1. INTRODUCTION

The fourth United States Naval Observatory (USNO) CCD Astrograph Catalog, UCAC4, is an all-sky, astrometric catalog of 113,780,093 objects complete to about magnitude 16 (Figure 1) in the instrumental system, which is close to R magnitudes. It contains accurate positions and proper motions (PMs) on the International Celestial Reference System (ICRS) at a mean epoch around 2000, observed magnitudes, Two Micron All-Sky Survey (2MASS) magnitudes for about 110 million stars, and AA VSO Photometric All-Sky Survey (APASS) five-band (B, V, g, r, i) APASS data for over 51 million stars. The published UCAC4 data are a compiled catalog of positions and PMs, based on final reductions of the UCAC observational catalog of positions and many other astrometric catalogs.

The 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). A 4k by 4k CCD with 9 μm pixel size was used at the “red lens” of the astrograph in a single bandpass (579–643 nm) with just over 1 deg^2 field of view. 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.

UCAC4 is an incremental update of the large amount of work performed earlier to arrive at the UCAC1 Zacharias et al. (2000), UCAC2 (Zacharias et al. 2004), and UCAC3 (Zacharias et al. 2010) data releases. The positional precision of the CCD observations and the mean UCAC4 catalog positions are very similar to those of UCAC3; see statistics presented in Zacharias et al. (2010). The most significant improvement of UCAC4 over UCAC3 is the lower level of systematic errors in the PMs north of the Southern Proper Motion (SPM) area (δ > −20'). All-sky color plots of PMs and number of stars per sky area are provided on the UCAC4 release DVD. Table 1 gives some general statistics about UCAC4 data (see also the “readme” file of the public release).

As with UCAC3, the UCAC4 release 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. The released UCAC4 is a compiled catalog, similar to UCAC3, and UCAC2. However, we plan to make individual epoch CCD observations available in the future if desired by the community (please contact lead author). Separate papers about new double stars found in the UCAC observational catalog and the extragalactic link to International Celestial Reference Frame (ICRF) quasars are in preparation.

2. UCAC4 VERSUS UCAC3

The main differences between UCAC4 and UCAC3 data are the following.
Figure 1. Histogram of UCAC4 model magnitude distribution. The slight discontinuity near magnitude 9 is likely caused by the saturation limit of the long exposure.

Bug fixes: add missing stars, remove multiple entries, apply magnitude equation (CTE) corrections properly for all exposure times.

NPM data: are used to derive PMs of faint stars north of about $-20^\circ$ declination; discontinue use of Schmidt plate data.

Systematic error corrections: a final tweak of the magnitude equation corrections of the CCD data brings the positional system of UCAC4 closer to the UCAC2 system.

High proper motion stars: were identified in the UCAC observational catalog and those positions used for UCAC4.

APASS: DR6 photometry in the B, V, g, r, and i bands added.

Photometric calibrations: APASS data are used to calibrate instrumental UCAC magnitudes over the entire dynamic range.

Photometric bias: as a function of CCD x-coordinate removed.

Bright stars: added from FK6, Hipparcos, and Tycho-2 catalogs.

Hipparcos star numbers: are linked to UCAC4 data which allow easy inclusion of Hipparcos catalog data such as parallaxes.

Cross reference: to Tycho-2 and UCAC2 star catalog numbers added.

3. CCD DATA AND PROCESSING

UCAC4 is based on the same pixel reduction as UCAC3 (Zacharias 2010) and the same astrometric reduction pipeline from x, y data to $\alpha$, $\delta$ of individual observations (Finch et al. 2010b) was used, except for bug fixes, a minor update of the magnitude equation correction, and adopting a lower threshold to include more single observations of faint stars.

3.1. Positions

Positions in UCAC4 are on the 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, utilizing the 2MASS data (Skrutskie et al. 2006) and east–west flip observations as described in Finch et al. (2010b).

Instead of the bin-by-bin corrections for the poor charge-transfer efficiency (CTE) effect on positions as used for UCAC3, a smooth function with magnitude was adopted for the UCAC4 reductions using the same calibration data (based on 2MASS) as before. CTE corrections for the 200 and 40 s exposures (mainly used for the extragalactic link program) as well as for 5 and 10 s exposures were not applied correctly for UCAC3. This bug has been fixed for UCAC4, affecting only few CCD frames. Overall the astrometric accuracy of UCAC4 observational positions has not changed significantly from the UCAC3 release.

3.2. Completeness

The missing stars and multiple entries of some stars in UCAC3 were traced back to a bug in the merge stage of individual observations to mean CCD-based positions. This problem was corrected and a limit of 2.0 arcsec was imposed to combine images to a single star. This change lead to more stars with a blended image flag in UCAC4 than before; however, it avoids listing unrealistic close, “resolved” companions of unreal double stars. After checking sample double stars discovered in UCAC data with the 26 inch speckle camera, potentially new real double stars were identified in UCAC4 and will be published separately.

