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 U.S. Naval Observatory CCD Astrograph Catalog (UCAC1). The UCAC1 data were obtained from observations performed at CTIO between February 1998 and November 1999, using the 206 mm aperture 5–element lens astrograph and a 4k x 4k CCD. Only small systematic differences in position between Tycho–2 and UCAC1 up to 15 milliarcseconds (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 expected from the combined formal, internal errors, also depending on magnitude. The Tycho–2 Catalogue has the more precise positions for bright stars (V$\leq 10^m$) while the UCAC1 positions are significantly better at the faint end ($11^m \leq V \leq 12.5^m$) of the magnitude range in common. UCAC1 goes much fainter (to R$\approx 16^m$) than Tycho–2; however complete sky coverage is not expected before mid 2003.

Subject headings: astrometry: catalog

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), (Høg et al. 2000b) and the first U.S. Naval Observatory CCD Astrograph Catalog, UCAC1, for 27 million stars on the Southern Hemisphere (Zacharias et al. 2000). Both catalogs are important steps towards 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 re–reduction 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* is presented here utilizing the UCAC1 positions. A similar comparison between the Tycho–1 Catalogue and CCD astrograph test data was presented earlier (Zacharias et al. 1997a).

The U.S. Naval Observatory CCD Astrograph (UCAC) project was planned and initiated in the mid 1990s (Gauss et al. 1996), (Zacharias 1997), (Zacharias et al. 1997b). 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$\approx 8 - 16^m$. Thus, particularly, the new, faint extension of the Tycho–2 catalog (11^m to 12.5^m) is very well covered by these indepen-

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dent ground–based observations.

Both catalogs are on the Hipparcos system, thus the International Celestial Reference System (ICRS). The epoch difference of about 8 years is bridged by proper motions given in the Tycho–2 catalog at the expense of introducing a third error contribution besides the positional errors of both catalogs. The UCAC is not a photometric catalog, with only approximate magnitudes given in a single bandpass (red). 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 for the Tycho–2 and in particular the UCAC projects. Another important catalog comparison between the Tycho–2, the ACT (Urban et al. 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 which 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 which also provides new, slightly improved positions for the stars previously given in Tycho–1. The mean epoch for the Tycho observations is in the range of 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. 2000a). 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. 200b). The medians of those standard errors per magnitude bin are given in Table 1 (σ_T), 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 to the previous release, the AC2000 (Urban et al. 1998b). Assuming a mean difference of 7.7 years between the Tycho–2 and UCAC1 epochs and taking the formal errors of the Tycho–2 proper motions from (Høg et al. 2000a), we obtain the error contribution due to proper motions, σ_{PM}, also given in Table 1.

2.2. UCAC1

The UCAC astrometric sky survey started in February 1998 at Cerro Tololo, Chile. In this first, preliminary catalog, data are included up to November 1999, 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 2-fold overlap pattern of fields, with a long and a short exposure on each field. The 5–element lens astrograph of 206 mm aperture uses a single 4k by 4k CCD detector, providing a $61'$ field of view with a scale of 0.9"/pixel. Stars in the range of 10 to 14th magnitude are the most precise with an estimated positional error of $\approx$20 mas. Brighter stars are overexposed on the long exposures, hence only the short exposures generally contribute to positions of stars around magnitude 8 to 9.5. Stars brighter than 8.0^m are also saturated on most short exposures. For faint stars, the precision degrades to about 70 mas at the limiting magnitude of R$\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 with the Tycho–2 data, the UCAC1 proper motions are mainly derived from AC and Tycho–2 data, thus 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 individual star in common.

The UCAC1 was reduced using Hipparcos, Tycho–1 and ACT data, thus mainly depends on the original Tycho–1 Catalogue stars plus the

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

proper motions derived from the AC2000 reductions. In particular, all new, faint stars in Tycho–2 which are not in Tycho–1 are field stars in UCAC1, thus were not used as reference stars. Therefore UCAC1 positions of those 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 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 6–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 if the magnitude dependent systematic errors are inherent in the UCAC x, y–data or 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 ($\approx 2...6$) individual observations per star. The (squared) mean of these individual sigmas over all stars in a magnitude bin is an estimate of the standard error of the positional precision of the catalog and is given in Table 1 as σ_U. This σ_U is slightly underestimated due to 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 due to 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 given in Table 1 for both catalogs are for about the same stars on each line. The last column in Table 1 gives the expected combined standard error of (Tycho–2 − UCAC1) position differences as derived from internal, formal errors only.

