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# BRIGHT STAR ASTROMETRY WITH URAT

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RESUMEN

El Telescopio Robótico Astrométrico del Observatorio Naval de los Estados Unidos de América (URAT) está observando el cielo del norte desde Abril 2012 para un sondeo astrométrico. Múltiples traslapos por año se realizan en un único filtro (680−750 nm) usando la "lente-roja" de un astrógrafo de 20 cm y un mosaico de grandes CCDs. Además del sondeo regular y profundo hasta magnitud 18.5, se hacen exposiciones cortas con una rejilla en el objetivo para tener acceso a estrellas tan brillantes como de tercera magnitud. En este trabajo se describe de forma sucinta el programa, las observaciones y las reducciones. Se obtienen posiciones a nivel de 8 a 20 msa para 66,202 estrellas Hipparcos en la época actual. Estas son comparadas con Hipparcos para investigar su incertidumbre. Alrededor de un 20% de las estrellas Hipparcos observadas tienen posiciones inconsistentes con las predichas por el Catálogo Hipparcos a un nivel 3 sigma o superior (alrededor de 75 msa o más de discrepancia en posición). Algunas estrellas ahora se observan a un segundo de arco (o 25 sigma) desplazadas de la posición predicha por el Catálogo Hipparcos.

ABSTRACT

The U.S. Naval Observatory Robotic Astrometric Telescope (URAT) is observing the northern sky since April 2012 for an astrometric survey. Multiple overlaps per year are performed in a single bandpass (680−750 nm) using the "redlens" 20 cm aperture astrograph and a mosaic of large CCDs. Besides the regular, deep survey to magnitude 18.5, short exposures with an objective grating are taken to access stars as bright as 3rd magnitude. A brief overview of the program, observing and reductions is given. Positions on the 8 to 20 mas level are obtained of 66,202 Hipparcos stars at current epochs. These are compared to the Hipparcos Catalog to investigate its accuracy. About 20% of the observed Hipparcos stars are found to have inconsistent positions with the Hipparcos Catalog prediction on the 3 sigma level or over (about 75 mas or more discrepant position offsets). Some stars are now seen at an arcsec (or 25 sigma) off their Hipparcos Catalog predicted position.

*Key Words:* astrometry — catalogs — surveys

## 1. INTRODUCTION

Since April 2012 the U.S. Naval Observatory (USNO) is conducting the USNO Robotic Astrometric Telescope (URAT) survey. The goal of this project is to establish a deep (18+ mag), very accurate (10 mas level), optical reference frame based on the Hipparcos / ICRF system using UCAC4 reference stars. The program will also identify nearby stars unbiased by proper motion selection and obtains accurate positions of bright stars at current epochs, which is the topic of this paper. Using the global coordinate system of Hipparcos through the UCAC4 reference stars, the URAT observations nevertheless give accurate positions of individual Hipparcos stars largely independent of the Hipparcos catalog. The URAT observations of these bright stars are compared to the Hipparcos Catalog to assess the accuracy of the Hippacos Catalog positions and proper motions and to identify discrepancies, i.e. stars which in reality are not at the position predicted by the Hipparcos Catalog.

## 2. INSTRUMENT

The "redlens" of the USNO astrograph is now fully utilized with its new, large focal plane of 286 mm diameter using a mosaic of 4 STA1600 CCDs (Fig. 1). Each CCD has 10,560 by 10,560 pixels and covers about 7 square deg of sky at 0.9 arcsec/pixel resolution. The dewar window serves as filter for the fixed 680−750 nm bandpass. A completely new tube structure was designed and built by the USNO instrument shop in Washington DC. Observations are performed at NOFS. For more details see Zacharias et al. (2012, 2015) and the URAT homepage[2].