For UCAC4, an even lower threshold was adopted for faint observed images to enter intermediate star lists, including objects with positions based on center-of-mass centroid instead of a successful image profile fit. However, these objects entered the UCAC4 catalog only if either a match with at least another observation existed, or a 2MASS match could be established, or a reasonable PM could be obtained by matches with early epoch data. Whenever no formal position error from the CCD data of a star could be derived (no successful image profile center fit, for whatever reason) the positional error was set to 900 mas (1 pixel), which leads to early mean epochs and large PM errors when combined with other catalogs to arrive at the UCAC4 compiled catalog data. This approach allowed the completeness level of the UCAC4 catalog to be pushed to a new high with an estimated 110 million real stars (and about 92,000 galaxies), but also allowed some artifacts to enter UCAC4, estimated to be on the few percent level, particularly near bright, overexposed stars.

As with UCAC3, overexposed stars were propagated in the catalog production pipeline for reasons of completeness. For those stars, and other problematic images, the image center fit often failed, which is indicated in the catalog by the number of “used images” being zero. In these cases no fit position could be obtained, instead the provided position is only approximate, based on the centroid (first moments) of the light distribution.

| Number of Stars | Description |
|-----------------|-------------|
| 113,780,093     | Total number of entries (mostly stars) in UCAC4 |
| 109,921,682     | With 2MASS identification |
| 106,689,821     | With proper motions |
| 81,897,551      | With two epoch proper motions |
| 27,245,403      | With three or more epoch proper motions |
| 80,806,744      | With two or more images from “good fit” CCD obs. |
| 48,323,349      | Matched with UCAC2 |
| 54,690          | Matched with LEDA galaxies |
| 76,020          | Matched with 2MASS extended source catalog |
| 8,925           | Supplemented stars (no CCD observation) |
| 121,350         | With a matched Hipparcos star ID |
| 104,681         | With astrometry substituted by FK6/Hip/Tycho-2 |

Table 1 General Statistics of UCAC4 Catalog Entries
in the pixel data. Contrary to UCAC3, all stars brighter than observed magnitude 8.5 in UCAC4 were compared to external catalogs and astrometric data from these were substituted when deemed more reliable than UCAC observations (see Section 6.2).

### 3.3. Photometry

As with UCAC3, UCAC4 gives two observed magnitude estimates, based on the volume of the image profile model fitted, and a true aperture photometry. 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.

Early APASS DR2 data of 9 million stars distributed all over the sky were used for photometric calibrations of UCAC-observed CCD magnitudes. Contrary to previous releases, a photometric bias as a function of the pixel $x$-coordinate was removed in the instrumental magnitudes before constructing the UCAC4 catalog. This bias is caused by the poor CTE performance of the detector and affects the model and aperture magnitudes similarly, but not identically. The bias is also a function of magnitude and slightly depends on exposure time. Figure 2 shows examples for two ranges in brightness. A linear model was adopted to correct for this bias with respect to the center of the CCD field. Different slope parameters as a function of $x$-pixel coordinate were applied for NOFS and CTIO data, as well as for long and short exposures and binned by magnitude group. Linear interpolation by magnitude was adopted for applying corrections. The largest effect of this bias is about ±0.2 mag.

The following procedure was performed separately for UCAC4 aperture and model magnitudes to correct for the non-linearity of the UCAC instrumental magnitudes. A preliminary UCAC magnitude was calculated after applying the $x$-pixel bias correction and using Tycho-2 stars for the photometric zero point. This UCAC preliminary magnitude was then compared to the APASS $r$ magnitude and magnitude differences plotted as a function of APASS $(V - r)$ (see Figure 3). This color–color diagram was fitted with linear and second-order polynomials in sections to allow calculation of an estimated UCAC-bandpass magnitude when only APASS $V$ and $r$ are given. Very blue $(V - r \leq -0.1)$ and very red $(V - r \geq 1.0)$ stars were excluded in this process. The differences between UCAC4 observed and UCAC-bandpass estimated magnitudes (from APASS $V, r$) as a function of UCAC observed magnitude (Figure 4) give the desired corrections to the preliminary UCAC magnitudes to make them linear with respect to the APASS photometric system. A zero-point offset is included in these corrections to force the resulting UCAC–APASS($r$) color to be zero for $(V - r) = 0$.

As noted in earlier releases, the largest deviations of the UCAC magnitude scale are seen at bright magnitudes near saturation, requiring a correction on the order of 0.5 mag. The faint end needed a correction of about 0.3 mag. For UCAC4, the use of the APASS data allowed these magnitude scale and offset corrections to be determined much more accurately and reliably than in earlier releases.

