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Extending the ICRF into the Infrared: 2MASS–UCAC Astrometry

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Abstract.

An external comparison between the infrared 2MASS and the optical UCAC positions was performed, both being on the same system, the ICRS. About 48 million sources in common were identified. Random errors of the 2MASS catalog positions are about 60 to 70 mas per coordinate for the $K_S = 4$ to 14 range, increasing to about 100 to 150 mas for saturated and very faint stars. Systematic position differences between the 2 catalogs are very small, about 5 to 10 mas as a function of magnitude and color, with somewhat larger errors as a function of right ascension and declination. The extension of the ICRF into the infrared has become a reality.

1. Introduction

The International Celestial Reference Frame (ICRF) is defined by a few hundred radio sources (Ma & Feissel 1997). The optical representation of the ICRF is the Hipparcos Celestial Reference Frame (HCRF) of about 100 thousand stars. The optical system has been densified by the Tycho-2 Catalogue, and recently by the USNO CCD Astrograph Catalog (UCAC) (Zacharias et al. 2000, 2004). The Two-Micron All Sky Survey (2MASS) (Skrutskie et al. 1997; Cutri et al. 2003) is primarily a highly accurate infrared (IR) photometric catalog. It also provides accurate positions at its observational epoch (1997 to 2001) for over 470 million sources. The 2MASS represents the best extension of the ICRF into the IR currently available. Here we investigate the astrometric performance of the 2MASS catalog by comparing it with UCAC2 (Zacharias et al. 2004).

Contrary to the defining, extragalactic sources, stars are moving significantly. No proper motions are available from 2MASS, so this astrometric coordinate system at IR wavelengths is currently limited to positions only. However, it is closely tied to the optical system, thus "inheriting" proper motions from optical data, as far as they are available. As with the current optical system, the 2MASS IR system is not directly linked to the defining sources. It depends on a link *via* moving stars, affected by the same potential problems of possible deviations from an inertial system. However, these deviations are expected to be well below 1 mas/yr in rotation, with the zero point of coordinate systems coinciding to within about 3 mas at current epochs. This is smaller than the systematic errors seen in the 2MASS to UCAC comparison as a function of various parameters.

Of course, we also assume the optical and IR centroids of the matched stars coincide. There is no reason to believe otherwise on the mas level. Most sources are stars. A random scatter is introduced by unresolved double stars, where the centroid location can be a function of the bandpass.

Table 1. 2MASS observational details.

2 telescopes	Mt. Hopkins, Cerro Tololo
observing epochs	1997 Jun – 2000 Dec (North)
	1998 Mar – 2001 Feb (South)
aperture	1.3 meter
J (1.24 μm), H (1.66 μm),	K_S (2.16 μm) simultaneously
survey tiles	8.5' by 6 degree (RA by Dec)
6 samples (1.3 sec)	each point on the sky
raw data volume	24.5 TB
all-sky release data volume	50 GB compressed
all-sky release date	March 2003
number of point sources	470,992,970
other data	atlas images, extended sources

Table 2. UCAC2 observational details.

1 telescope	USNO Twin astrograph
observing epochs	1998 Feb – 2001 Sep (CTIO)
	2001 Nov – 2004 May (NOFS)
aperture	0.2 meter
detector	4k x 4k CCD (0.9"/px, 9 μm, 61' FOV)
2 exposures / field	2–fold overlap of fields
single bandpass	579–642 nm
positional errors	30 mas for r = 8 .. 10
	20 mas for r = 10 .. 14.5
	70 mas for r = 16

2. Observations

Both, 2MASS and UCAC2 positions are on the same system, the ICRS, due to the use of Tycho-2 reference stars. This also means that 2MASS and UCAC2 positions of r $\approx$ 8 to 12 mag stars are highly correlated (= Tycho2 stars). Some observational details of the 2 surveys are summarized in Table 1 and 2. 2MASS

