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COMPARING TYCHO-2 ASTROMETRY WITH UCAC1

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ABSTRACT

The Tycho-2 Catalogue, released in February 2000, is based on the ESA *Hipparcos* space mission data and various ground-based catalogs for proper motions. An external comparison of the Tycho-2 astrometry is presented here using the first US Naval Observatory CCD Astrograph Catalog (UCAC1). The UCAC1 data were obtained from observations performed at Cerro Tololo Inter-American Observatory (CTIO) between 1998 February and 1999 November, using the 206 mm–aperture five-element lens astrograph and a 4K × 4K CCD. Only small systematic differences in position between Tycho-2 and UCAC1, up to 15 mas, are found, mainly as a function of magnitude. The standard deviations of the distributions of the position differences are in the 35 to 140 mas range, depending on magnitude. The observed scatter in the position differences is about 30% larger than that expected from the combined formal, internal errors, also depending on magnitude. The Tycho-2 Catalogue has the more precise positions for bright stars ($V \leq 10$ mag, while the UCAC1 positions are significantly better at the faint end (11 mag $\leq V \leq$ 12.5 mag) of the magnitude range in common. UCAC1 data go much fainter (to $R \approx 16$ mag) than Tycho-2 data; however, complete sky coverage is not expected before mid-2003.

Key words: astrometry — catalogs

1. INTRODUCTION

Two new major astrometric catalogs became available in early 2000. The Tycho-2 Catalogue, for the brightest 2.5 million stars (Høg et al. 2000a, 2000b), and the first US Naval Observatory CCD Astrograph Catalog (UCAC1), for 27 million stars in the southern hemisphere (Zacharias et al. 2000). Both catalogs are important steps toward the extension of the optical reference frame (Zacharias 1998) beyond the densities and magnitudes of the *Hipparcos* Catalogue.

The Tycho-2 Catalogue is a new, extended version of the original Tycho Catalogue (ESA 1997), based on a rereduction of the ESA *Hipparcos* space mission Tycho data and over 140 ground-based catalogs for the Tycho-2 proper motions. An external comparison of the Tycho-2 *astrometry* utilizing the UCAC1 positions is presented here. A similar comparison between the Tycho-1 Catalogue and CCD astrograph test data was presented earlier (Zacharias et al. 1997b).

The US Naval Observatory CCD Astrograph (UCAC) project was planned and initiated in the mid-1990s (Gauss et al. 1996; Zacharias 1997; Zacharias, Germaine, & Rafferty 1997a). Observations started at the south celestial pole in 1998, and full sky coverage is expected by mid-2003. For the comparison presented in this paper, these new high-precision observations were available for about 80% of the southern hemisphere, covering the magnitude range $R \approx$ 8–16 mag. Thus, particularly, the new faint extension of the Tycho-2 catalog (11–12.5 mag) is very well covered by these independent ground-based observations.

Both catalogs are on the *Hipparcos* system, thus on the International Celestial Reference System (ICRS). The epoch difference of about 8 yr is bridged by proper motions given in the Tycho-2 catalog at the expense of introducing a third error contribution in addition to the positional errors of both catalogs. With only approximate magnitudes given in a single bandpass (red), the UCAC is not a photometric catalog. Therefore *no* external *photometric* comparison of the Tycho-2 data can be presented here. Both Tycho-2 and UCAC1 are of great importance to the general astronomical community, and the astrometric comparison presented here is also of benefit to the Tycho-2 and in particular to the UCAC projects. Another important catalog comparison between the Tycho-2, the ACT Reference Catalog (ACT; Urban, Corbin, & Wycoff 1998a), and the *Hipparcos* Catalogue is in preparation (Urban et al. 2000).

2. DESCRIPTION OF THE CATALOGS

Here we briefly describe properties of both catalogs that are relevant for this comparison. For more details, the reader is referred to the papers mentioned in the introduction.

2.1. *Tycho-2*

The major improvement of the Tycho-2 Catalogue over the original Tycho Catalogue is the faint extension, providing positions for some 1.5 million more stars, extending its limiting magnitude to about $V = 12.5$. This was made possible by a new reduction procedure that also provides new, slightly improved positions for the stars given in Tycho-1. The mean epoch for the Tycho observations is in the range 1990.72 to 1992.36, depending on the individual star. The estimated precision of the Tycho positions is a function of magnitude, as given in Table 1, adopted from Høg et al.