## 3. OBSERVATIONS

For the regular survey each field is observed with a 240 and a 60 sec exposure. During the week of

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[2]www.usno.navy.mil/usno/astrometry/optical-IR-prod/urat

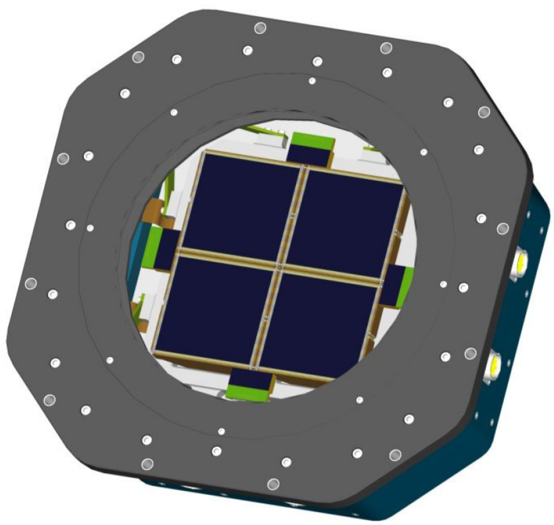

Fig. 1. URAT focal plane assembly design by Semiconductor Technology Associates (STA). The window has a clear aperture of 300 mm. The 4 large CCDs have 111 million pixels each.

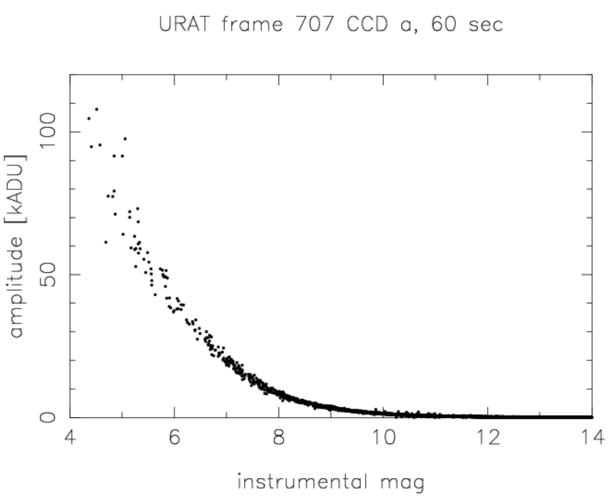


Fig. 2. Fit amplitude of individual star images as a function of instrumental magnitude for an example of URAT exposure and CCD.

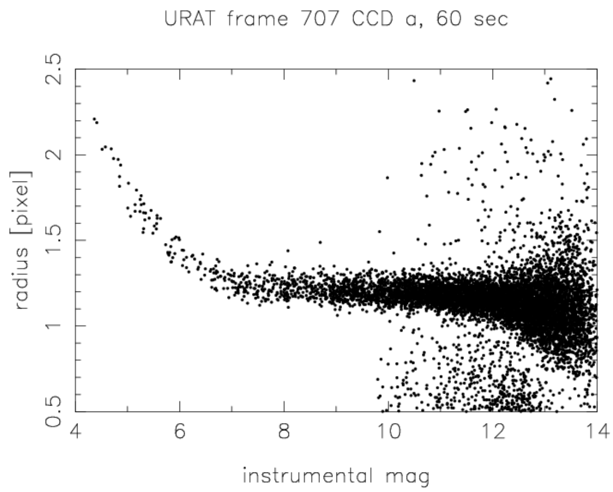


Fig. 3. Fit radius of individual star images as a function of instrumental magnitude for an example of URAT exposure and CCD.

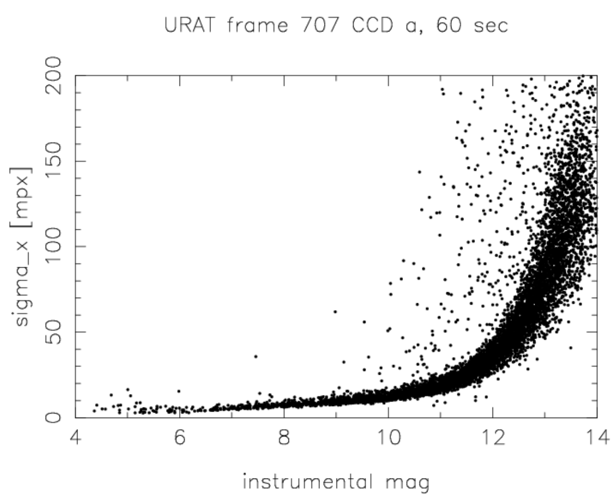


Fig. 4. Position fit error of individual star images as a function of instrumental magnitude for an example of URAT exposure and CCD.

