Maintenance of the link to Hipparcos

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Abstract. The optical wavelength astrometric reference frame is currently based on observations made by the Hipparcos astrometric satellite. Unfortunately, since the Hipparcos Celestial Reference Frame (HCRF) is comprised of bright stars which are sparsely distributed on the sky, the frame often is inappropriate for astronomical and astrometric programs requiring a denser distribution of faint stars. Thus, significant effort has been channeled into the densification of the HCRF. We discuss optical reference frame densification programs and the maintenance of the link between these programs and the HCRF.

1 Introduction

Following IAU resolution B1.2 (24th General Assembly, Manchester, 2000) only Hipparcos stars without known multiplicity (flags C,G,O,V,X) are to be used for astrometric reference frame link and densification work. This subset of Hipparcos stars defines the Hipparcos Celestial Reference Frame (HCRF). However, in many cases as mentioned below, Hipparcos stars are too bright and too sparse to be used as reference stars directly. Almost all current densification projects rely on the Tycho-2 Catalogue (Høg et al., 2000), which is on the HCRF (within its limits).

The Tycho-2 actually involves 2 aspects. Positions near the central Hipparcos epoch (1991.25) are based on the Hipparcos/Tycho space mission data (ESA 1997). The accuracy of densification catalogs here depend on how successful the Hipparcos Catalogue and the Tycho data have been put on the same system, which is believed to be on the sub-mas level. The Tycho-2 proper motions on the other hand have been derived from a combination of many ground-based, early epoch catalogs, which have been put onto the HCRF as good as possible before deriving the proper motions. Particularly at the faint end, systematic errors are possible. The projects discussed here are not yet ready to externally assess the link between HCRF and Tycho-2. However, some projects have the potential to allow such an evaluation in the near future.

Over 10 years after the successful Hipparcos mission a first attempt was made to improve upon the original link between the HCRF and the extragalactic ICRF (Bobylev et al., 2004). The possible error in the alignment between the 2 systems increases with time, approaching about 3 mas estimated standard error per axis at the 2005 epoch. The ongoing USNO extragalactic link program has the potential to externally test the HCRF to ICRF link. Observations were completed by end of 2004 and reductions are in progress. First results were presented at the Lowell astrometry meeting (Zacharias & Zacharias, 2005).

For the Hipparcos system maintenance issue in a broad sense, several observational programs are ongoing. These fall into 3 categories: 1) densification of the reference frame at optical wavelengths, 2) extension of the Hipparcos frame to infrared (IR) wavelengths, and, 3) critical check on the radio to optical reference frame link itself.

An overview and the status of these projects is given below. Much is work in progress without results on reference frame issues at this time.

2 Densification

An overview is given in the IAU reviews about ground-based (Zacharias, 1998) and space-based (Röser 1998) densification programs. There is currently no astrometric space mission close to a launch date.

Table 1 gives an overview of the ground-based densification programs. All except the 2MASS project (see below) are at optical wavelengths. The meaning of the column "type" is: S = astrometric program but selected area in the sky only, A = all-sky astrometric, and G = general survey, no emphasize on astrometry. The number of stars in each catalog is given in millions (M). The quoted positional errors are 1 sigma estimated external errors per coordinate. When a range is given, the errors depend mainly on the magnitude. Release years beyond 2005 are estimates.

NOMAD is the Naval Observatory Merged Astrometric Dataset (Zacharias et al. 2004). For each star "the best" astrometry and photometry is picked from various catalogs including Hipparcos, Tycho-2, UCAC, USNO-B, and 2MASS. Cross-references are given in NOMAD but not all columns from the original catalogs are copied into NOMAD. NOMAD is not a compiled catalog. Although all catalogs merged into NOMAD are on the ICRF within their limitations, systematic differences between individual catalogs do exist. The original catalog positions merely have been copied into NOMAD. Figure 1 shows an example for the UCAC to USNO-B differences, most of which can be attributed to the USNO-B.

