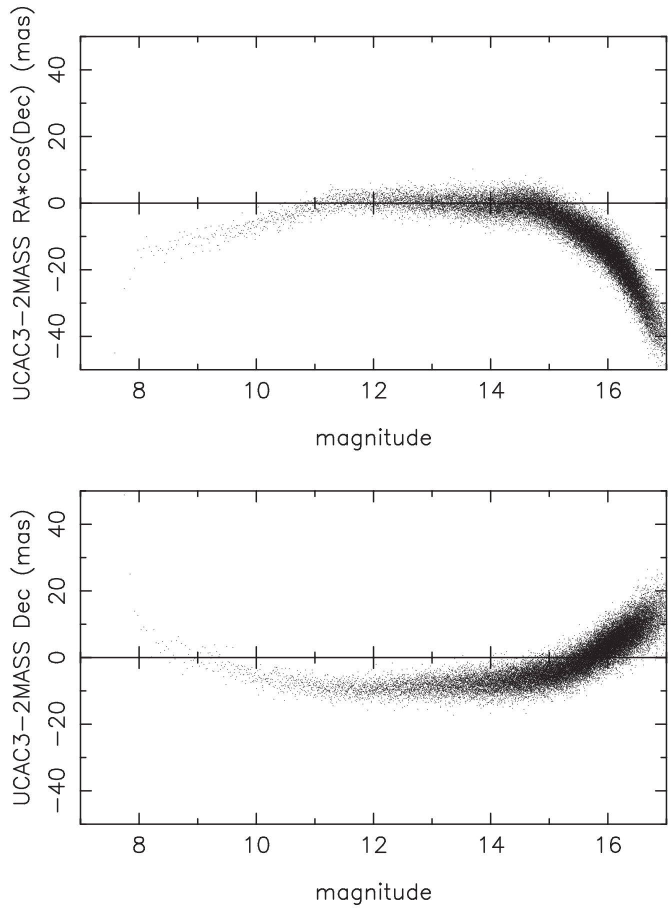

Figure 28. Position differences UCAC3−2MASS at the 2MASS epoch using UCAC3 proper motions, as function of magnitude. These data are for the southern hemisphere.

6.6. Other, External Checks

A sample of about 800 stars of the Small Magellanic Cloud were identified in UCAC2 and UCAC3. The mean proper motion was determined to be about +4.0 and −3.5 mas yr^{-1} for R.A. and decl., respectively (UCAC2), and +0.4, −2.5 mas yr^{-1} for UCAC3 (P. Massey 2009, private communication). The scatter in proper motion values was found to be comparable between UCAC2 and UCAC3.

7. THE CATALOG

The UCAC3 data files are organized in 0°.5 wide declination zones, numbered from 1 to 360 beginning at the South Celestial Pole. Within each zone, stars are sorted by ascending right ascension. Each 84 byte fixed length, binary record contains all the data for a star. The byte order is that of the native intel-type processor binary data format. For some computers, a byte-swap might be needed. Table 3 describes all data items for each star. Detailed remarks are given in the readme file which comes with every data distribution (DVD or online). Sample access code (in Fortran) is provided as well.

While the MPOS number (last column on each data record; MPOS stands for mean (CCD data) positions and is a running, unique, internal star number) mainly provides a means to identify known HPM stars, the primary star identification number should be of the form 3UCzzz-nnnnnn. The "3UC" is constant and indicates the UCAC3 catalog. The three digit "zzz" number is the zone the star is in, followed by a dash and a six digit number which is the record number of the star in that zone. Thus, the official designation of the star 42 in zone 7 would be 3UC007-000042.

Similar to UCAC2, UCAC3 is a compiled catalog giving the weighted mean position and proper motion of stars based on all input catalogs, including the CCD data.

UCAC3 does contain some non-stellar objects, mainly galaxies. There is no star/galaxy separation parameter based on pixel data in UCAC3. However, flags are provided which indicate matches with known non-stellar objects, from the 2MASS extended source catalog, the LEDA galaxy catalog, and non-stellar flags copied from the SuperCOSMOS and SPM data.