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TABLE 1

INTERNAL PRECISION OF TYCHO-2 AND UCAC1 POSITIONS

V_T (mag) (1)	σ_T (mas) (2)	σ_{PM} (mas) (3)	R_U (mag) (4)	σ_U (mas) (5)	σ_{T-U} (mas) (6)
8.0	5	10	7.5	≥ 60	≥ 61
8.5	6	10	8.0	40	42
9.0	9	11	8.5	35	38
9.5	14	12	9.0	30	35
10.0.....	21	13	9.5	24	35
10.5.....	32	15	10.0	16	39
11.0.....	48	17	10.5	16	53
11.5.....	70	19	11.0	16	74
12.0.....	93	21	11.5	17	97
12.5.....	110	24	12.0	17	114

NOTES.—Internal precisions are listed as a function of Tycho visual and UCAC red magnitudes. Col. (1): Tycho visual magnitude, V_T. Col. (2): Tycho-2 position, σ_T. Col. (3): Error contribution from the proper motions, σ_{PM}. Col. (4): UCAC red magnitude, R_U. Col. (5): UCAC1 position, σ_U. Col. (6): Formal expected error in the difference between the Tycho position and the UCAC1 position, σ_{T-U}.

(2000b). An internal error of a position component for each star in Tycho-2 is derived from the signal-to-noise ratio of the combined signal for the ≈ 130 transits per star made by the *Hipparcos* satellite, as explained in Høg et al. (2000b). The medians of those standard errors per magnitude bin are listed in column (2) of Table 1, providing a robust estimate of the standard error.

Proper motions have been derived utilizing the Tycho-2 positions and a large number of ground-based catalogs, including a new reduction of the Astrographic Catalogue (AC) data. Significant changes were made here, particularly in the magnitude-dependent systematic error corrections of the AC data as compared with the previous release, the AC2000 (Urban et al. 1998b). Assuming a mean difference of 7.7 yr between the Tycho-2 and UCAC1 epochs and taking the formal errors of the Tycho-2 proper motions from Høg et al. (2000b), we obtain the error contribution due to proper motions, listed in column (3) of Table 1.

2.2. *UCAC1*

The UCAC astrometric sky survey started in 1998 February at Cerro Tololo, Chile. In this first, preliminary catalog, data are included up to 1999 November. Thus the mean epoch of the catalog is about 1999.0. The UCAC survey is performed in a single bandpass (579–642 nm) with a twofold overlap pattern of fields and a long and a short exposure on each field. The five-element lens astrograph of 206 mm aperture uses a single 4K × 4K CCD detector, providing a 61′ field of view with a scale of 0.″9 pixel^{-1}. Data for stars in the range 10th–14th magnitude are the most precise, with an estimated positional error of ≈ 20 mas. Brighter stars are overexposed on the long exposures, hence only the short exposures generally contribute to positions of stars in the range 8–9.5 mag. Stars brighter than 8.0 mag are also saturated on most short exposures. For faint stars, the precision degrades to about 70 mas at the limiting magnitude of $R \approx 16$.

A first catalog (UCAC1) for 27 million stars (Zacharias et al. 2000) was released by the end of March 2000.[2] Preliminary proper motions are included for all stars in UCAC1. Those proper motions have not been used here at all. For the magnitude range overlapping the Tycho-2 data, the UCAC1 proper motions are mainly derived from AC and Tycho-2 data, thus they are highly correlated with the Tycho-2 proper motions. For this catalog comparison the Tycho-2 proper motions were used to update the Tycho-2 positions to the UCAC epoch of each star in common.

The UCAC1 was reduced using *Hipparcos*, Tycho-1, and ACT data (Urban, Corbin & Wycoff 1998a) and thus mainly depends on the original Tycho-1 Catalogue stars and the proper motions derived from the AC2000 reductions. In particular, all new, faint stars in Tycho-2 that are not in Tycho-1 are field stars in UCAC1, and thus were not used as reference stars. Therefore UCAC1 positions of these stars are largely independent of Tycho-2 positions. Both Tycho-2 and UCAC1 are in the same system (*Hipparcos*), except for a possible, slight alteration caused by the use of ACT proper motions.