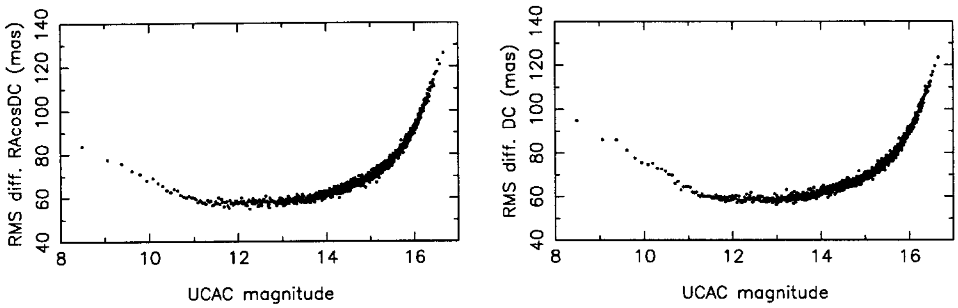

Figure 1. RMS 2MASS–UCAC2 position differences as a function of magnitude for declination zone $-40°$ to $-30°$, right ascension on the left, declination on the right. Other areas in the sky look very similar.

covers the entire sky, while UCAC2 covers 86% of the sky ($90° \leq \delta \leq \approx +45°$). More details are given at the respective home pages *ad.usno.navy.mil/ucac* and *www.ipac.caltech.edu/2mass/releases/allsky/*.

UCAC2 and 2MASS positions were cross-correlated using a match radius of 0.5 arcsec. The 47,958,962 common sources represent 99.23% of all UCAC2 sources. The UCAC2 proper motions were applied to bring the UCAC2 positions to the observational epoch of individual 2MASS sources. Errors from proper motions are negligible here because of the small epoch difference between UCAC2 and 2MASS ($\approx$ 1 to 2 years).

The positional errors of UCAC2 are negligible in this comparison for stars in the R= 10 to 14.5 magnitude range (see Table 2). From internal estimates and comparisons with other catalogs, the expected positional errors in the 2MASS data is about 70 mas for K_S = 4 to 14.5, with larger errors for saturated and faint stars.

3. Results

3.1. Random Errors

Figure 1 shows the root-mean-square (RMS) differences between the 2MASS and UCAC2 positions for 2 declination zones. This and all following similar figures show binned data with one plot dot representing the mean over 5000 stars. This confirms the 2MASS average random position errors to be about 60 to 70 mas for the mid-magnitude range, independent of location in the sky. The increased scatter beyond R=15 is due to the decreasing signal-to-noise ratio of the UCAC2 data, conforming to 70 mas external errors per coordinate at R=16. The increased scatter at the bright end is caused by larger errors in both catalogs as compared to the mid-magnitude range. For these bright stars the error contributions from each catalog individually can not be separated without additional external data or assumptions.

3.2. Systematic Errors

Figure 2 shows the 2MASS–UCAC2 position differences as a function of UCAC magnitude (between V and R) for the same declination zones as Fig. 1. The