full Moon, short exposures (10 or 20) and 30 sec are taken with an objective grating which provides diffraction images about 5 magnitudes fainter than the central image. Another about 2 magnitudes dynamical range is gained by the clocked anti-blooming (CAB) feature of the CCDs. Fig. 2 shows the image profile fit amplitude versus instrumental magnitude. Traditional saturation is reached around 30k ADU, thus at about instrumental magnitude 6.7. Beyond saturation the image profiles get wider (Fig. 3), however, the image fit position error (Fig. 4) remains low (10 milli-pixel or less), up to about 2.5 magnitudes brighter than saturation. Beyond that systematic errors become too large for sufficient calibration. Typical 10 and 30 sec exposures saturate around calibrated URAT magnitude 9 and 10, respectively. The 1st order grating images of these exposures saturate around magnitude 4 and 5, respectively.

Multiple exposures per area of sky were taken with diagonal shifts of field center to allow the same star fall onto different parts of the CCD and different CCDs. Typically 10 exposures per star and observing run of several nights duration were obtained.

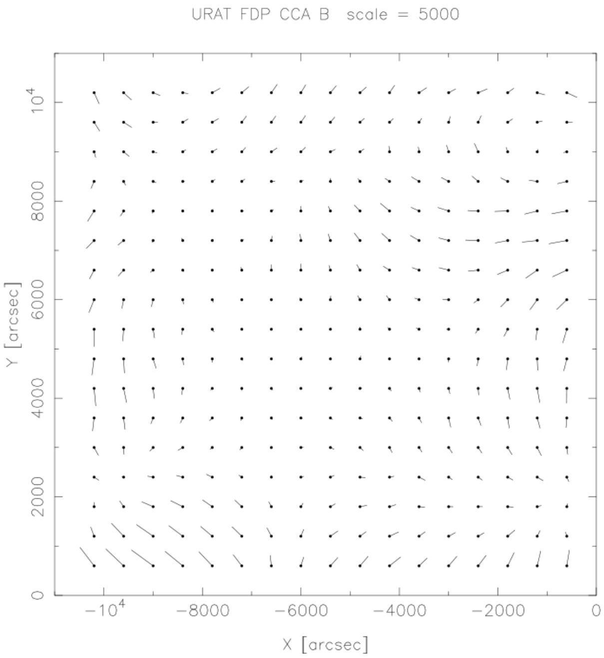


Fig. 5. Example of a field distortion pattern, derived from URAT exposures of a single night for CCD B. The vectors are scaled by a factor of 5000.

## 4. REDUCTIONS

Astrometric reductions of all data were performed using UCAC4 reference stars. A single CCD exposure typically has between 500 and 5000 such reference stars, thus "averaging out" systematic zonal errors of the UCAC4 or Tycho-2 over 3 degrees. An 8-parameter "plate" model (linear + tilt terms) was adopted. The 3rd order optical distortion of the lens is too small to require such a term in the model. However, a general field distortion pattern was constructed and applied for each CCD separately, which takes out systematic errors as a function of $x, y$ pixel location due to residual distortions, e.g., caused by the filter and lens (Fig. 5).

The $x, y$ data were also corrected for the pixel phase error, a sine-wave as a function of sub-pixel coordinate and amplitude of about 5 to 15 mas, depending on the width of image profiles. Systematic position errors (separately for $x$ and $y$ coordinates and CCD) of saturated images were found to depend on time. The data were split into groups by epoch and separate corrections derived and applied. Examples are shown in Figs. 6 and 7. These corrections are typically in the range of 10 to 100 mas. Individual positions of stars (per exposure, CCD and grating order) were combined to weighted mean positions for all observations of an individual run (observing period around a given full Moon). These positions were then compared to the Hipparcos Catalog (van Leeuwen 2007) positions predicted for the URAT mean observing epoch utilizing the Hipparcos Catalog's proper motions and parallaxes.