8. PROBLEMS AND WARNINGS

8.1. Overview

UCAC3 is not as "clean" as UCAC2. The goal here was to enhance the completeness of the catalog, showing every possible star on the sky detected within the accessible magnitude range. This could only be accomplished by allowing faint and uncertain objects to enter the catalog as well, resulting in an increased fraction of erroneous entries in UCAC3. Some specific problems are addressed below.

Users looking for reliable reference stars should check on some of the flags and auxiliary data entries. UCAC3 records without 2MASS match or without derived proper motion are

Table 3
Data Items for Each Star in UCAC3

Item	Label	Format[a]	Unit	Description	Remark
1	ra	I*4	mas	Right ascension at epoch J2000.0 (ICRS)	(1)
2	spd	I*4	mas	South pole distance epoch J2000.0 (ICRS)	(1)
3	im1	I*2	millimag	UCAC fit model magnitude	(2)
4	im2	I*2	millimag	UCAC aperture magnitude	(2)
5	sigmag	I*2	millimag	UCAC error on magnitude	(3)
6	objt	I*1		Object type	(4)
7	dsf	I*1		Double star flag	(5)
8	sigra	I*2	mas	s.e. at central epoch in R.A. (*cos decl.)	
9	sigdc	I*2	mas	s.e. at central epoch in decl.	
10	na1	I*1		Total numb. of CCD images of this star	
11	nu1	I*1		Numb. of CCD images used for this star	(6)
12	us1	I*1		Numb. of catalogs (epochs) used for proper motions	
13	cn1	I*1		Total numb. of catalogs (epochs) initial match	
14	cepra	I*2	0.01 yr	Central epoch for mean R.A., minus 1900	
15	cepdc	I*2	0.01 yr	Central epoch for mean decl., minus 1900	
16	pmrac	I*4	0.1 mas yr^{-1}	Proper motion in R.A. *cos(decl.)	
17	pmdc	I*4	0.1 mas yr^{-1}	Proper motion in decl.	
18	sigpmr	I*2	0.1 mas yr^{-1}	s.e. of pmR.A. * cos(decl.)	
19	sigpmd	I*2	0.1 mas yr^{-1}	s.e. of pmdecl.	
20	id2m	I*4		2MASS pts key star identifier	
21	jmag	I*2	millimag	2MASS *J* magnitude	
22	hmag	I*2	millimag	2MASS *H* magnitude	
23	kmag	I*2	millimag	2MASS *Ks* magnitude	
24	icqflg	I*1	(3 items)	2MASS cc.flg*10 + phot.qual.flag, *J*,*H*,*Ks*	(7)
25	e2mpho	I*1	(3 items)	2MASS error photom. (1/100 mag), *J*,*H*,*Ks*	(8)
26	smB	I*2	millimag	SuperCOSMOS (SC) Bmag	
27	smR2	I*2	millimag	SC R2mag	(9)
28	smI	I*2	millimag	SC Imag	
29	clbl	I*1		SC star/galaxy classif./quality flag	(10)
30	qfB	I*1		SC quality flag Bmag	(11)
31	qfR2	I*1		SC quality flag R2mag	(11)
32	qfI	I*1		SC quality flag Imag	(11)
33	catflg	I*1	(10 items)	mmf flag for 10 major catalogs matched	(12)
34	g1	I*1		Yale SPM object type (g-flag)	(13)
35	c1	I*1		Yale SPM input cat. (c-flag)	(14)
36	leda	I*1		LEDA galaxy match flag	(15)
37	x2m	I*1		2MASS extend.source flag	(16)
38	rn	I*4		MPOS star number; identifies high PM stars	(17)

Notes. The extensive remarks are given in the readme file of UCAC3.
[a] I means integer, followed by the number of bytes.

questionable. Overexposed and problem stars do have some images from the CCD data excluded, up to excluding all images, when the derived position is entirely based on an unweighted mean of all available detections (center of light). Those stars certainly should be excluded from use as reference stars, as should all those with an internal position error exceeding some limit set by the user.