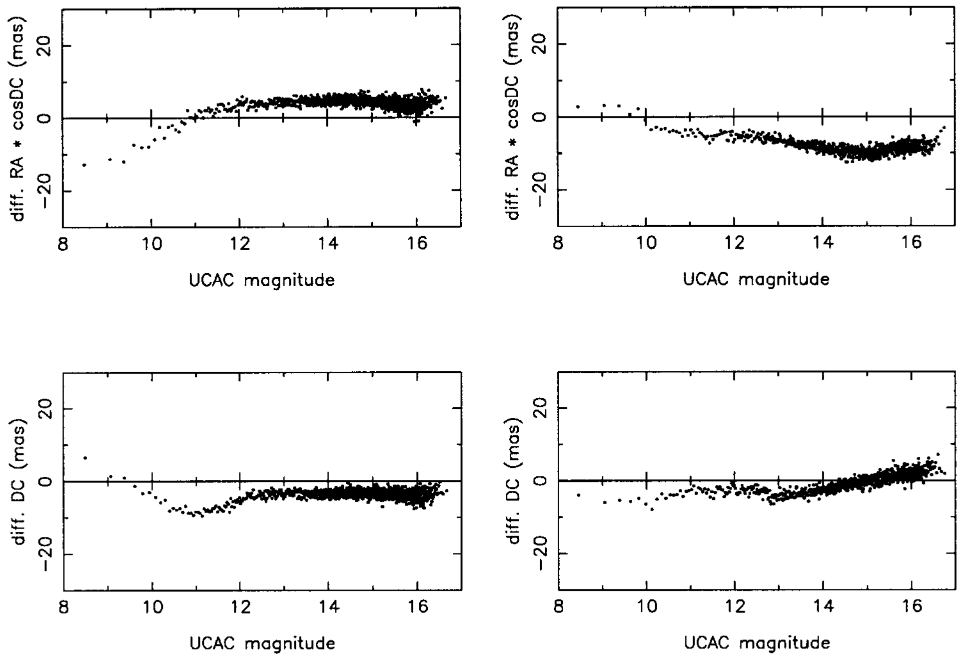

Figure 2. 2MASS−UCAC2 position differences as a function of magnitude for declination zones −40° to −30°, and +30° to +40°, on the left and right, respectively, RA on top, Dec below.

results are similar for other areas in the sky, showing different patterns. Systematic differences are only on the 5 to 10 mas level which is amazing and shows the high astrometric quality of both data sets. In particular, there is no significant (linear) magnitude equation between the 2 catalogs.

Figure 3 shows the position differences as a function of 2MASS J magnitude. The transition between the patterns for bright and faint stars ($\Delta\alpha$) is more pronounced for the J magnitude than the UCAC magnitude. The slight discontinuity is related to the 2MASS observations (see below).

Figure 4 shows the systematic differences as a function of color (UCAC2 r − 2MASS J), which are also in the 5 to 10 mas range. The slope (linear color equation) is generally less than 2.5 mas/mag, almost insignificant. The average offset of the $\Delta\alpha$ plot for the −40° to −30° zone (left hand side) is caused by the magnitude equation (see Fig. 3), it is not an effect of color.

Figure 5 shows the systematic position differences as a function of right ascension for the same declination zones as before. The binning (5000) is the same as before and the larger scatter than before is obvious. Similarly, Figure 6 shows the position differences as a function of declination, here for 2 slices along right ascension, 3 to 4 hours and 15 to 16 hours, respectively. The increased scatter near 8h and 16h in the −30° to −40° plots and near 6h and 20h in the +30° to +40° deg plots in Figure 5 is likely the result of increasing confusion in the Galactic Plane.