2.1 UCAC

A major program for the densification of the optical reference frame is the UCAC project (USNO CCD Astrograph Catalog). This all-sky survey gives 20 mas positions for stars in the about 10 to 14 mag range, with a limiting magnitude of about R=16. The first release (UCAC1) was published in March 2000 (Zacharias et al., 2000), containing positions and proper motions of 27 million stars on the Hipparcos System (HCRF). Reductions of the UCAC1 positions rely on the original Tycho Catalogue (Tycho-1). UCAC1 proper motions of bright stars ($R \leq 12^m$) utilize mainly Astrographic Catalogue (AC2000) data (Urban et al., 1998), and faint stars the USNO A2 (Monet, 1998).

In September/October 2001, the astrograph was relocated from CTIO (Chile) to the Naval Observatory Flagstaff Station (NOFS) in Arizona. All sky observations were completed in May 2004. The last Kitt Peak 0.9m run for the extragalactic link program was performed in December 2004 with parallel observing at the astrograph.

The second data release (UCAC2) includes observations up to mid December 2002. Contrary to UCAC1 the UCAC2 positions are based on the Tycho-2 catalog and improved proper motions are provided utilizing a part of recent re-measures of the AGK2 plates performed on the USNO Washington StarScan measuring machine, as well as PMM remeasures of the NPM and SPM data. The UCAC2 contains over 48 million stars, covers 86% of the sky and was released at the 2003 IAU in Sydney (Zacharias et al., 2004).

For the final UCAC3 the pixel raw data will be re-reduced to achieve a higher completeness and improve on astrometric and photometric reductions. The over 1200 tapes (4.5 TB) are being loaded to RAID disk arrays; however, UCAC3 will not be ready before 2006.

Table 1. Important, recent catalogs for astrometry.

Name of catalog	mag. range	bandpass (approx.)	number of stars	pos.err. (mas)	type	release year	comment
ACR-2	10–17.5	R	1.2 M	26– 60	S	1999	equator. areas
M2000	– 17	V	2.3 M	35–100	S	2001	+11 to +18 decl.
CMC12	9 – 17	r'	6.3 M	36–113	S	2002	−3 to +3 decl.
CMC13	9 – 17	r'	many	35–100	S	2003	+3 to +30 decl.
UCAC1	8 – 16	579-643	27 M	25– 70	(A)	2000	−90 to −15 decl.
UCAC2	8 – 16	...	48 M	20– 70	(A)	2003	−90 to +40 decl.
UCAC3	8 – 16	...	70 M	20– 70	A	2006	all sky
GSC-2.2	12 – 20	B,V	456 M	300	G	2002	posit., photom.
USNO-A2	12 – 20	...	526 M	200	G	2001	posit., photom.
USNO-B	12 – 20	...	1000 M	200	G	2002	incl. proper motions
SDSS	15 – 23	u,b,v,r,z	many	50–150	G	2003	about 5000 sq.deg
2MASS		J,K,H	471 M	60–100	G	2003	infrared survey
NOMAD	-1 – 20	B,V,R,J,H,K	1100 M	10–200	A	2005	merged data set