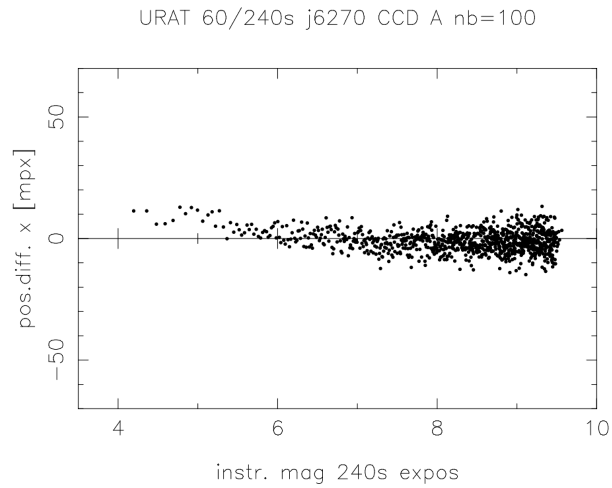


Fig. 6. Position differences along $x$ between 240 and 60 sec exposures of the same field, averaged over all exposure pairs of night j6270 for CCD A.

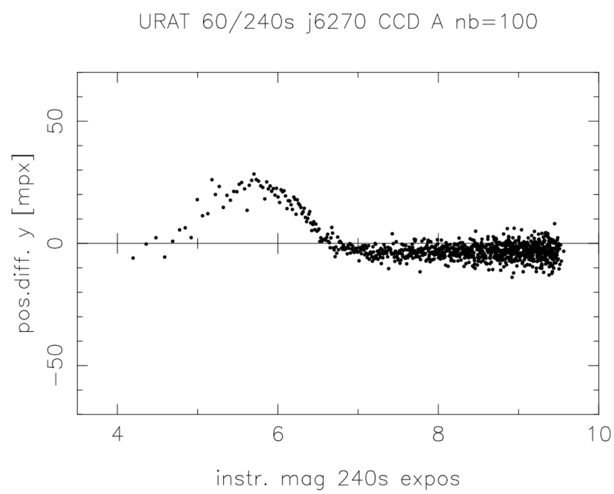


Fig. 7. Same as previous figure for $y$ coordinate.

## 5. RESULTS

Over 29,000 exposures from 85 nights of 17 runs (epoch groups) with grating observations between April 2012 and June 2014 were used for this investigation. These URAT observations cover almost all sky between declinations $-5°$ and $+89°$ and contain over a billion individual positions. Among these, 66,202 Hipparcos stars were identified, the subject of this investigation.

The distribution of the URAT observed mean image profile amplitudes of the Hipparcos stars is

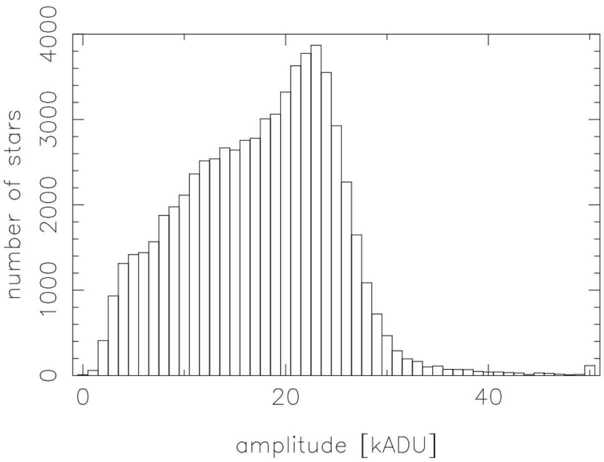


Fig. 8. Distribution of amplitudes of URAT images.