Finally, the corrected UCAC magnitudes were run through the Tycho-2 zero-point routine again to arrive at the calibrated magnitudes of individual CCD frames. Combining individual CCD frame photometry to mean catalog magnitudes and calculating error estimates were performed in the same way as for UCAC3 (Zacharias et al. 2010). Remaining systematic errors in UCAC4 observed magnitudes are estimated to be about 0.05–0.1 mag, because many UCAC observations were performed under non-photometric sky conditions, and the imperfection of the applied corrections. The latter is most pronounced around magnitude 9 as for example can be seen as the slight discontinuity in the Figure 1 histogram. This is a magnitude calibration issue and not a missing star issue.
4. PROPER MOTIONS

The UCAC4 catalog heavily relies on the AC2000.2 Astrometric Catalogue (Urban et al. 2000), unpublished data from over 5000 astrograph plates measured with the StarScan machine (Zacharias et al. 2008), the NPM (Klemola et al. 1987; Hanson et al. 2004), and the SPM (Girard et al. 1998, 2011) data. All procedures to derive the UCAC4 PMs remained the same as for earlier releases, see for example the UCAC1 paper (Zacharias et al. 2000). Most of the early epoch catalog used to derive UCAC4 PMs also remain the same as for UCAC3. However, Lick Observatory Northern Proper Motion (NPM) first epoch data (Lick1 catalog) were used for UCAC4, and field zero-point corrections for the Yale–San Juan SPM first epoch data (YSJ1 catalog) were applied. Both sets of plates were digitized at the Precision Measure Machine (PMM; Monet & Levine 2001) at NOFS, with subsequent data reductions as a joined effort by Yale University and USNO, Washington (Zacharias et al. 2010). Thus, for UCAC4, no Schmidt survey plate data were used at all, which lead to a significant improvement in the UCAC PMs north of the SPM sky area ($\delta \geq -20^\circ$).

As with UCAC3, only the first epoch, blue SPM plate material was utilized for UCAC4 PMs of faint stars in the south. In the meantime, the Yale astrometry group completed their reductions and derived a catalog of positions and absolute PMs based on early and recent epoch SPM project observations, the SPM4, (Girard et al. 2011) utilizing galaxies to establish the PM zero point. Due to the common first epoch data, even with differences in the reduction algorithms, the SPM4 and UCAC4 PMs will be correlated. Table 2 provides statistics about matches of UCAC4 stars with other catalogs as used to derive PMs.

4.1. NPM Data

All applicable Lick Observatory NPM first epoch plates (blue sensitive emulsion) were used to construct a star catalog with mean epoch near 1950 covering the about $-25^\circ \leq \delta \leq +90^\circ$ area of sky. These were among the earliest plates scanned on PMM and no pixel data could be saved at the time. The provided data were the $x, y$ pixel locations of stellar images measured on individual PMM CCD “footprints” with the PMM pipeline mapping parameters already applied.

In order to be able to run these data through the StarScan (Zacharias et al. 2008) pipeline, the previously applied PMM modeling was removed to obtain raw $x, y$ pixel centroid data. The StarScan pipeline then generated new, global $x, y$ data on the coordinate system of a plate using improved modeling.

The global $x, y$ data then was sent to the Yale astrometry group for further astrometric reductions to obtain $\alpha, \delta$ coordinates on the sky, applying elaborate systematic error corrections by utilizing the various orders of grating images and two sets of exposures in each field. These procedures follow closely the reduction process of the SPM plates (Girard et al. 2011), with some modifications due to differences in magnitude overlaps of grating images between SPM and NPM data. The resulting, unpublished catalog “Lick1” of over 168 million stars and galaxies was sent to USNO, Washington, to provide the early epoch positions of faint stars for UCAC4 PMs.

4.2. SPM and NPM Corrections

Despite the great care taken to control systematic errors as a function of magnitude and $x, y$ location, residual magnitude equations remain in the NPM and SPM first epoch data, the Lick1 and YSJ1 catalogs. First, the field-dependent systematic errors were corrected, then the overall zero point of the PMs per NPM and SPM field. All UCAC stars with preliminary PMs were associated with the nearest field centers of NPM and SPM plates. A tangential plane projection then provides the $x, y$ location of UCAC stars on NPM and SPM plates.

4.2.1. Field-dependent Corrections

The preliminary UCAC PMs, derived only from the CCD data mean positions and NPM or SPM first epoch positions were binned (0:5) on the NPM and SPM plate pattern separately for various declination zones but combining data from several fields along right ascension (R.A.). Mean PMs per $x, y$ bin were...
Figure 5. Average preliminary “proper motions” between UCAC epoch CCD observations and NPM first epoch data before corrections as functions of bins on the NPM plate tangential plane. Data are averaged over 72 fields along declination = 0°, excluding 20% of the high and low proper motions in each bin. The longest vectors are about 3 mas yr⁻¹.

4.2.2. Proper Motion Zero-point Corrections

Here, we follow a procedure adopted for the construction of the SPM4 catalog (Girard et al. 2011). Besides systematic errors as a function of x, y location on NPM or SPM plates, an overall magnitude equation (field by field) was found when looking at PMs of galaxies. In order to utilize as many galaxies as possible, the entire Lick1 (NPM) and YSJ1 (SPM) catalogs were matched with the 2MASS extended source catalog, not just those objects present in UCAC. Position differences between 2MASS and Lick1 catalog positions were calculated for over 678,000 galaxies with formal position errors less than 400 mas and averaged by Lick1 field. The positional offsets of typically 100 mas are attributed to systematic errors in the Lick1 data at an average magnitude around R = 16.