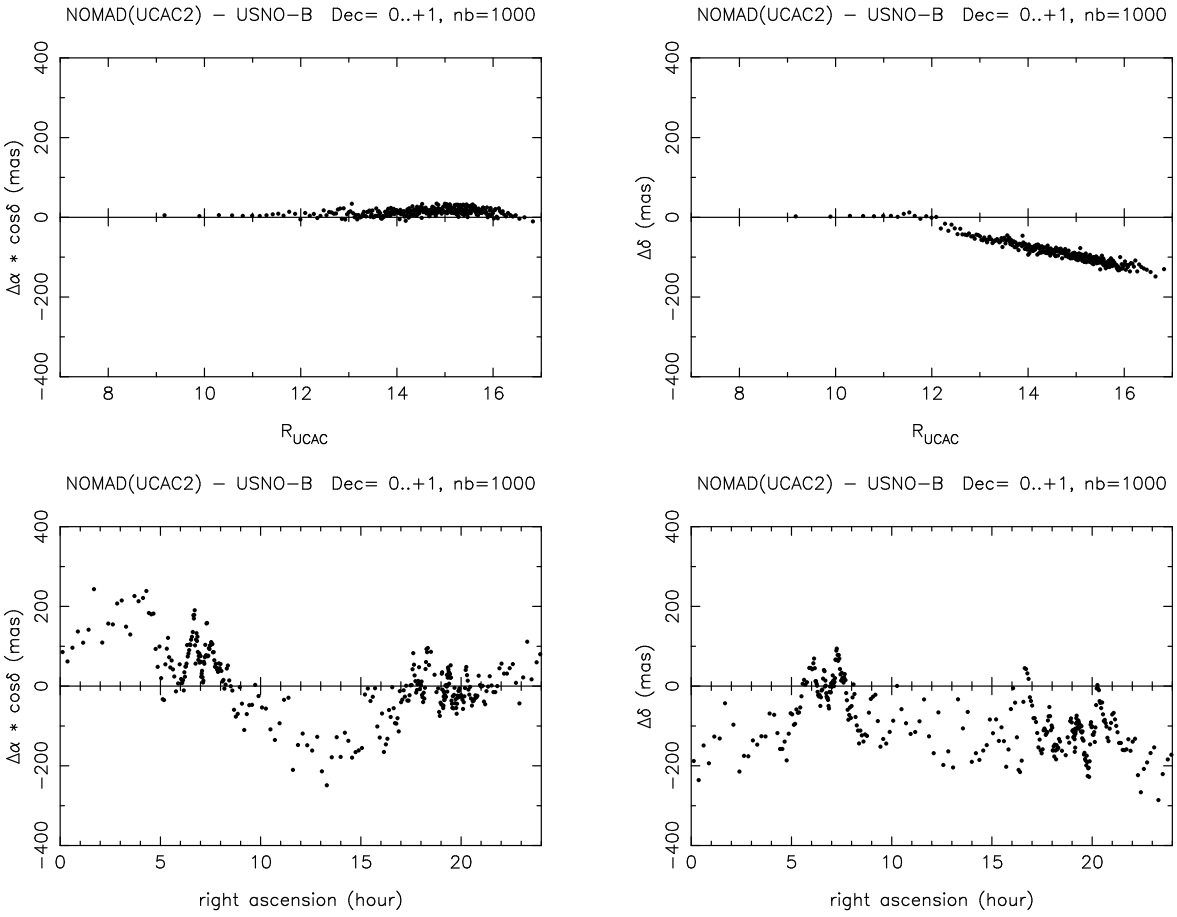

Fig. 1. UCAC2 minus USNO-B systematic position differences. Examples are shown as a function of magnitude and right ascension.

2.2 Other densification projects

Other major densification projects are the CMC, M2000 and ACR. The Carlsberg Meridian Circle (CMC12 and CMC13) program, is a joint effort of institutes from Denmark, UK, and Spain. The declination zone −3 to +30 degree has been observed in drift-scan mode with a re-furbished transit circle instrument (Evans, Irwin &Helmer, 2002). A northern extension is being observed. A similar project, the M2000 catalog has been produced by the Bordeaux Observatory for the +11 to +18 degree zone (Ducourant et al. 2002). The second release of the Astrometric Calibration Regions (ACR) obtained from the Flagstaff Astrometric Scanning Transit Telescope (FASTT) are available since a few years (Stone, Pier & Monet, 1999). All these projects use Tycho stars to link to the Hipparcos system.

The Sloan Digital Sky Survey (SDSS) concluded its deep 5-band photometric survey in areas around the galactic north pole. Astrometry is tied to the HCRF via Tycho-2 and preliminary UCAC positions, where available. When using UCAC data, the SDSS positions are more accurate than using Tycho-2 stars by a factor of about 2 due to the high accuracy and density of UCAC.