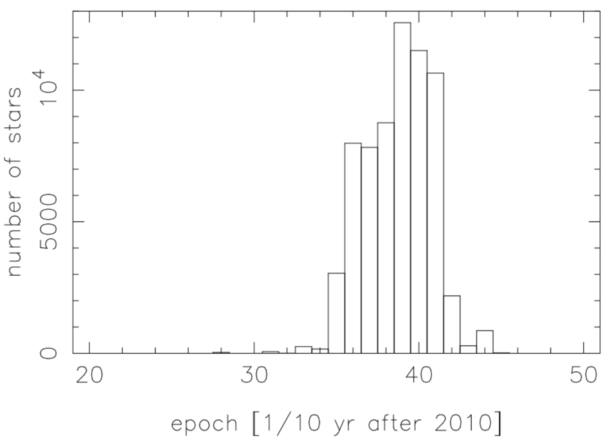


Fig. 9. Distribution of URAT observational epochs.

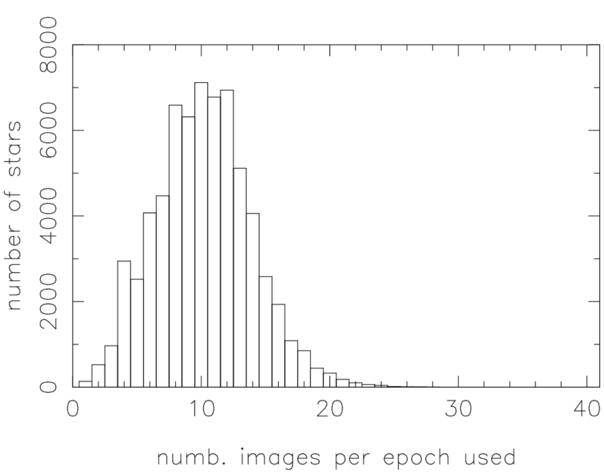


Fig. 10. Distribution of number of observations per observing run of several nights around a full Moon.

shown in Fig. 8. Thus most data are not saturated (under 30k ADU) and only for a small fraction of stars the CAB regime is used. Fig. 9 shows the distribution of epochs of these URAT observations, which thus have an epoch difference of about 22.5 years to the original Hipparcos mean observing epoch (1991.25). The mean number of URAT observations per star and observing run of several nights is shown in Fig. 10.

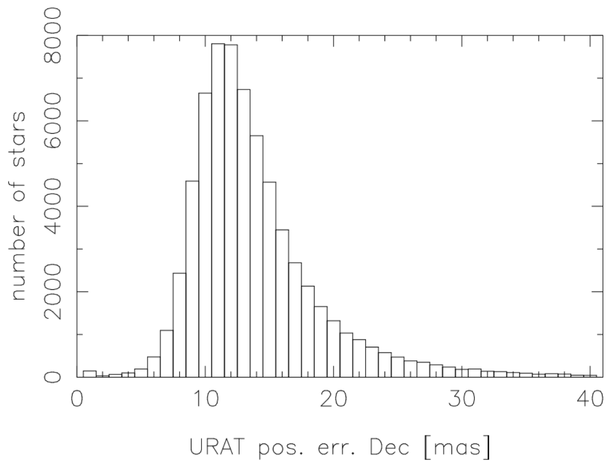


Fig. 11. Distribution of URAT position errors (Dec).

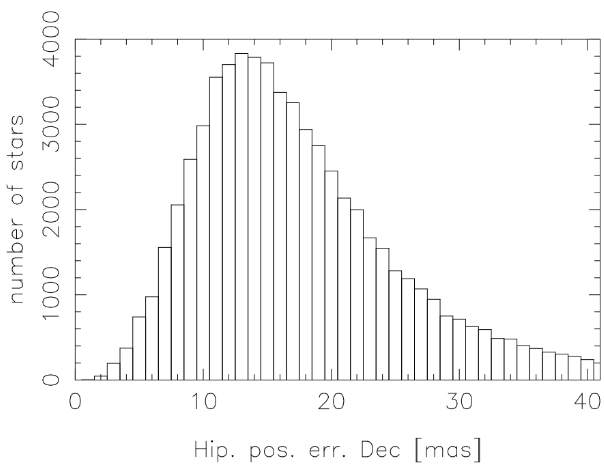


Fig. 12. Distribution of Hipparcos position errors at URAT epoch (Dec).