8.2. Erroneous Close Doubles

Due to a processing error, some stars appear twice in UCAC3 with very similar positions (typically 0–200 mas separation). This can happen for single stars (dsf flag = 0) or components of true doubles, making them appear to be quadruple stars. A total of 771,018 such erroneous pairs were identified among the single stars with separation up to 2 arcsec, which would have to have dsf $\geqslant$ 1 if they were real doubles. This is about 0.8 % of the UCAC3 entries. However, a simple exclusion of objects without 2MASS identification gets rid of these false close components, leaving a single, valid star. This criterion alone removes over 99.4% of the problem cases, and might be advisable in general. A total of about 2.65 million objects in UCAC3 have no 2MASS identification, and some 0.77 million of those belong to this single problem group alone.

8.3. Bright Star Problems

The adopted algorithm to detect and characterize double stars from the UCAC pixel data erred on the side of completeness. It did also pick up spurious noise near some bright stars as "new components." A simple relationship was found (see also an upcoming paper by B. Mason et al. 2010, in preparation) to exclude those. All objects with separations of less than 7 arcsec and combined magnitudes (sum of two components) of less than 18 are likely false. UCAC3 doubles in the remaining parameter space showed a very high degree of confirmation with the USNO speckle camera at the 26 inch telescope. This test was limited by the capabilities of the instrument, reaching to about 12th magnitude for the secondary star.

In general, the long exposures of UCAC saturate around magnitude 10, while the short exposures saturate at about magnitude 8. Thus, for stars in the 8–10 mag range only two

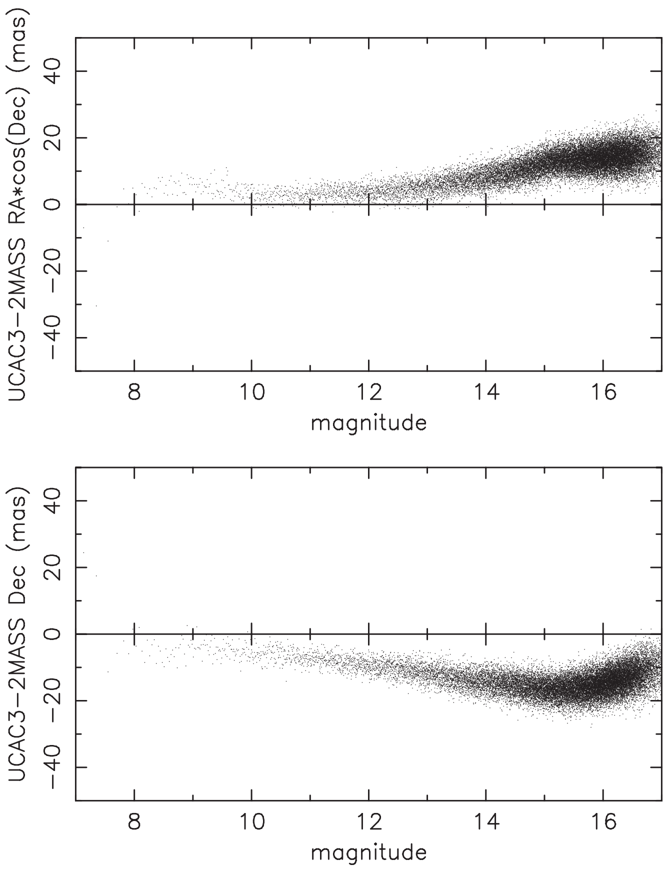

Figure 29. Similar to the previous figure but for the northern hemisphere.

observations are available from the regular overlap pattern of observed fields. Stars brighter than 8th magnitude generally have no fitted position at all but are kept in UCAC3 when detected and a center-of-light approximate position is available. One should inspect the *nu1* value, giving the number of images from CCD data used for the mean position. If it is zero, the position given in UCAC3 is only very approximate and can be off by arcseconds.

Stars of about magnitude 6 and brighter are likely not in UCAC3 at all. An updated version of the NOMAD catalog of all stars to about 20th magnitude including all naked-eye stars is in preparation as part of the UCAC4 effort.