All CCD frames of the UCAC1 data were reduced individually using the astrometrically suitable reference stars on each frame with a linear six-parameter mapping model. The low charge transfer efficiency (CTE) of our CCD results in significant coma-like systematic errors along the x-coordinate (right ascension). The effect in the raw data is up to ± 70 mas. These errors have been corrected to first order. Remaining systematic errors are believed to be on the 10 mas level. The remaining residuals versus coma are ≤ 10 mas for most part in both axis. There is an asymmetric feature of up to 20 mas in the x-coordinate for a small fraction of the stars. These plots and more details can be found in the UCAC1 paper (Zacharias et al. 2000).

A magnitude equation was already noticed in the residuals of the CCD frame reductions, mainly for the x-coordinate. However, for this first catalog neither corrections for a magnitude term were applied nor were such terms included in the reduction model. At this point it is not obvious whether the magnitude-dependent systematic errors are inherent in the UCAC (x, y) data or are introduced by the ACT via proper motions. Future UCAC astrometric reductions will use the Tycho-2 Catalogue, which was not available at the time of UCAC1 reductions.

Weighted-mean catalog positions were obtained from the individual positions. Precisions of the mean positions are obtained from the scatter of the few (≈ 2–6) individual observations per star. The (squared) mean of these individual σ values over all stars in a magnitude bin is an estimate of the standard error of the positional precision of the catalog and is listed in column (5) of Table 1 as σ_U. This σ_U is slightly underestimated because of the correlations of the individual field-star positions from the short and long exposure frames, which use a significant number of reference stars in common for their reductions.

The precision of the UCAC1 positions is also a function of magnitude. For magnitudes $R_U \leq 11$, the precision of UCAC1 positions is underestimated because of the correlation with the reference stars. For the UCAC data the R_U red magnitude has to be used. On average, the color index is $V_T - R_U \approx 0.5$, thus the precisions in position listed in Table 1 (see columns [2] and [5]) for both catalogs are for about the same stars on each line. Column (6) of Table 1 lists the

[2] See also http://ad.usno.navy.mil/.

expected combined standard error of position differences between Tycho-2 and UCAC1 as derived from internal formal errors only.

3. RESULTS OF THE CATALOG COMPARISON

In total, close to 1.0 million stars have been found to be common to the Tycho-2 Catalogue and UCAC1, adopting a match radius of 500 mas. By excluding the Tycho-1 stars (reference stars of UCAC1) and adopting the same match radius we find 597,809 stars in common.

3.1. *Systematic Errors*

Position differences between Tycho-2 and UCAC1 at the UCAC1 epoch are plotted versus Tycho V magnitude in Figure 1. All stars in common are shown here. Using only the stars not included in Tycho-1 gives just the faint part of the plots shown in Figure 1. One dot represents the mean of 2000 stars. A magnitude equation is clearly present, with systematic differences up to ± 15 mas over a range of ≈ 5 mag. While the magnitude equation for the right ascension component, x, is almost linear, it is nonlinear for the declination component, y.

The systematic errors as a function of magnitude vary with declination, as can be seen in Figure 2. Here the position differences between Tycho-2 and UCAC1 are plotted versus declination. The general offset is due to the fact that the majority of stars (faint end) have a nonzero position