Figs. 11 and 12 show the distribution of URAT and Hipparcos positional errors at the URAT epoch, respectively. Results for the declination component are shown, which are similar to the results along RA. Both data sets are of comparable precision at current epochs. Fig. 13 shows the RMS combined error which is to be used as error for the position differences to be looked at next.

The distributions of the URAT−Hipparcos position differences are shown in Figs. 14 and 15 for the RA and Dec components, respectively. Fig. 16

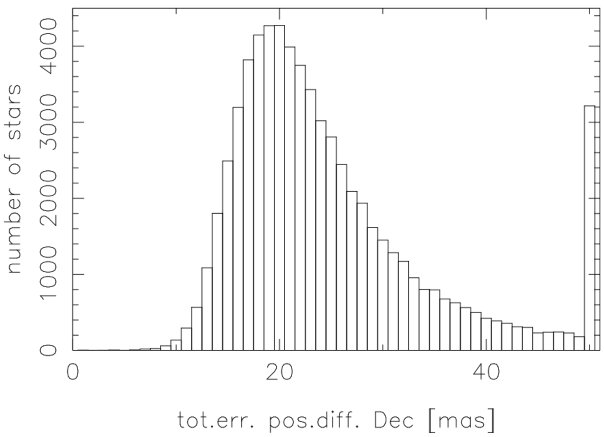


Fig. 13. Distribution of URAT-Hipparcos position difference errors (Dec).

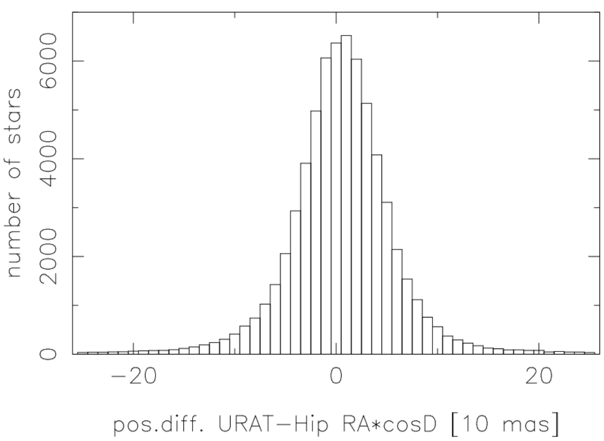


Fig. 14. Distribution of URAT-Hipparcos position differences (RA*cosDec).

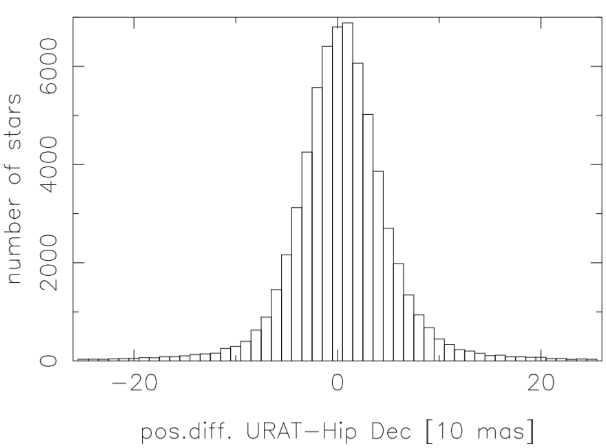


Fig. 15. Distribution of URAT-Hipparcos position differences (Dec).

shows the same as Fig. 15, however, normalized by the total, combined error of the position difference

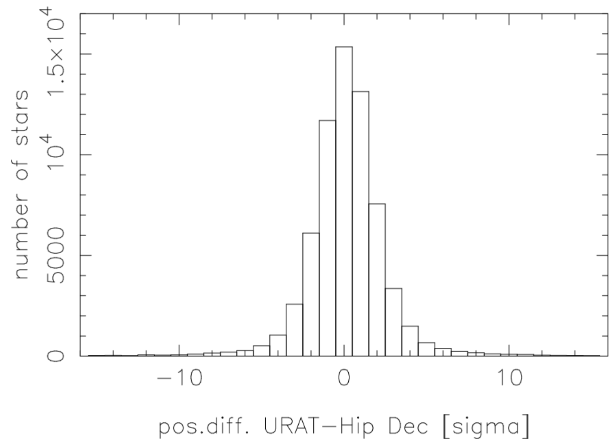


Fig. 16. Distribution of URAT-Hipparcos normalized position differences (Dec).