World wide web links for all mentioned projects are provided in Table 2. Most projects are ongoing and only preliminary data are available now. A comparison between the UCAC1 and Tycho-2 has been published (Zacharias et al. 2000). The current, astrometric, ground-based catalogs have mainly systematic errors as a function of magnitude, typically on the 20 to 30 mas level. Variations as a function of color as well as location in the sky (mainly zonal, declination dependent) are also possible. A detailed comparison between the various position catalogs is planned in the near future.

Table 2. World wide web links to densification projects.

Project	link
ACR-2	ftp.nofs.navy.mil /pub/outgoing/calibregions
M2000	www.obs.u-bordeaux1.fr/m2a/soubiran/equipe/JF/M2000/m2000.htm
CMC12,13	www.ast.cam.ac.uk/ dwe/SRF/cmc12.html
UCAC	ad.usno.navy.mil/ucac
GSC-2.2	www-gsss.stsci.edu/gsc/gsc2/GSC2home.htm
USNO A,B	www.nofs.navy.mil/projects/pmm/
SDSS	www.sdss.org
2MASS	www.ipac.caltech.edu/2mass/
NOMAD	www.nofs.navy.mil/nomad

3 IR observations

3.1 2MASS

The major program to extend the Hipparcos frame into wavelengths other than optical or radio is the 2-micron All Sky Survey (2MASS) project. IR photometry (J,H,K) has been obtained with 2 identical telescopes (north, south) for over 400 million point sources. The astrometry is on the HCRF and the average error per catalog position coordinate is around 80 mas with much smaller systematic (zonal and magnitude dependent) errors.

In 2001, pre-release 2MASS data was obtained by USNO from R. Stiening (private communication) and a comparison with UCAC positions was made. Overall a very good agreement was found, with largest systematic position differences being 50 mas. The results helped to better understand systematic errors in the 2MASS data and lead to improvements in the reduction pipeline. For the final release a significant improvement in the accuracy of 2MASS positions was achieved, with similar random errors in positions as reported on the preliminary data (Zacharias et al., 2005).

End of 2002 new, preliminary 2MASS data were received and compared to preliminary UCAC2 positions. Observations for both projects were obtained almost at the same epoch. The 2MASS data is strictly reduced with Tycho-2 data for reference stars, as is UCAC2. Thus for stars not in Tycho-2 (mainly R $\geq$ 12) the UCAC2–2MASS differences are truly external. Some results are presented in Figures 2 and 3. Systematic errors as a function of magnitude are small except for the critical link area around 9 to 11th magnitude. There are also significant variations as a function of location in the sky and color of the stars (Figure 3). Note, the systematic differences are highlighted in these plots due to binning of a large number of stars. The average precision of a single star is about 20 to 70 mas in UCAC2 and 60 to 100 mas in 2MASS, while the systematic errors are only on the 10 to 20 mas level.