8.4. Missing Stars

A detailed comparison of UCAC3 with UCAC2 revealed close to a million stars missing from UCAC3 which are in the UCAC2 release. A match of those objects with 2MASS and the CMC14 catalog (Copenhagen Univ., IoA & RIOA 2006) shows that at least 99% of these seem to be legitimate stars (G. Harald & J. Greaves 2009, private communication). The magnitude distribution of these stars follow the general distribution for UCAC3, indicating a "random" effect. These stars are also distributed all over the sky with clustering along the galactic plane, roughly following the general distribution of stars. Most of these stars are no "problem" candidates and the reason for them not being in UCAC3 is not known at this point; however, a correlation to the processing error which resulted in double entries (see above) is suspected. UCAC3 is a completely new reduction independent of what has been detected and processed in the UCAC2 pipeline reductions.

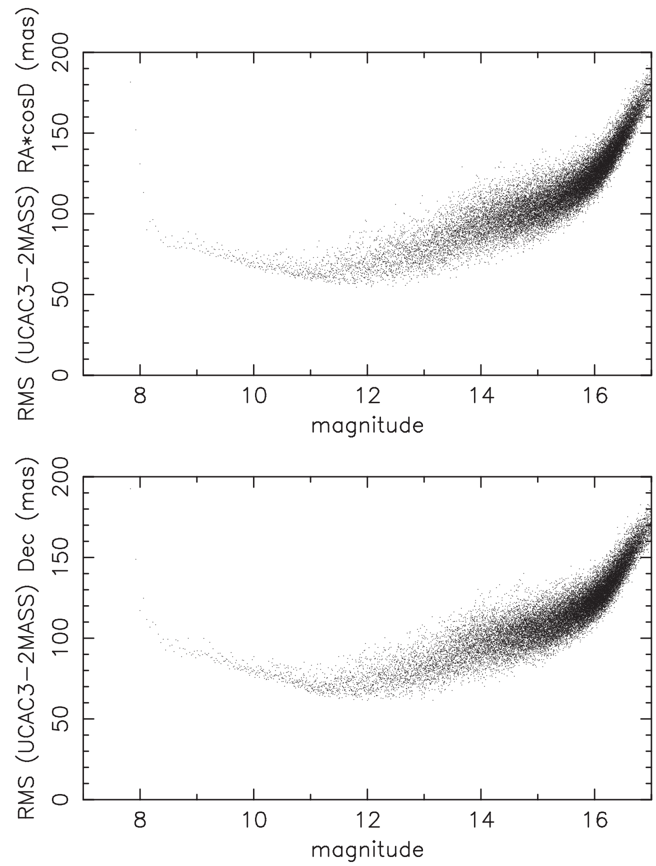

Figure 30. rms position differences UCAC3−2MASS at the 2MASS epoch using UCAC3 proper motions, as function of magnitude. These data are for the southern hemisphere.