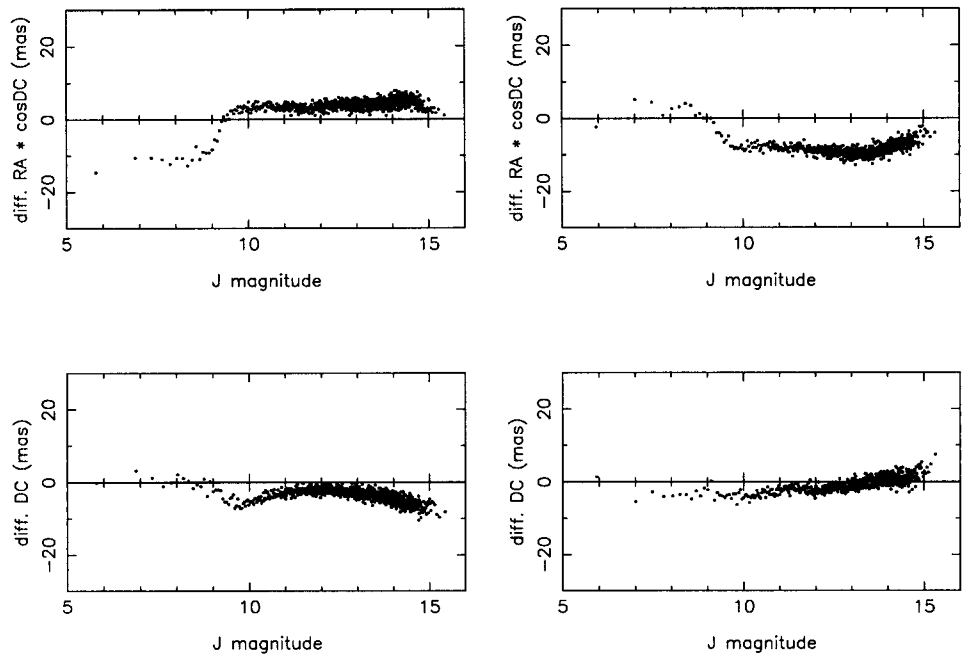

Figure 3. 2MASS–UCAC2 position differences as a function of 2MASS J magnitude for the same declination zones as before.

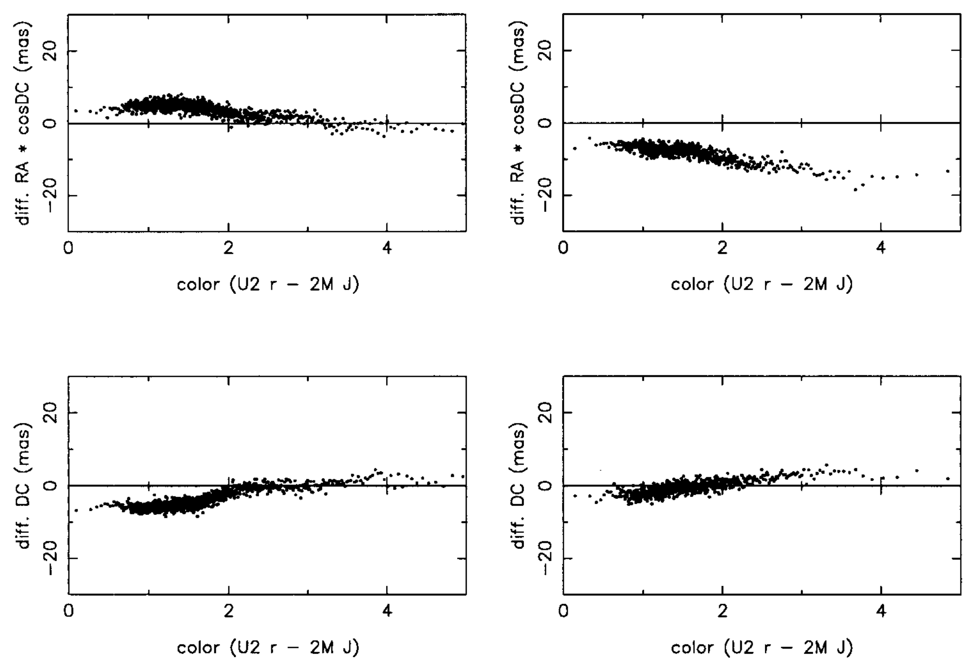

Figure 4. 2MASS–UCAC2 position differences as a function of color (UCAC r - 2MASS J) for the same declination zones as before.