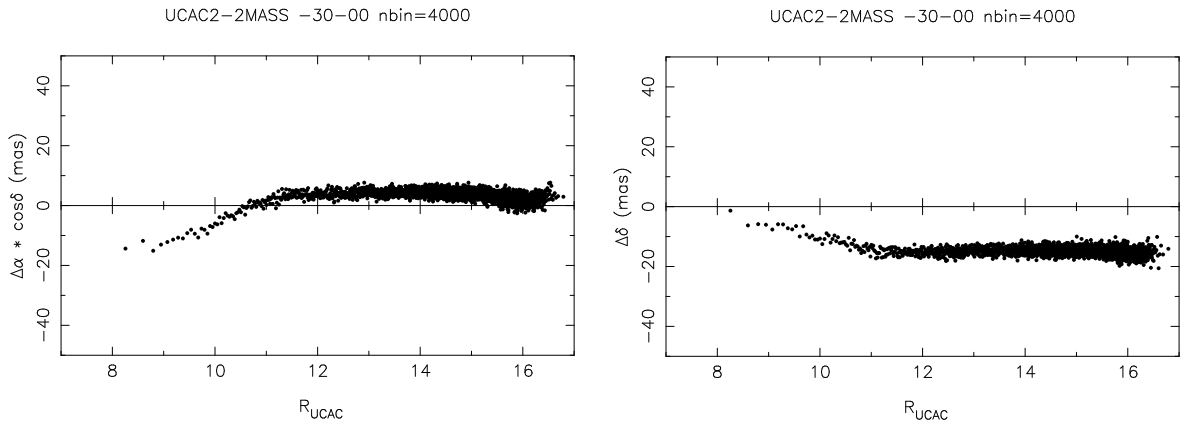

Fig. 2. Sample comparison between UCAC2 (optical) and 2MASS (IR) pre-release positions. Position differences for stars in the −30 to 0 degree declination range are shown as a function of UCAC red magnitude. Each dot represents the mean over 4000 stars to highlight systematic differences.

3.2 Other efforts

At the 1.55m Strand telescope in Flagstaff, test observations were performed with a large format (1k chip) IR detector of selected extragalactic link sources. Currently optical observations are being performed with an even larger field of view (2k detector) and lower noise characteristics.

As far as other wavelengths are concerned, radio observations are usually tied directly into the ICRF. X-ray and Gamma-ray observations are being linked to dense optical catalogs like the USNO A and B, thus are typically on the 200 mas level if an optical identification can be made at all.