Similarly, average position differences between Lick1 and the Hipparcos catalog (using Hipparcos PMs) were calculated field by field for a total of over 68,000 acceptable stars at the Lick1 epoch. Again, the position offset was attributed to systematic errors in the Lick1 data at a mean magnitude of about 7.5. Of the 1390 NPM fields in Lick1, a total of 1347 were found with sufficient data from both the galaxies and Hipparcos stars. For the remaining fields, no corrections were applied. An example of the results is shown in Figure 6 for a range of fields and the x-coordinate (along R.A.). The position differences with Hipparcos are less pronounced than in this example for the y-coordinate (declination). Results for the SPM (YSJ1) data are similar with pronounced systematic offsets for the Hipparcos data (±200 mas) and low significant, small offsets for the galaxy data, similar to NPM.

A linear magnitude equation in the Lick1 data was assumed between the position offsets at the bright end (Hipparcos stars) and the faint end (galaxies). The full correction, as derived from the above procedure, was applied whenever the formal error on the position offsets (for Hipparcos stars and galaxies separately) is less than 50 mas. For larger errors per field and coordinate the above derived corrections were scaled down by a factor of 50 mas divided by formal error. Then, the position
difference between bright and faint offsets was divided by the 8.5 mag difference to arrive at the magnitude equation slope. Positions of all Lick1 objects were then corrected differentially for this magnitude equation to force the position offsets (Lick1 − Hipparcos, Lick1 − galaxies) to zero. The YSJ1 (SPM) data were handled in the same way.

4.3. High Proper Motion Stars

Stars with high proper motions (HPM) were handled specifically. In the north, the LSPM-North Catalog (Lepine & Shara 2005) of 61,977 new and previously known HPM stars having PMs greater than 0′′15 yr\(^{-1}\) was used. In the south, many smaller surveys along with the Revised NLTT Catalog (Salim & Gould 2003) were used, which produced 17,730 unique HPM stars greater than 0′′15 yr\(^{-1}\). In both the north and south, a supplemental list of PM stars greater than 0′′15 yr\(^{-1}\) from the Tycho-2 and Hipparcos catalogs was used to fill in any gaps. In chronological order, the smaller southern surveys used include: (1) seven papers covering various portions of the southern sky by Wroblewski and collaborators (Wroblewski & Torres 1989, 1991, 1994, 1996, 1997; Wroblewski & Costa 1999, 2001), (2) UK Schmidt Telescope survey plates of 40 survey fields by Scholz and collaborators (Scholz et al. 2000), (3) The Calan-ESO survey (Ruiz et al. 2001), (4) SuperCOSMOS-RECONS PM survey of the entire southern sky (Henry et al. 2004; Subasavage et al. 2005a, 2005b; Finch et al. 2007; Boyden et al. 2011), (5) the Southern Infrared Proper-Motion Survey (Deacon et al. 2005), (6) Lepine’s SUPERBLINK survey of a portion of the southern sky (Lepine 2008), and (7) UCAC3 PM survey (Finch et al. 2010a, 2012).

Then, we identified these stars in our CCD observations using a two-step approach. For each individual exposure, we established a list of HPM stars which could be present in that field. HPM star positions were calculated for the epoch of that exposure and then matched with the individual R.A., decl. observations of that exposure to identify and flag HPM stars on each exposure (object type = 3). Contrary to UCAC3, a UCAC4-based solution for mean position and PM was attempted for all stars, including the HPM stars. The position and PM solution obtained by the above procedure was substituted by zero PM and the mean CCD data position at mean observational epoch for the following cases:

1. PM solution failed or showed large errors (≥500 mas, ≥50 mas yr\(^{-1}\));
2. derived PM is larger than 500 mas yr\(^{-1}\) in either component;
3. derived mean epoch is earlier than 1947; and
4. difference between mean catalog position and mean CCD data position is ≥3 arcsec.

The mean CCD position of a star is the UCAC observed position obtained by combining data of individual exposures of that star. Stars with early mean epoch are problematic; including poor CCD position data or possible mismatches across involved catalogs. The stars cut by the above criteria are thus added to the group of “no PM” stars, i.e., those that did not match up with other catalogs to even begin the PM calculation. All stars were then checked against the external set of HPM stars. The PM from the external catalog was used for stars with no UCAC4 PM solution and for those where the difference in PM for either component exceeded 40 mas yr\(^{-1}\). Thus, we trust the external catalog data more than the UCAC4 derived PMs in those cases.

5. COMPARISONS WITH OTHER CATALOGS

For the following comparisons with the UCAC4 release data, only stars with unique, single matches to the respective catalogs were used. A match radius of 2.0 arcsec was adopted for positions at the desired common match epoch, by applying PMs as specified below. Tests with a match radius of 1.0 arcsec gave almost identical results.