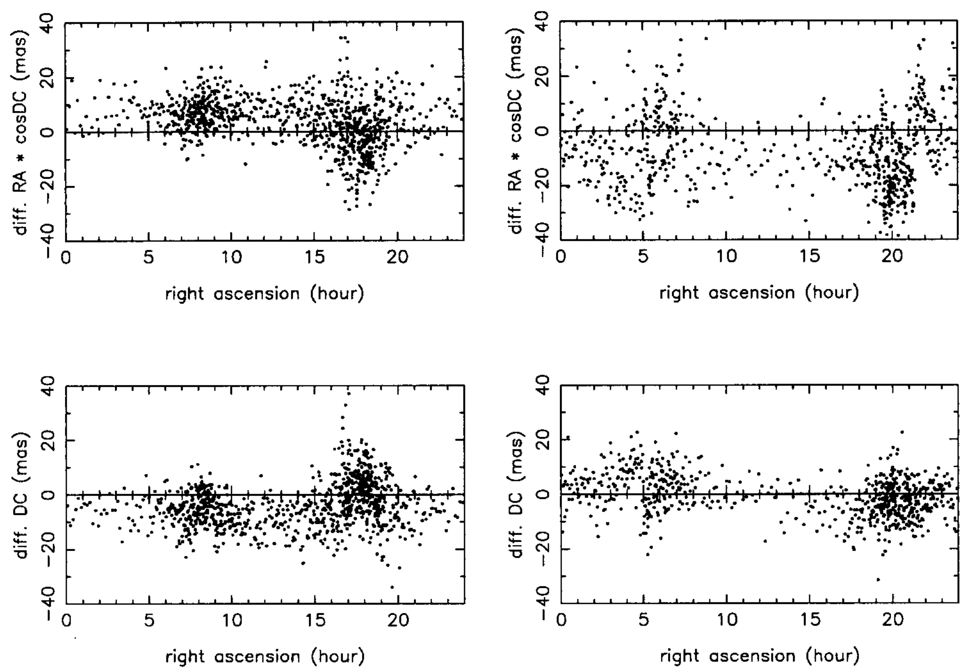

Figure 5. 2MASS−UCAC2 position differences as a function of right ascension for the same declination zones as before.

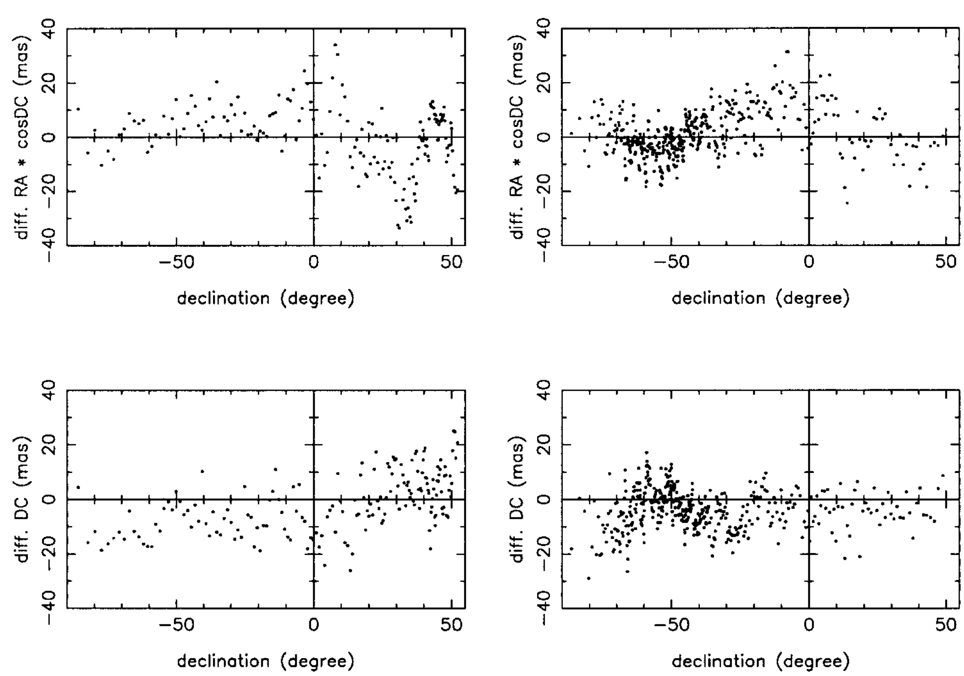

Figure 6. 2MASS−UCAC2 position differences as a function of declination for the RA = 3 to 4 h (left) and 15 to 16 h (right) slice.