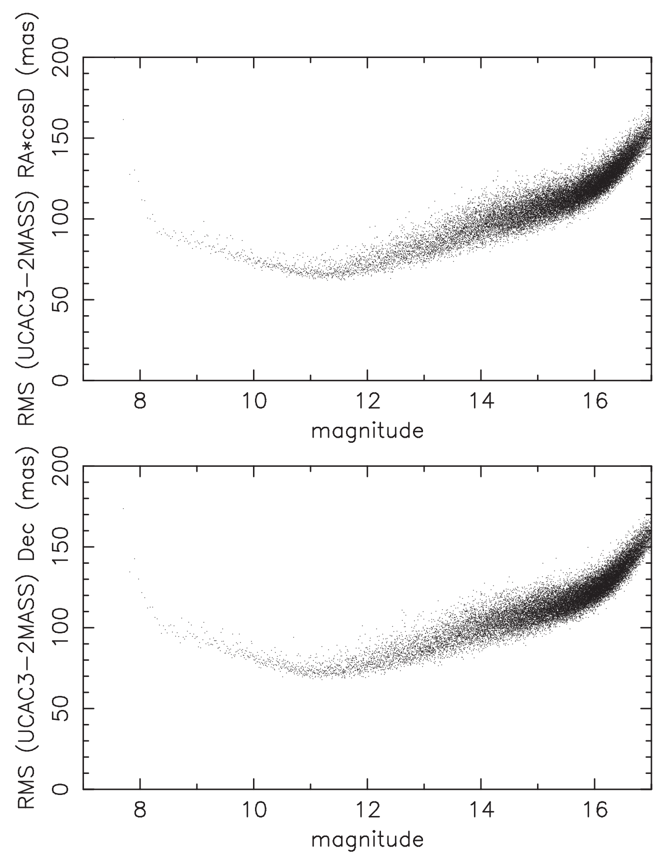

Figure 31. Similar to the previous figure but for the northern hemisphere.

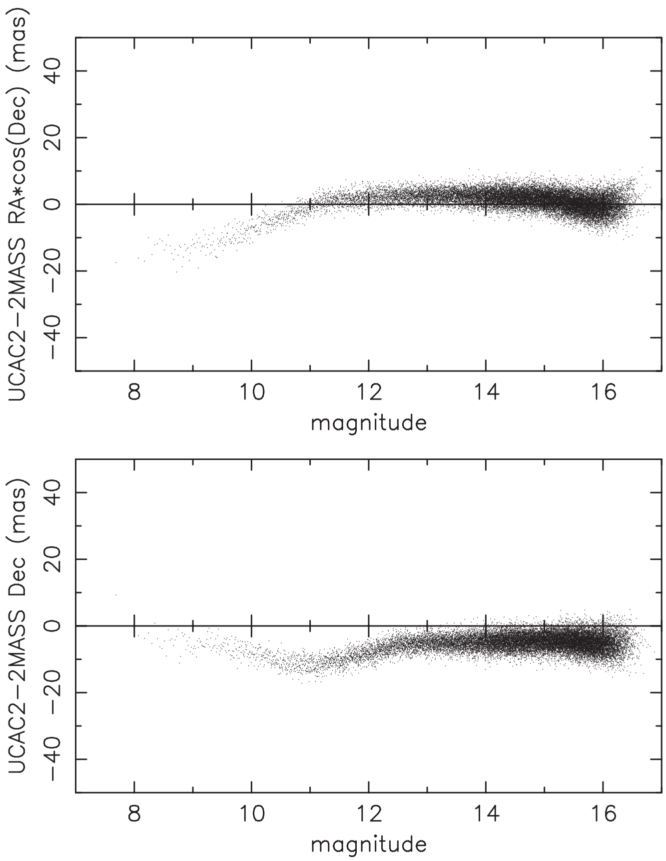

Figure 32. Position differences UCAC2−2MASS at the 2MASS epoch using UCAC2 proper motions, as function of magnitude. These data are for the southern hemisphere.

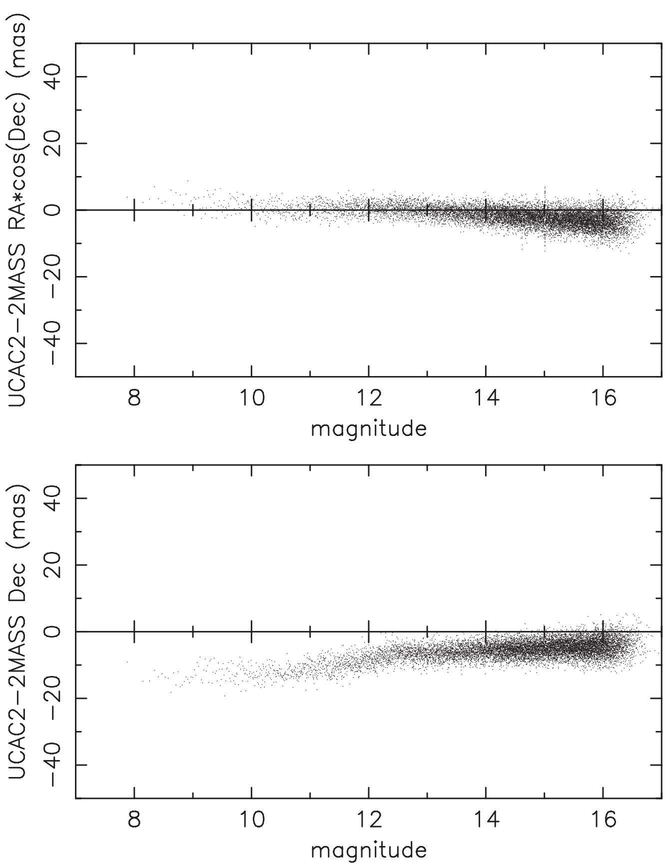

Figure 33. Similar to the previous figure but for the northern hemisphere.