5.1. UCAC2

Figures 7–12 illustrate the systematic differences between the UCAC4 and UCAC2 data releases regarding magnitude and positions, for the southern and northern hemispheres separately. Almost all of the 48.3 million entries in UCAC2 were matched with UCAC4. For the figures, we excluded flagged double stars as well as stars with a formal position error larger than 150 mas. The differences in photometry between UCAC4 and UCAC2 display small scatter but complex, large systematic offsets (Figures 7 and 8). The UCAC4 photometric system is expected to be significantly better than the UCAC2 data due to the better calibrations. Figures 7 and 8 show results for aperture photometry, while results for model magnitudes are very similar. Largest differences are seen at the bright end where UCAC2 data suffer from uncalibrated nonlinearities near saturation, which already were removed in UCAC3. Small discontinuities on the 0.02 mag level seen in Figure 8 are not of any concern.
Figure 9. Average position differences UCAC4–UCAC2 for the southern hemisphere as a function of UCAC4 aperture magnitude.

Figure 10. Same as the previous figure for northern hemisphere data.

Figure 11. Average position differences UCAC4–UCAC2 for the southern hemisphere as a function of declination.

Figure 12. Same as the previous figure for northern hemisphere data.
because UCAC magnitudes will have larger local systematic errors anyway.

Figures 9 and 10 show the systematic position differences (at epoch 2000) between UCAC4 and UCAC2 for the southern and northern hemispheres, respectively, as a function of magnitude. Systematic differences are only a few up to 10 mas over the entire range. The relative differences (shape of these patterns) are determined mainly by differences in the CTE calibration models used for the data sets, while the absolute zero point is determined by the mean of Tycho-2 stars around magnitude 10–11 (common system between UCAC2, UCAC4, and Tycho-2 by design).

Figures 11 and 12 show the UCAC4–UCAC2 position differences as a function of declination. The mean offset in these figures is determined by the mean offset in the previous figures at faint magnitudes, where the majority of stars are. Local variations in these data are very small (few mas) with the exception of $\Delta \delta$ around $+50^\circ$, where the UCAC2 data run out and only a small range in R.A. is being averaged over.

5.2. 2MASS

Figures 13 and 14 show position differences between UCAC4 and 2MASS as a function of magnitude, for the southern and northern hemispheres, respectively. The UCAC4 PMs are used to bring the UCAC4 positions to the 2MASS epoch (about 1998–2002) for each individual star matched uniquely within 2 arcsec. Figures 15 and 16 show these position differences as a function of declination. Each dot represents the mean over 3000 stars, excluding stars with a UCAC4 double star flag and those with an estimated position error larger than 150 mas. This exclusion effectively cuts stars fainter than about 16.5 mag.

The systematic UCAC4 minus 2MASS position differences are typically about 10 mas, with additional local systematic variations. The sawtooth pattern can be explained by residual systematic errors in the UCAC4 PMs, based on Lick1 and YSJ1 data ($5^\circ$ is the size of individual NPM, SPM plate fields). For those first epoch data no position averaging over plate boundaries was performed. Plots similar to Figures 13 and 14 comparing 2MASS with UCAC3 and UCAC2 were presented in the UCAC3 release paper Zacharias et al. (2010). We note that the position system of UCAC4 agrees better with 2MASS than did UCAC3. This is the result of a better magnitude-dependent correction (CTE) for faint stars in UCAC4 versus UCAC3. Note, although 2MASS positions were not directly used in the UCAC4 final astrometric “plate” solution, 2MASS data were used to correct some magnitude-dependent systematic errors in UCAC4 data. Thus, 2MASS and UCAC4 are somewhat correlated.

5.3. Proper Motion Catalog Comparisons

To highlight possible systematic errors in PMs between various catalogs, a random slice of the sky between right ascension 6.0 and 6.1 hr was picked. Such a slice is narrow enough to sample parts of individual first epoch plates instead of averaging over an entire zone or several plates. Thus, limitations in astrometric calibrations as a function of the location of stars on the x, y plane of a plate will become apparent.

The UCAC4 was matched with the PPMXL (Roeser et al. 2010), XPM (Fedorov et al. 2009), and SPM4 (Girard et al. 2011) catalogs and differences in PMs are plotted as a function...
of declination in Figures 17–19. The range of $-60^\circ \leq \delta \leq -30^\circ$ is chosen to give sufficient coverage from the SPM data. The difference between XPM and PPMXL can be inferred by taking the differences between the UCAC4–XPM and UCAC4–PPMXL plots.

All catalogs are somewhat correlated, for example, the UCAC4 and SPM4 share some first epoch astrograph data, and XPM and PPMXL share Schmidt plates survey data. Nevertheless, significant systematic differences in PMs between all catalogs typically on the 2 mas yr$^{-1}$ level, up to about 6 mas yr$^{-1}$ locally are apparent, with the UCAC4 versus SPM4 differences being somewhat smaller.