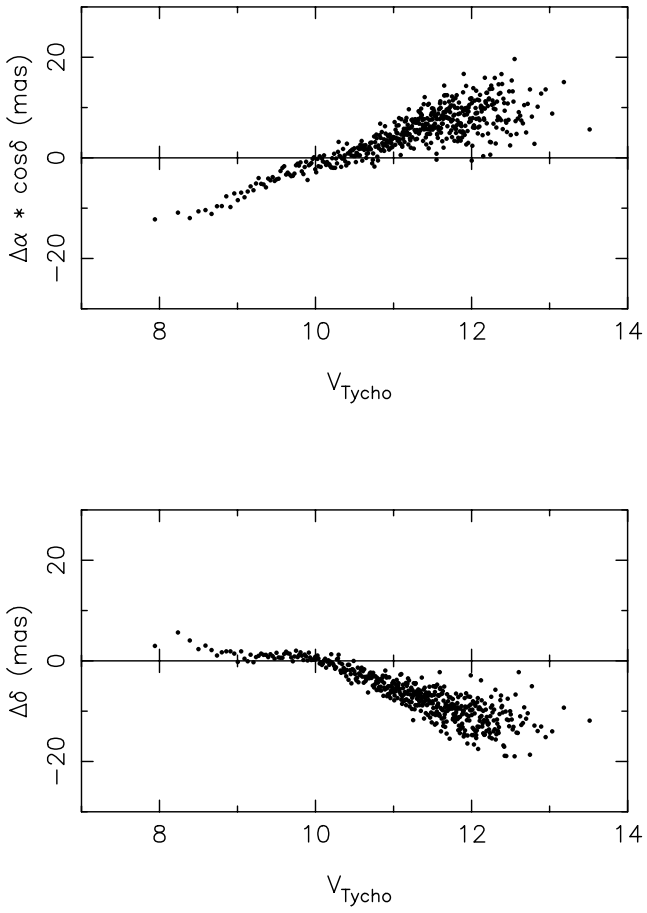

FIG. 1.—Position differences between Tycho2 and UCAC1 as a function of Tycho V magnitude. All stars in common are included. One dot represents the mean of 2000 stars.

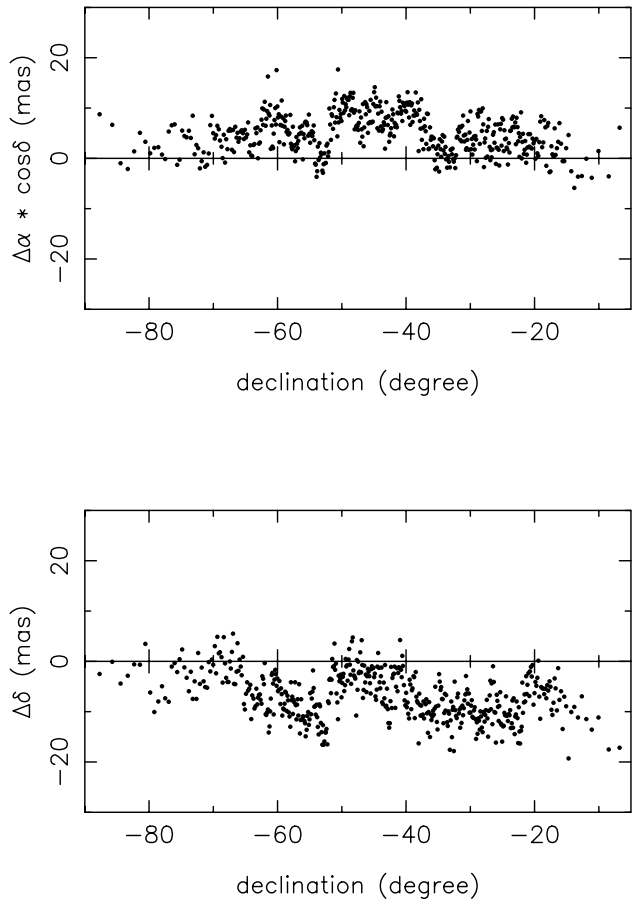

FIG. 2.—Position differences between Tycho2 and UCAC1 as a function of declination. One dot represents the mean for 2000 stars.

difference due to the magnitude equation. The variation of this offset, and thus the magnitude equation, follow a zonal pattern in declination. A plot of the differences versus right ascension shows no pattern. Neither are there additional significant systematic errors of the position differences with respect to color. Figure 3 shows plots for the $\Delta\alpha \cos\delta$ and $\Delta\delta$ components versus the $B-V$ Tycho color index.

3.2. *Error Budget*

In the following statistics, only the non–Tycho-1 stars are used. Table 2 summarizes the results by magnitude bins, with all position items given in mas. The listed V_T magnitude is for the center of each bin, while n gives the number of stars available per magnitude bin. The standard deviations given in Table 2 for the x-coordinate are obtained from

$$\sigma_x = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n}}$$

and are similarly obtained for the y-coordinate, where x_i and y_i are the individual position differences between Tycho-2 and UCAC1 and $\bar{x}$ and $\bar{y}$ are their arithmetic means for that magnitude bin. To exclude outliers, two approaches were taken. First the $(x_i - \bar{x})^2$ values were sorted and the largest 10% were rejected. The resulting standard errors from this cut of the distribution are listed in Table 2 in the σ_{cx} and σ_{cy} columns. The second method used the 25th to 75th percentile of the distribution of the position differences around their mean. Assuming the central parts of our position differences distributions are Gaussian, σ_{qx}