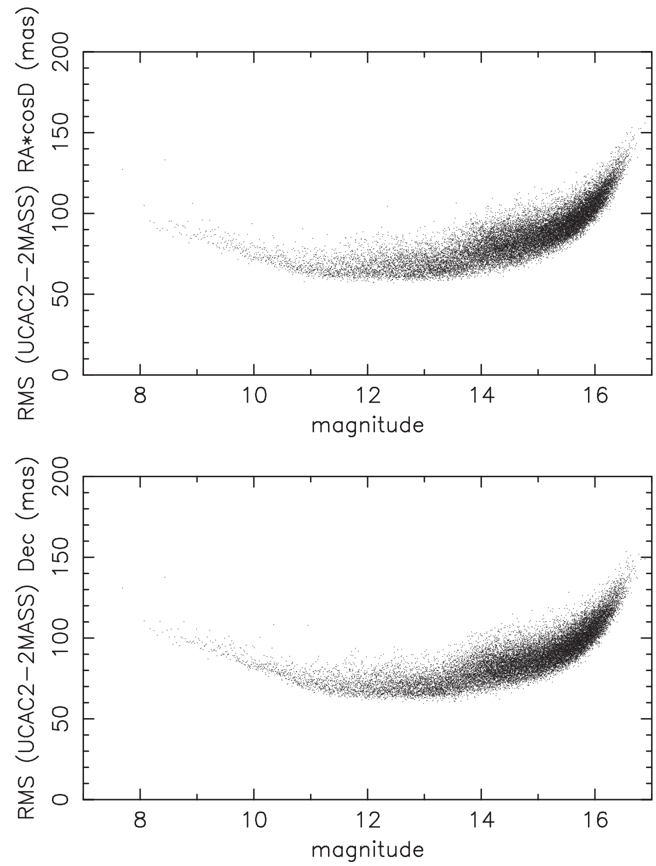

Figure 34. rms position differences UCAC2−2MASS at the 2MASS epoch using UCAC2 proper motions, as function of magnitude. These data are for the southern hemisphere.

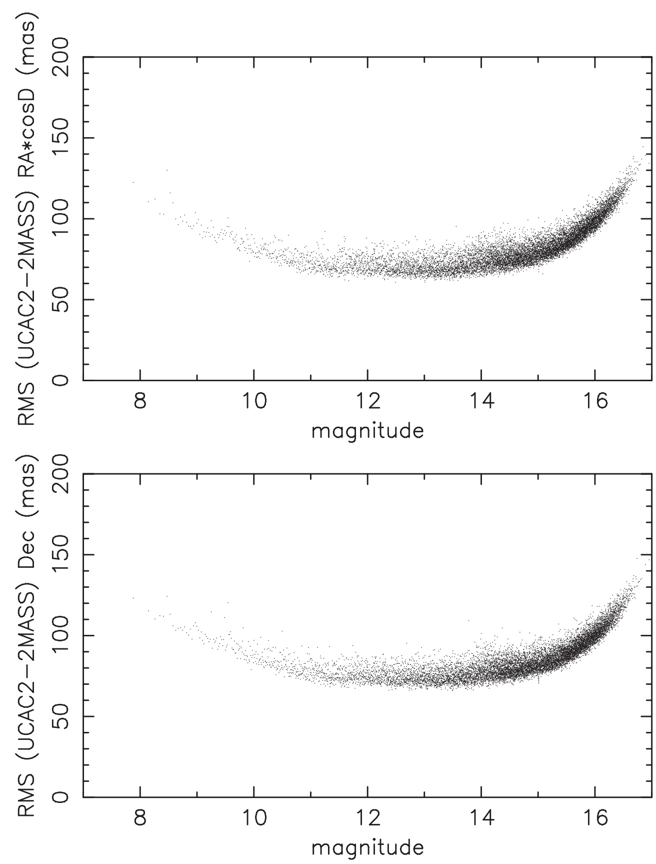

Figure 35. Similar to the previous figure but for the northern hemisphere.