5.4. Other External Checks

UCAC4 PMs in R.A. versus PMs in decl. are plotted in Figure 20 for a field around the open cluster M67. Stars within 20 arcmin of the cluster center and with formal, random errors in PM $\leq 7$ mas yr$^{-1}$ per component (which excludes 4% of the stars) are plotted. From these UCAC4 data, the mean PM of the cluster is found to be about $\mu_\alpha \cos \delta = -9.5$ mas yr$^{-1}$ and $\mu_\delta = -4.5$ mas yr$^{-1}$ with an estimated formal error of about 1 mas yr$^{-1}$ (and expected systematic errors somewhat larger than that). These values compare very well with the published absolute PM for M67 ($-9.6$ and $-3.7$ mas yr$^{-1}$) from a recent paper (Bellini et al. 2010) based on Canada–France–Hawaii Telescope data and tied to galaxies.

6. THE CATALOG

6.1. Main Zone Files

The UCAC4 data files are organized in 0:2 wide declination zones, numbered from 1 to 900 beginning at the south celestial pole. Within each zone, stars are sorted by ascending right ascension. These 900 zone files are binary, containing 78-bytes fixed length records with integers for each catalog entry (mostly stars). 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 as Vizier catalog I/322 at CDS). Sample access code (in Fortran and C) is provided as well as index and other auxiliary files. The UCAC4 distribution on DVD furthermore contains all-sky plots showing catalog density and mean PMs, historic information such as relevant papers, presentations and a snapshot of the UCAC Web sites including pictures. The online version provides real numbers in ASCII format versus the original integer data and gives declination in degrees while the DVD release gives south pole distance in mas (Table 3).

The official star identification name is of the format UCAC4-zzz-nnnnn. The three digit “zzz” number is the zone number for a star, while “nnnnnn” is the six digit record number for that star along its zone file (with leading zeros, if needed).

Similar to previous releases, UCAC4 is a compiled catalog giving the weighted mean position and PM of stars based on all input catalogs, including the CCD data. Subject to available resources, USNO plans to release the individual CCD...
Table 3
Data Items for Each Entry (Star) in UCAC4

| Item | Label | Format | Unit | Description |
|------|-------|--------|------|-------------|
| 1    | ra    | I*4    | mas  | Right ascension at epoch J2000.0 (ICRS) |
| 2    | spd   | I*4    | mas  | South pole distance epoch J2000.0 (ICRS) |
| 3    | magm  | I*2    | millimag | UCAC fit model magnitude |
| 4    | maga  | I*2    | millimag | UCAC aperture magnitude |
| 5    | sigmag| I*2    | 0.01 mag | UCAC error on magnitude |
| 6    | objt  | I*1    |      | Object type |
| 7    | cdf   | I*1    |      | Combined double star flag |
| 8    | sigra | I*1    | mas  | m.e. at mean epoch in R.A. (*cos decl.) |
| 9    | sigdec| I*1    | mas  | m.e. at mean epoch in decl. |
| 10   | nai   | I*1    |      | Total number of CCD images of this star |
| 11   | nu1   | I*1    |      | Number of CCD images used for this star |
| 12   | cdu1  | I*1    |      | Number of catalogs (epochs) used for PM |
| 13   | cepra | I*2    | 0.01 yr | Mean epoch for R.A., minus 1900 |
| 14   | cepdc | I*2    | 0.01 yr | Mean epoch for decl., minus 1900 |
| 15   | pmrac | I*4    | 0.1 mas yr⁻¹ | Proper motion in R.A. *cos(decl.) |
| 16   | pmdc  | I*4    | 0.1 mas yr⁻¹ | Proper motion in decl. |
| 17   | sigpnr| I*1    | 0.1 mas yr⁻¹ | m.e. of pmRA * cos(decl.) |
| 18   | sigpm  | I*1   | 0.1 mas yr⁻¹ | m.e. of pmDec |
| 19   | pts_key| I*4  |      | 2MASS pts key star identifier |
| 20   | j_m   | I*2    | millimag | 2MASS J magnitude |
| 21   | h_m   | I*2    | millimag | 2MASS H magnitude |
| 22   | k_m   | I*2    | millimag | 2MASS Ks magnitude |
| 23   | icf   | I*1    |      | 2MASS cc_flg*10 + ph_qual.flag for J |
| 24   | (2)   | I*1    |      | 2MASS cc_flg*10 + ph_qual.flag for H |
| 25   | (3)   | I*1    |      | 2MASS cc_flg*10 + ph_qual.flag for Ks |
| 26   | e2mpho| I*1    | 0.01 mag | m.e. 2MASS J magnitude j_msigcom |
| 27   | (2)   | I*1    | 0.01 mag | m.e. 2MASS H magnitude h_msigcom |
| 28   | (3)   | I*1    | 0.01 mag | m.e. 2MASS Ks magnitude k_msigcom |
| 29   | apasm | I*2    | millimag | B magnitude from APASS |
| 30   | (2)   | I*2    | millimag | V magnitude from APASS |
| 31   | (3)   | I*2    | millimag | g magnitude from APASS |
| 32   | (4)   | I*2    | millimag | r magnitude from APASS |
| 33   | (5)   | I*2    | millimag | i magnitude from APASS |
| 34   | apase | I*1    | 0.01 mag | m.e. of B magnitude from APASS |
| 35   | (2)   | I*1    | 0.01 mag | m.e. of V magnitude from APASS |
| 36   | (3)   | I*1    | 0.01 mag | m.e. of g magnitude from APASS |
| 37   | (4)   | I*1    | 0.01 mag | m.e. of r magnitude from APASS |
| 38   | (5)   | I*1    | 0.01 mag | m.e. of i magnitude from APASS |
| 39   | gcflg | I*1    |      | Yale SPM g-flag*10 + c-flag |
| 40   | icf   | I*4    |      | merged FK6–Hipparcos–Tycho source flag |
| 41   | (2)   | I*2    |      | AC2000 catalog match flag |
| 42   | (3)   | I*2    |      | AGK2 Bonn catalog match flag |
| 43   | (4)   | I*2    |      | AGK2 Hamburg catalog match flag |
| 44   | (5)   | I*2    |      | Zone Astrog. catalog match flag |
| 45   | (6)   | I*2    |      | Black Birch catalog match flag |
| 46   | (7)   | I*2    |      | Lick Astrog. catalog match flag |
| 47   | (8)   | I*2    |      | NPM Lick1 catalog match flag |
| 48   | (9)   | I*2    |      | SPM YSJ1 catalog match flag |
| 49   | leda  | I*1    |      | LEDA galaxy flag |
| 50   | x2m   | I*1    |      | 2MASS extend.source flag |
| 51   | rmm   | I*4    |      | Unique star identification number |
| 52   | zn2   | I*2    |      | Zone number of UCAC2 (0 = no match) |
| 53   | rm2   | I*4    |      | Running record number along UCAC2 zone |