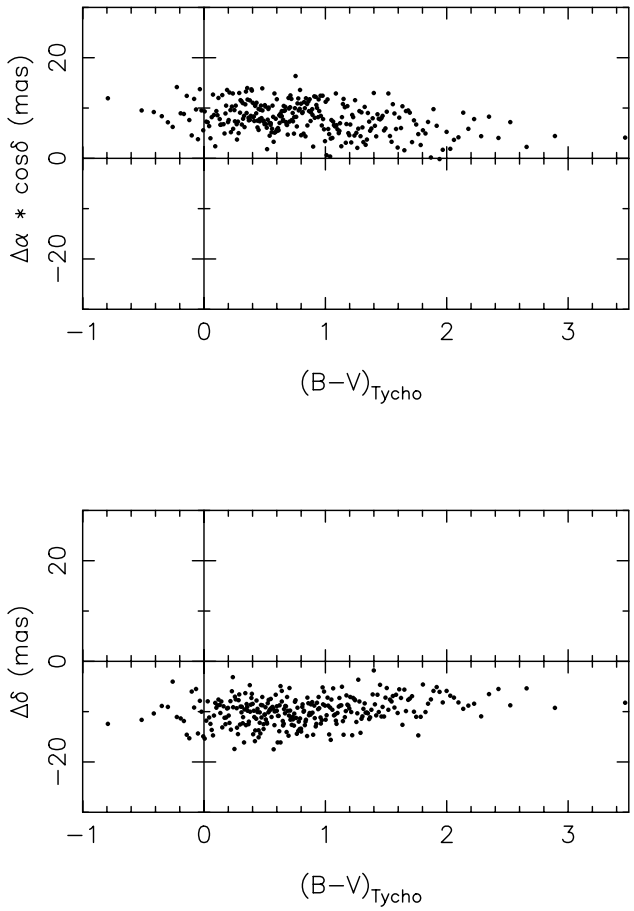

FIG. 3.—Position differences between Tycho2 and UCAC1 as a function of color index. One dot represents the mean for 2000 stars.

and σ_{qy} values were derived (see Table 2). For easy comparison, the last column of Table 2 lists the *expected* combined standard error from the formal errors alone for our position differences, which has been copied from Table 1.

4. DISCUSSION

4.1. *Magnitude Equation*

A comparison with the Yale Southern Proper Motion (SPM) data (Platais et al. 1998) shows that the apparently linear magnitude equation in UCAC1 for the right ascension component does not extend to fainter magnitudes. Results are presented in Zacharias et al. (2000), indicating good agreement between UCAC1 and SPM positions around 15th magnitude for both coordinates. The systematic pattern as a *function of declination* can best be understood to originate from the proper motion part in this comparison. Individual zones in the AC might be responsible for this signature. A plausible magnitude-dependent error of ≈ 100 mas at a 1900 AC epoch would lead to an error in the ACT proper motions consistent with a 10 mas offset seen in our comparison at the 1999 UCAC1 epoch.

The overall offset in Figure 2 results from an average slope in the magnitude equation and the fact that the mean magnitude of the stars in comparison here is fainter than the mean magnitude of the reference stars used in the UCAC1 reductions. This *mean* magnitude equation in the 8 to 12 mag range comes possibly from the UCAC (x, y) data. Many images of these stars are close to the pixel saturation level, within a factor of ≈ 3 in the amplitude counts in either the long or the short exposure. It is also conceivable that remaining systematic errors associated with the CTE effect show up as pure magnitude terms. A systematic error in the Tycho-2 data of ≈ 5 to 10 mas at the faint end cannot be excluded from this comparison either. However, this is unlikely, based on studies made in the Tycho-2 construction (comparison with *Hipparcos*). Future reductions of the UCAC data will help to clarify this issue.

TABLE 2

RESULTS OF THE CATALOG COMPARISON

V_T (mag)	n	σ_{cx} (mas)	σ_{cy} (mas)	σ_{qx} (mas)	σ_{qy} (mas)	σ_{T-U} (mas)
8.0.....	8	98	86	88	23	≥61
8.5.....	19	42	31	56	35	42
9.0.....	25	24	36	27	34	38
9.5.....	36	56	45	56	39	35
10.0.....	155	47	43	50	52	35
10.5.....	4088	59	49	72	61	39
11.0.....	58564	65	57	79	71	53
11.5.....	204984	79	72	96	88	74
12.0.....	209416	99	92	119	113	97
12.5.....	112272	118	111	143	137	114

NOTES.—Results of the comparison are shown as a function of V_T magnitude. Only the Tycho-2 stars not contained in Tycho-1 are included. The number of stars in a given magnitude bin is listed as n. The standard errors for x and y are for $\Delta\alpha \cos\delta$ and $\Delta\delta$, respectively. For more details, see § 3.2.