8.5. Bogus Proper Motions

Some proper motions will be bogus due to an incorrect match of stars between two and more catalogs, sometimes spanning several decades. This is particularly a problem for the faint stars, which rely sometimes on only two catalog positions, the CCD observation at UCAC epoch and one other, deep catalog at a much earlier epoch. Fortunately, for both large catalogs (SPM and SuperCOSMOS), we have proper motions available which were applied to bring the positions of individual stars to the mean UCAC epoch before matching. Nevertheless, some objects are expected to be mismatched and the resulting bogus proper motions could be large, contaminating any legitimate new HPM stars in UCAC3. This was found to be the case when checking a large sample of such stars with real sky images (Finch et al. 2010).

8.6. Systematic Errors in Proper Motions

The above detailed catalog comparisons reveal a possible problem with UCAC3 proper motions at the faint end. Due to the sole use of Schmidt plate data for proper motions of faint stars in the north, and the large systematic differences of UCAC3 with respect to 2MASS for faint stars in the south, we recommend using stars of about 16th magnitude and fainter in UCAC3 with caution. If possible, they should be avoided as reference stars.

9. DISCUSSIONS AND CONCLUSIONS

UCAC3 is the first all-sky catalog of this series. From the details presented above, it appears that the systematic errors of the CCD observations for UCAC3 are corrected even better than they were in UCAC2 (see, for example, the CTIO/NOFS overlap area, the comparison with SPM2 and PM2000). The magnitude dependent systematic errors seem to be well controlled, with the exception of the very faint end of UCAC3 (around 16th mag and fainter). Comparing Figures 13, 24, 28, and 32, suggests a systematic error in UCAC3 positions (both coordinates) as a function of magnitude for stars around magnitude 16. UCAC2, SPM2, and 2MASS agree, while differences of any of these catalogs with UCAC3 show some systematic deviations.

The use of Schmidt Survey data likely caused a problem for the proper motions of faint stars ($R \geqslant 14$), even partly affecting the area covered by the new reductions of the SPM data, and particularly affecting the northern hemisphere. Although the formal errors in proper motions significantly dropped for a large number of stars as compared to UCAC2, systematic errors as function of location on Schmidt plates crept into the UCAC3 catalog, increasing the scatter when compared, for example, with the 2MASS catalog.

A significant improvement of the photometry in UCAC3 was achieved, which is handled properly for the first time. The complete re-reduction of the pixel data also extended the limiting magnitude, providing more and fainter stars in UCAC3 than in earlier releases.

At the bright end, the residuals of the Tycho-2 reference stars show some remaining magnitude equations. If we assume the internal calibrations of the UCAC3 CCD observations (utilizing the East/West flip data) are correct, this indicates magnitude equations in the Tycho-2 catalog itself of about 1–2 mas mag^{-1}. Assuming the *Tycho* space-based observations are free of such errors, this indicates uncorrected errors in the order of 100–200 mas in the Astrographic Catalog (AC) whose average epoch is around 1900. The AC (Urban et al. 2001) is the major ground-based catalog used to obtain the Tycho-2 proper motions.

The major remaining steps to be taken to conclude this project are (1) utilize overlap conditions of the regular two-fold center-in-corner pattern of fields observed with the CCD astrograph to reduce coordinate dependent errors introduced by the reference stars, (2) include re-reductions of the NPM data for proper motions in the north, eliminating the need to resort to Schmidt plate data, (3) check on the extragalactic link by employing the dedicated observations in ICRF fields and their corresponding deep CCD imaging with larger telescopes, and (4) fix above mentioned problems. These are the goals for UCAC4.

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