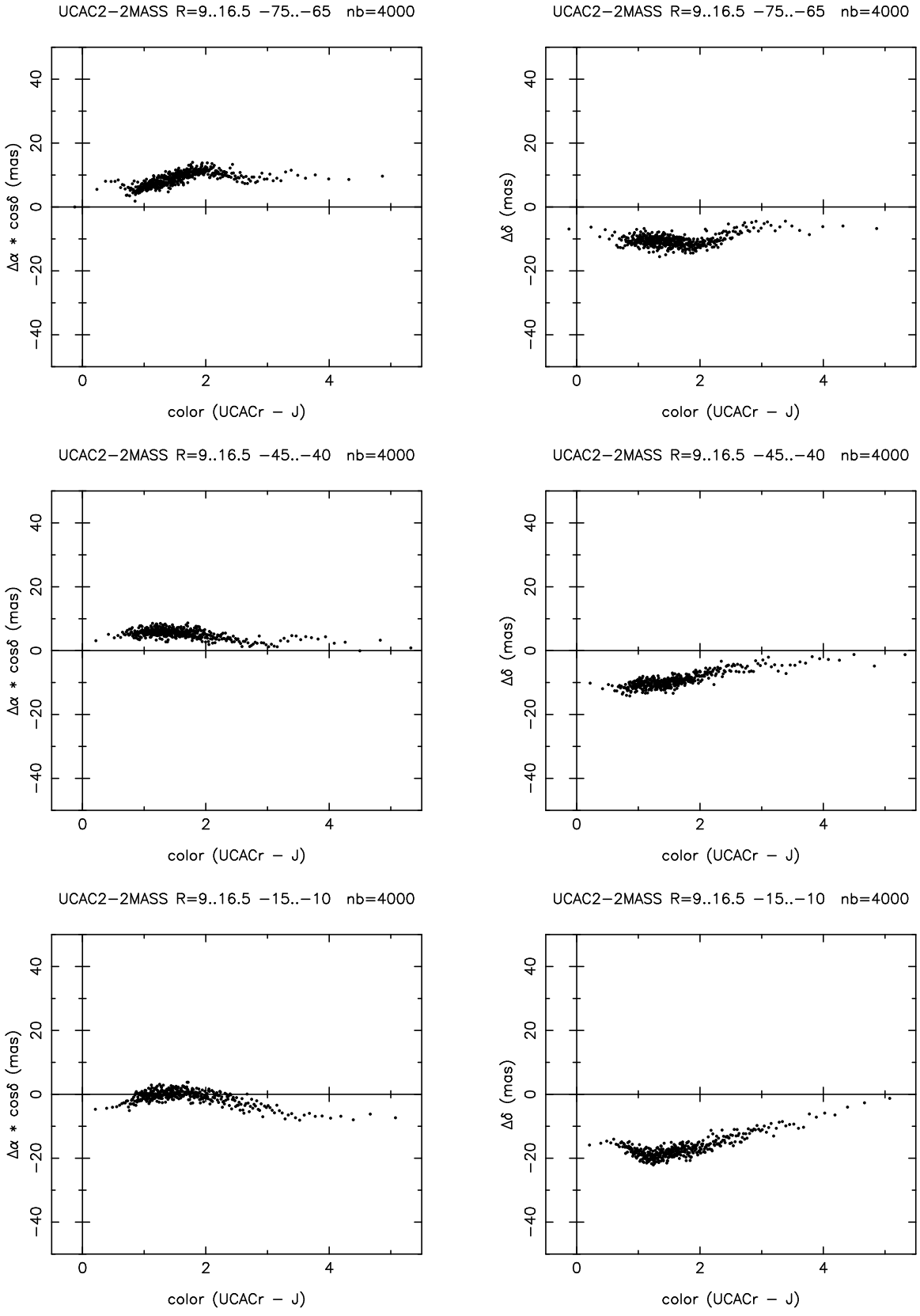

Fig. 3. Similar to the previous figure for UCAC−2MASS position differences (RA on the left, Dec on the right) are shown as a function of color. The data are split into declination zones (top to bottom), showing a clear variation with area in the sky.

4 Radio–optical extragalactic link program

A comprehensive extragalactic link program is part of the UCAC project. The goal is to eventually provide a link between the ICRS and the UCAC, independent of HCRF (using block adjustment procedures) and then quasi externally assess the HCRF-ICRF link accuracy. As a first step traditionally reduced CCD frames provide optical positions of ICRF counterparts supposedly on the HCRF, using Tycho-2 and UCAC anonymous secondary reference stars in a 2-step procedure. Preliminary results from a subset of the data were published (Assafin et al., 2003; Zacharias & Zacharias, 2005).

The Assafin et al. paper is based on optical positions of about 120 ICRF sources which were obtained in 3 observing runs at CTIO and KPNO during 2001, supplemented with some observations by the 1.6-meter LNA (Brazil) of optically faint targets. It uses the UCAC2 general-survey as reference stars.

The Zacharias & Zacharias paper is the first to utilize the special USNO astrograph observations performed in parallel with the deep CCD imaging. Advantages of this approach are:

same bandpass of astrograph and deep CCD frames (579–643 nm): minimizing differential refraction effects of the atmosphere

simultaneous observations of astrograph and deep field observations to avoid problems with unknown proper motions of anonymous secondary stars used to link the data

extra observing at the astrograph provides much higher precision of star positions than regular UCAC survey data alone

east and west of pier observations with the astrograph of ICRF fields provide good calibration of systematic errors to enhance the astrometric accuracy beyond the general UCAC survey data

The goal of this project is to improve the accuracy of the HCRF to ICRF link by a factor of 2 beyond what has been obtained initially with the Hipparcos and ground-based effort. This observational program was completed by end of 2004 and a total of about 500 ICRF sources (including extensions 1 and 2) are likely to show measurable optical counterparts on our deep CCD imaging data, covering both the northern and southern hemisphere.

5 Future Developments

The late Christian de Vegt envisioned a next generation, dedicated, astrometric survey telescope (de Vegt, Laux, & Zacharias, 2003; Laux & Zacharias, 2005). The USNO Robotic Astrometric Telescope (URAT) project is based on this design (Zacharias, 2005). The 0.85 m aperture 3.6m focal length planned instrument has a 4 degree field of view. The goal is to obtain positions of stars on the 5 to 10 mas level for the 14 to 18 mag range with a limiting magnitude of about 20. A direct tie to the defining ICRF sources would be possible. Narrow bandpass observations will also allow to access Hipparcos stars. Funds have been secured for the detector development (large-format, monolithic chip), and optical design studies are in the final stages.

Space-based projects of relevance for astrometry are the NASA Space Interferometry Mission (SIM, planet quest), the ESA GAIA mission and

NASA roadmap study Origins Billions Star Survey (OBSS) (Johnston et al., 2004). However, none have lauch dates before 2010.

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