Notes. Extensive remarks are given only in the readme file of the UCAC4 as part of the release data. This table strictly describes the data of the DVD release. The online version served at CDS provides real numbers in ASCII format and declination instead of south pole distance.

a “I” means integer, followed by the number of bytes.
b “m.e.” stands for mean (or standard) error.

Observations (positions at epoch). To obtain this about 50 GB large data set, please contact the lead author.

UCAC4 does contain about 92,000 galaxies. No star/galaxy separation parameter based on pixel data is present in UCAC4. However, flags are provided that indicate matches with known non-stellar objects, from the 2MASS extended source catalog, the LEDA galaxy catalog, and non-stellar flags copied from the SPM data.
6.2. Supplement Stars and Data

Contrary to previous releases, UCAC4 was supplemented by bright stars in the attempt to provide a catalog complete from the brightest naked eye stars to about $R = 16$. First, information from the Tycho-2 and Hipparcos (including annexes) catalogs were merged with FK6 (Wielen et al. 1999) data. In order of priority, astrometric data are taken from FK6 if available, else from the 2007 Hipparcos release (van Leeuwen 2007), else from the original Hipparcos catalog (ESA 1997), or else from Tycho-2 (Høg et al. 2000). This combined catalog of over 2.5 million stars was matched with UCAC4 and stars not found in UCAC4 observational data within 2 arcsec were added to the UCAC4 release catalog. Also, a total of two HPM stars was added manually. For these supplemented stars as well as for all UCAC4 entries identified as Hipparcos stars, a unique star ID number (column 51 of the zone files) of below 1 million was assigned and additional data provided in a separate table indexed with that star number. Thus, most of the Hipparcos catalog data (including parallaxes) are linked to UCAC4 entries.

A cross reference to the Tycho-2 catalog was created and added to the release in a separate file. This file contains 2,549,788 entries linking the original Tycho-2 star number (three parts) to the official UCAC4 star number (zone number and record along zone) and the main data table column 51 entry (single, unique star ID number).

7. DISCUSSIONS AND CONCLUSIONS

The UCAC4 is the final release of this project, providing an all-sky, astrometric catalog to $R = 16$ mag. Figure 21 shows the distribution of mean epochs of UCAC4 stars. The recent epoch CCD observations dominate, while for some stars the mean epoch can go back several decades. For these stars the weight of the CCD observations used in the calculation of PM is low, which can happen due to a number of reasons like faintness of star or elongated image due to multiplicity.

Figure 22 shows the distribution of UCAC4 PMs (here for the R.A. component) on a logarithmic scale. The declination PM distribution looks very similar. The overdensities near 100 and 200 mas yr$^{-1}$ are likely caused by contaminations of stars with mismatched positions between early and late epoch data at the cutoff match threshold.

Figure 23 shows the distribution of UCAC4 formal position errors at mean epoch, which peaks near 18 mas. Most stars have formal position errors of between 15 and 100 mas, depending on magnitude. Real position errors at current epoch are larger due to propagation of PM errors and additional systematic errors. The positions at mean epoch in UCAC4 are closer to the UCAC2 and 2MASS systems than those of the UCAC3 release. UCAC4 also contains more stars and includes bug fixes that makes UCAC3 obsolete now.