3. Results of the Catalog Comparison

In total, close to 1.0 million stars have been found in common between the Tycho–2 Catalogue and UCAC1, adopting a match radius of 500 mas. 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 (Tycho–2 − 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 the range of ≈5 magnitudes. While the magnitude equation for the right ascension component (x) is almost linear, it is non–linear 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 (Tycho–2 − UCAC1) position differences are plotted versus declination. The general offset is due to the fact that the majority of stars (faint end) have a non–zero position difference due to the magnitude equation. The variation of this offset, and thus the magnitude equation, follows a zonal pattern in declination. A plot of the differences vs. right ascension shows no pattern. There are also no 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 vs. $(B - V)$ 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 units of 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 are obtained from

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

and similarly for the y–coordinate, where x_i, y_i are the individual (Tycho–2 − UCAC1) position differences and $\bar{x}, \bar{y}$ are their arithmetic means for that magnitude bin. In order to exclude outliers, two approaches were made. 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 given in Table 2 in the σ_{cx}, σ_{cy} columns. The second method used the 25 to 75 percentile of the distribution of the position differences around their mean. Assuming the central parts of our position differences distributions to be Gaussian, σ_{qx}, σ_{qy} values were derived (see Table 2). For easy comparison, the last column of Table 2 gives the *expected* combined standard error for our position differences, from the formal errors alone, 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 consistend 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 those stars are close to the pixel saturation level, within a factor of ≈3 in the amplitude counts in either the long or 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 can not 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.

4.2. Error budget

There are 5 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 like 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 $(\sigma_{cx}, \sigma_{cy})$ nor the 50% quantile standard errors are likely to eliminate those problem stars from the statistics. Also, positional shifts 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, will have different offsets w.r.t. 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 differenctial color refrection is

about 10 mas for the UCAC bandpass and a zenit 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 3 internal errors (catalog 1, catalog 2, 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 (typical 40 to 50% underestimation of errors) between observed and expected standard errors are seen in the mid range of fainter than 9th and brighter than 11th magnitude. This is the transition area between positions based on short exposures only and 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 w.r.t. the formal errors is relatively small; ranging from insignificant to $\approx$10% when compared with the $(\sigma_{cx}, \sigma_{cy})$ (cut distribution), and about 20% when compared to the $(\sigma_{qx}, \sigma_{qy})$ numbers. This gives an external verification of the accuracy of the Tycho–2 astrometry and sets an upper limit to the ratio of true/formal errors to about 1.2 at the faint end of the catalog, which includes the majority of the stars. At those 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 11 to 16 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 (Johnston et al. 1999) input catalog. The Tycho–2 Catalogue covers all sky and is the preferred astrometric reference down to about magnitude V=10.5 or wherever 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 at http://ad.usno.navy.mil/ad/ucac/. 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.

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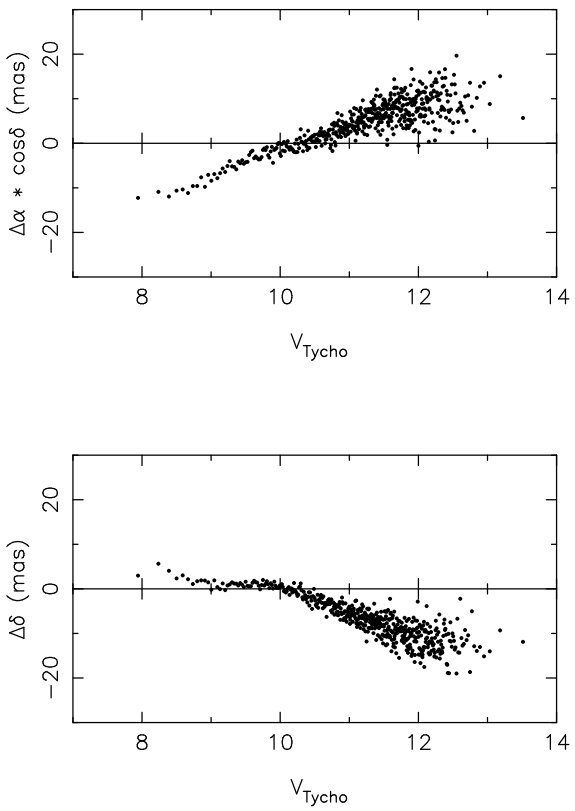

Fig. 1.— Position differences (Tycho2–UCAC1) as a function of Tycho V magnitude. All stars in common are included. One dot represents the mean for 2000 stars.