4.2. *Error Budget*

There are five contributions to the observed scatter in the position differences: random errors in both the Tycho-2 and UCAC1 positions at their mean epochs, random errors in the proper motions needed to bridge the epoch difference between the catalogs, additional noise from incompatibilities, and additional noise from systematic differences. The additional noise from incompatibilities includes items such as unknown multiplicity of stars, which shifts the center of light as a function of time and bandpass. It is conceivable that a relatively small number of multiple stars can bias the statistics significantly, particularly in the highest precision area, around 10th magnitude. Unresolved components on the few 100 mas level are likely to cause offsets in the photocenters on the 10 to 100 mas level, introducing a significant additional error. Neither the cut of the observed distribution (σ_{cx}, σ_{cy}) nor the 50% quantile standard errors are likely to eliminate those problem stars from the statistics. Also, positional shifts caused by differential refraction are not taken into account in the UCAC data. Individual stars, depending on their color and zenith distance at the time of observation, have different offsets with respect to the mean of the reference stars, contrary to the Tycho-2 data, which are collected outside the Earth's atmosphere. The difference in position between an O5 and an M5 main-sequence star due to differential color refraction is about 10 mas for the UCAC bandpass and a zenith distance of 45°. Thus there are physical reasons to expect a noise term in the observed scatter of the position differences in addition to the three internal errors (catalog 1, catalog 2, and proper motions), even in the absence of significant systematic errors.

For magnitudes $V \leq 9.0$, the statistics are affected by the

small number of available stars. Overall, the observed scatter in the position differences agrees very well with the expected formal errors at those magnitudes. In general the x-coordinate (right ascension) shows a significantly larger error than the y-coordinate. This very likely shows still unresolved systematic errors in the UCAC data due to the CTE problems along the x-axis.

The largest discrepancies (typically a 40% to 50% underestimate of the errors) between observed and expected standard errors are seen in the midrange, fainter than 9th and brighter than 11th magnitude. This is the transition area between positions based on short exposures only and those based on the combination of short and long exposures. Also, in this magnitude range, the combined formal error is lowest, allowing a moderate additional contribution from systematic errors to show up most pronounced.

At the faint end ($V \geq 11.0$) the excess of the observed scatter with respect to the formal errors is relatively small, ranging from insignificant to $\approx 10\%$ when compared with the cut distribution (σ_{cx}, σ_{cy}), and about 20% when compared to the (σ_{qx}, σ_{qy}) numbers. This gives an external verification of the accuracy of the Tycho-2 astrometry and sets an upper limit to the ratio of true to formal errors at about 1.2 at the faint end of the catalog, which includes the majority of the stars. At these magnitudes the UCAC1 positions, even if underestimated by their formal errors, are more accurate than the Tycho-2 positions. The high UCAC1 accuracy is also confirmed by a comparison with SPM data (Zacharias et al. 2000).

5. CONCLUSIONS

The Tycho-2 and UCAC1 positions overall are in good agreement, with systematic differences being very small by current astrometric catalog standards. This external comparison shows the observed scatter in the position differences to be 10 to 50% larger than the formal, internal precisions predict. A significant fraction of the additional errors can be explained by systematic errors present in the current UCAC1, which by all means is a preliminary catalog. The UCAC1 contains the best positions available today (at current epochs) for stars in the 11th to 16th magnitude range. UCAC today covers only 80% of the southern hemisphere, with no data in the north. When completed in 2003, it will form the basis for the FAME input catalog (Johnston et al. 1999). The Tycho-2 Catalogue covers all the sky and is the preferred astrometric reference down to about $V = 10.5$ mag or whenever no UCAC1 data are available.

We wish to thank the entire UCAC project team and the CTIO staff, in particular our observers D. Castillo and M. Martinez. More information on the UCAC project is available.[3] The UCAC1 is available on CD-ROM on request to nz@pisces.usno.navy.mil. The Tycho-2 Catalogue is available on CD-ROM on request to Tycho-2@astro.ku.dk or seu@pyxis.usno.navy.mil.

[3] See http://ad.usno.navy.mil/ad/ucac/.

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