Figure 24 shows the distribution of UCAC4 formal PM errors which peaks at 4 mas yr$^{-1}$. The small overdensities near 18 mas yr$^{-1}$ and 32 mas yr$^{-1}$ are caused by the adopted position error of 900 mas for no-fit CCD positions in the PM calculation process. The mean epochs of CCD observations, SPM, and NPM data are about 2000, 1972, and 1950, respectively, which lead to about 32 and 18 mas yr$^{-1}$ formal PM errors. Entries in UCAC4 with a formal PM error larger than about 12 mas yr$^{-1}$ should be considered problematic and might not correspond to real stars.
Systematic errors in PMs are estimated to be on the few mas/yr level as indicated by external comparisons with other high-precision (nearly) global catalogs which all claim to be on the same inertial system, the ICRS (Figures 17–19).

2MASS near-IR photometry has been added to UCAC4 as with earlier releases. For the first time a large fraction (about half) of the stars in UCAC4 now also list precise optical photometry in up to five bands from the APASS DR6 including some single observations. APASS $V$ and $r$ magnitudes of DR2 were used to calibrate the UCAC4 observed magnitudes (Figure 25), which should be more reliable than in any previous UCAC release. The UCAC4 magnitudes are near the Sloan $r$ magnitudes and between $V$ and $r$.

An effort was made to utilize block adjustment (BA) techniques (Zacharias 1992) for the final UCAC release. However, simulations indicated that the small size of individual CCD images combined with the only two-fold overlap pattern leads to very slow convergence. In light of still remaining systematic position errors in UCAC data on the 10–20 mas level, much more elaborate simulations are needed to prove any improvement of a BA solution of UCAC data over the classical solution adopted for UCAC4. Therefore the BA solution of the data has not been pursued further at this time.

Reductions of the extragalactic link data of UCAC is still in progress. There are indications for both local reference star zonal errors as well as blended images or host galaxy contamination of some sources when looking at the optical–radio position differences of ICRF sources (M. I. Zacharias et al., in preparation). However, no revised UCAC release after UCAC4 is planned. Significant improvements in global astrometry will come from new observations. The USNO Robotic Astrometric Telescope project is already underway (www.usno.navy.mil/usno/astrometry/optical-IR-prod/urat).

We thank everyone involved in the monumental NPM and SPM projects, in particular Bill van Altena, Arnold Klemola, Burton Jones, and Bob Hanson. For a complete acknowledgement regarding the UCAC project, please see the author list and acknowledgement sections in the UCAC2 and UCAC3 release papers. The following acknowledges only additional contributions directly related to this UCAC4 release paper. Sean Urban is thanked for his Hipparcos and Tycho-2 merged catalog, which was augmented with FK6 data here and used to supplement bright stars in UCAC4. We are grateful for the many constructive comments we received from the following testers of the UCAC4-beta data, in particular Rae Stiening (from...
Figure 22. Log of distribution of UCAC4 proper motions along R.A. The plot of proper motions along decl. looks similar.

Figure 23. Distribution of errors per coordinate for UCAC4 positions at epoch 2000, which is close to the mean epoch.

Figure 24. Distribution of UCAC4 proper motion errors per coordinate.

Figure 25. Aperture (ap) and model (m) magnitudes of UCAC4p photometric system as calibrated with APASS V and r magnitudes.

Ricky Smart (Torino, Italy), Sean Urban, Greg Hennessy, Paul Barrett, and Bob Zavala (USNO).

Francois Ochsenbein from CDS, Strasbourg is thanked for preparing the UCAC4 online release and the staff of CDS is thanked for hosting all UCAC releases over the years. Ralph Gaume is thanked for supporting the UCAC project as Head of the Astrometry Department over the many years. National Optical Astronomy Observatories (NOAO) are acknowledged for IRAF, Smithsonian Astrophysical Observatory for DS9 image display software, and the California Institute of Technology for the pgplot software. More information about the UCAC and follow-up projects is available at www.usno.navy.mil/usno/astrometry/. Finally, the referee (S. Röser) is thanked for valuable comments which improved this paper.

REFERENCES

Bellini, A., Bedin, L. R., Pichardo, B., et al. 2010, A&A, 513, 51
Boyd, M. R., Winters, J. G., Henry, T. J., et al. 2011, AJ, 142, 10
Deacon, N. R., Hambly, N. C., & Cooke, J. A. 2005, A&A, 435, 363
ESA 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA)
Fedorov, P. N., Myznikov, A. A., & Akhmetov, V. S. 2009, MNRAS, 393, 133
Finch, C. T., Henry, T. J., Subasavage, J. P., Jao, W. C., & Hambly, N. C. 2007, AJ, 133, 2898
Finch, C. T., Zacharias, N., & Henry, T. J. 2010a, AJ, 140, 844
Finch, C. T., Zacharias, N., & Wycoff, G. L. 2010b, AJ, 139, 2200
Finch, C. T., Zacharias, N., Boyd, M. R., Henry, T. J., & Hambly, N. C. 2012, ApJ, 745, 118