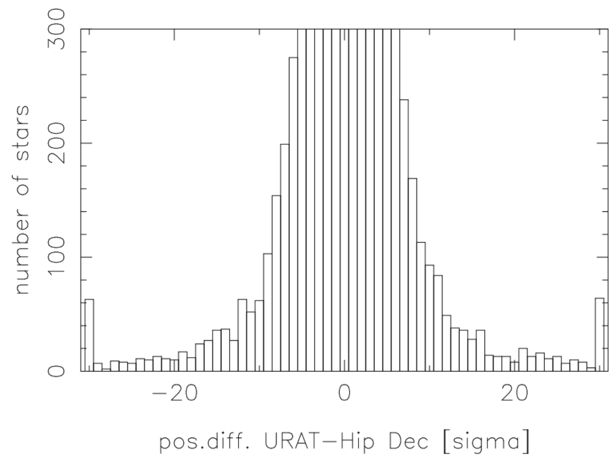


Fig. 17. Zoom of previous figure to highlight large position differences.

(i.e. in "sigmas"). It is obvious that a large fraction of stars show much larger position differences than predicted from Gaussian statistics. Fig. 17 shows a zoom-in of Fig. 16 to highlight the "outliers".

A quantitative evaluation of the large number of large URAT−Hipparcos position differences is provided in Tables. 1 and 2. The discrepancy between the current epoch actually observed positions of those stars and their predicted positions based on the Hipparcos Catalog (re-reduction version of 2007) is likely due to the correlations of parallax, proper motion and possible orbital motions estimated from a very short time span (3.5 years) of Hipparcos observations.

## 6. CONCLUSIONS

The large amount of highly accurate observations of bright stars by the URAT program allows a check on the accuracy of Hipparcos Catalog positions of

TABLE 1

STATISTICS OF LARGE URAT−HIPPARCOS POSITION DIFFERENCES [MAS].

| pos.diff. larger than (mas) | number of stars | percentage of stars |
|---|---|---|
| 1000 | 255 | 0.4 |
| 500 | 778 | 1.2 |
| 400 | 1087 | 1.6 |
| 300 | 1573 | 2.4 |
| 200 | 2651 | 4.0 |
| 150 | 3943 | 6.0 |
| 100 | 7569 | 11.4 |
| 75 | 13085 | 19.8 |

TABLE 2

STATISTICS OF LARGE URAT−HIPPARCOS POSITION DIFFERENCES [SIGMA].

| pos.diff. larger than ... sigma | number of stars | percentage of stars |
|---|---|---|
| 25.0 | 298 | 0.5 |
| 15.0 | 759 | 1.1 |
| 10.0 | 1489 | 2.2 |
| 8.0 | 2106 | 3.2 |
| 6.0 | 3387 | 5.1 |
| 5.0 | 4633 | 7.0 |
| 4.0 | 7240 | 10.9 |
| 3.0 | 13458 | 20.3 |

individual stars at current epochs. With typical precisions of 8 to 20 mas the URAT observations are at least as precise as the Hipparcos positions at mean epoch of 2014. Some discrepancies on the order of 25 sigma or arcsecond level are seen. The fraction of stars with position differences exceeding 3-sigma (75 mas) of combined URAT and Hipparcos formal positional errors is about 20% for our data sample of over 66,000 Hipparcos stars, mainly on the northern hemisphere.

**Acknowledgements.** The author thanks the entire URAT team. Please see the URAT1 release paper and readme file.

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