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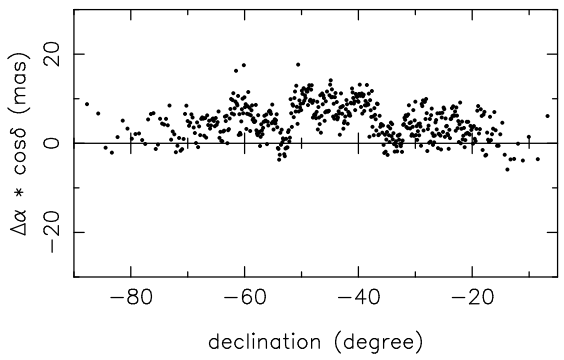


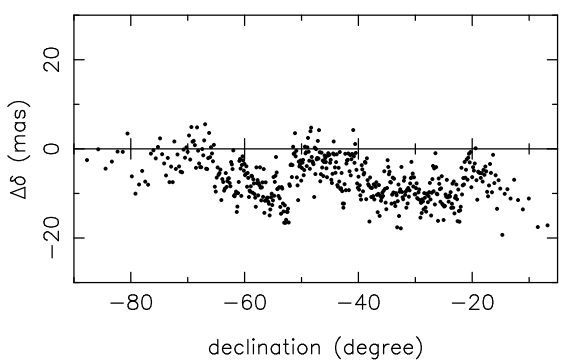
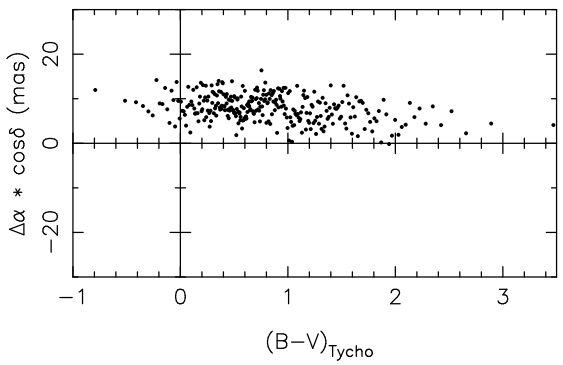


Fig. 2.— Position differences (Tycho2–UCAC1) as a function of declination. One dot represents the mean for 2000 stars.



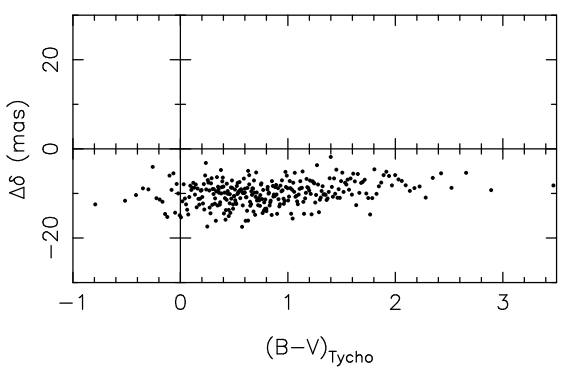


Fig. 3.— Position differences (Tycho2–UCAC1) as a function of color index. One dot represents the mean of 2000 stars.

Table 1: Internal precision of Tycho–2 (σ_T) and UCAC1 (σ_U) positions as a function of Tycho visual (V_T) and UCAC red (R_U) magnitudes. The error contribution from the proper motions is given in column σ_{PM}, and σ_{T-U} gives the formal expected error in the Tycho − UCAC1 position comparison.

V_T mag	σ_T mas	σ_{PM} mas	R_U mag	σ_U mas	σ_{T-U} mas
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

Table 2: Results of the catalog comparison using only the Tycho–2 stars not contained in Tycho–1 as a function of V_T magnitude. The column n gives the number of stars in a given magnitude bin. The standard errors for x and y are for $\Delta\alpha\cos\delta$ and $\Delta\delta$ respectively. For more details see the section 3.2.

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