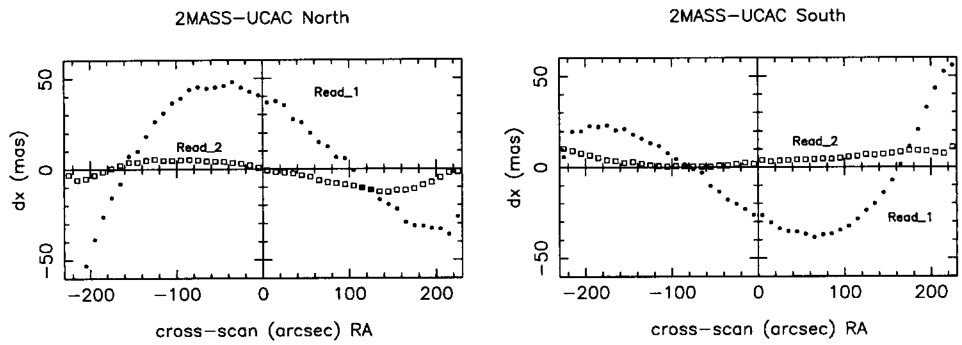

Figure 7. Systematic errors of 2MASS positions as a function of cross-scan coordinate (RA) for "Read1" of bright stars. The "Read2" (long exposures) for most of the stars show small errors.

3.3. Read1 Errors

The 2MASS measurements of bright stars were derived from short 51 ms exposures (Read1), while those of fainter stars were derived from longer 1.3 sec exposures (Read2). A field distortion effect was inadvertantly left uncorrected in the position reconstruction of the Read1 detections, resulting in a systematic error of about ± 50 mas for the x-coordinate (RA) as a function of cross-scan (RA) position, with a repeatable pattern for every about 500 arcsec. This is the single, largest systematic error contribution found in the 2MASS data.

4. ICRF–2MASS Comparison

Out of the 708 ICRF plus extension 1 sources, 391 could be identified with 2MASS sources. These counterparts are generally very faint and the mean expected random error of the 2MASS positions is over 100 mas. Nevertheless this test provides a valuable system check at the faint end of 2MASS with a direct comparison to the ICRF. Table 3 gives the results. The mean offsets in the (ICRF–2MASS) position differences are small. For a 400 mas cut (of outliers), the standard error of the mean is 6.4 mas, thus even the offset in RA (−9.1 mas) is only on the 1.5 sigma level, thus not significant. A plot of these differences as a function of declination or magnitude does not reveal any systematic trends.

5. Conclusions and Summary

The 2MASS positions (at current epoch) are as precise as the UCAC2 positions at its faint end ($r \approx 16$), which is about 70 mas per coordinate. For saturated and very faint 2MASS images the positional errors are about 100 to 150 mas. The 2MASS positions are more precise than the USNO A or B positions, which were derived from Schmidt plate scans, thus even benefiting optical astrometry, providing a dense (470 million stars), all sky net of reference stars. For stars in the $r = 10$ to 15 mag range, the UCAC is still preferable over 2MASS astrometry (by a factor of about 3).

Table 3. ICRF−2MASS position differences (mas).[a]

limit(mas)	ns	meanx	sigx	meany	sigy
200	302	-3.7	86	-0.7	87
300	350	-5.5	104	0.1	109
400	375	-9.1	124	0.2	124
500	391	-15.4	145	-2.5	139

[a] Results vary slightly as a function of the cut-off limit for outliers. ns gives the number of sources, mean and sig give the average position offset and scatter over all sources in the sample, for the x and y coordinate (RA, Dec), respectively. Unit is mas.

Compared to UCAC2 the 2MASS positions show small systematic differences (5 to 10 mas) as a function of magnitude and color, with larger scatter as a function of RA and Dec. Either one of the catalogs might have true systematic errors on this level. The largest systematic error of about 50 mas is a function of cross-scan (RA) for bright images, which were observed with the "Read1" short exposures.

The 2MASS catalog is on the ICRF, with no significant offsets in its coordinates. It is also on the Tycho-2 system, consistent with the HCRF for bright stars. Systematic errors of 2MASS positions w.r.t. Hipparcos stars have not been investigated here. The strength of 2MASS astrometry (applications) will be at fainter than Hipparcos magnitudes. The extension of the ICRF into the infrared has become a reality!

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