TYCHO ASTROMETRY FROM 30 MONTHS OF SATELLITE MISSION[1]

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Abstract. The Hipparcos satellite's star mapper gives photon counts in two spectral channels simultaneously, close to Johnson B and V. The transit times and the signal amplitudes for each star across two groups of four slits are derived and used for astrometry and photometry, respectively, and this constitutes the Tycho project. The present paper describes results of Tycho astrometric data processing, leading from the transit times to the astrometric parameters of the Tycho stars.

Some 30 months of Tycho observations, i.e. about 80 percent of the Hipparcos-Tycho mission, have been used to produce a working catalogue of Tycho positions, proper motions and parallaxes of a million stars. The external errors of this preliminary catalogue have been determined by comparison of 98 000 stars common with a preliminary, but much more accurate Hipparcos catalogue. External systematic errors of positions and annual proper motions are less than 0.5 milliarcsecond (mas) and the accidental errors per star are about 30 mas rms at $V = 10.5$ mag, the median magnitude of the catalogue. It is concluded that a satisfactory accuracy has been achieved.

1. Introduction

The Tycho experiment of the Hipparcos satellite (Perryman et al. 1992) supplies astrometric and photometric information. The data are analyzed by the Tycho Data Analysis Consortium (TDAC) as described by Høg

[1]Based on observations made with the ESA Hipparcos satellite

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et al. (1992). The work is carried out in cooperation with the two Hipparcos data reduction consortia, NDAC and FAST, and with the Hipparcos Input Catalogue Consortium (INCA). The preparatory tasks of the astrometry processing are carried out at the TDAC sites in Tübingen, Heidelberg, Strasbourg, Cambridge, Copenhagen and Lund, leading to the final astrometric processing at Copenhagen. The astrometric processing is the subject of the present paper.

The photon counts from the B_T and V_T channels of the star mapper are called the Tycho counts or, sometimes more briefly, the B and V counts. The complete counts are subject to a number of processing steps under the responsibility of TDAC. The transit time of a star crossing the star mapper slits (Fig. 1) is the basic astrometric datum obtained. In the astrometry process, the observed transit time for the added $B + V$ counts is compared with the predicted transit times obtained from the satellite attitude, a provisional grid calibration, and the approximate positions of the stars in the Tycho Input Catalogue (the 'Tycho stars'), leading to an identification of the transiting star and subsequently to an updating of its astrometric parameters. The mathematical formulation of the astrometry task is outlined by Høg et al. (1994) where the analysis of the first half of the mission is discussed.

At present, the geometry of the grid has been calibrated by means of a preliminary Hipparcos catalogue and provisional positions, proper motions and parallaxes of stars have been determined. These calculations are based on 'identified transits' from the first 30 months of the Tycho mission data. Final astrometric parameters will be obtained from the complete 36 month mission data after further verification of the processing, based on the combined Hipparcos catalogue, H30, derived by the FAST and NDAC consortia from 30 months of the mission (Lindegren et al. 1994). This will result in positions, proper motions and parallaxes for some 1 000 000 stars with an accuracy of about 30 mas rms for stars of $V = 10.5$ mag, the median magnitude of the catalogue. The standard error increases roughly by a factor of two per magnitude, for magnitudes fainter than $V = 7$, cf. Table 1, discussed in Sect. 4. The Tycho positions will therefore be much more accurate at the epoch of observation than in ground-based catalogues. But the observation error of proper motions and parallaxes is in fact larger than the true values of these quantities, for the majority of faint Tycho stars. Double stars with separations larger than about 2 arcsec will be resolved.

The photometric processing resulting in the Tycho magnitudes B_T, V_T, T, where the T magnitude is derived directly from the $B_T + V_T$ counts, is described by Großmann et al. (1994).

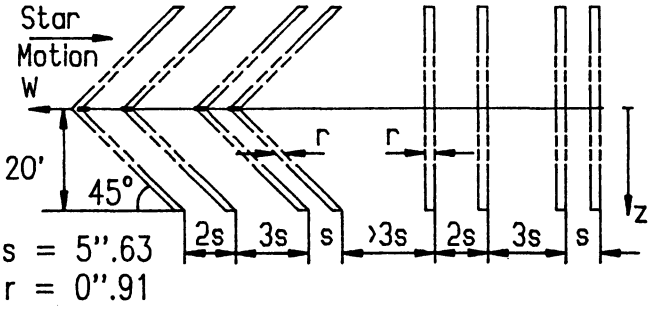

Figure 1. The star mapper slit system consists of the 'chevron' group of four inclined slits, and the group of 'vertical' slits, perpendicular to the motion of the stars.

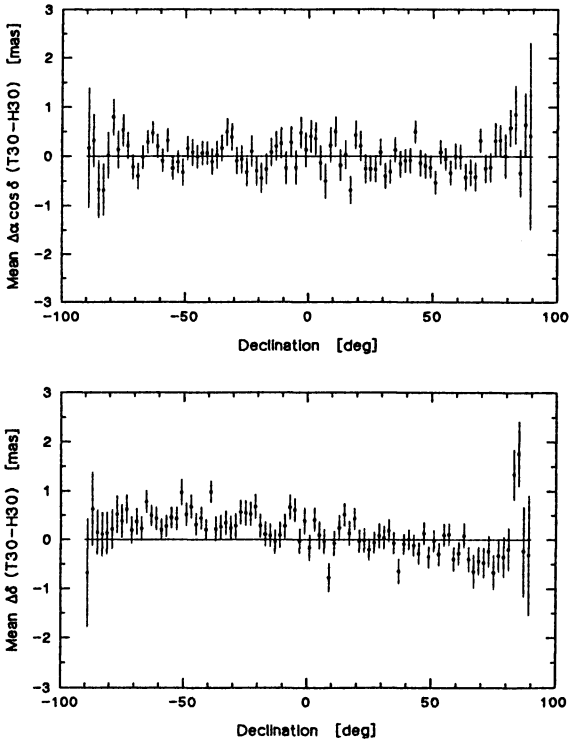

Figure 2. Systematic differences between preliminary Tycho and Hipparcos positions, T30−H30, at the epoch 1991.25 and as function of declination. The differences are generally less than 0.5 mas and are due to errors in the Tycho positions. The systematic trend in the lower plot is significant, but it is expected to disappear in the final Tycho positions. Similar plots versus right ascension (not shown here) appear as non-systematic as the upper plot.

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TABLE 1. Expected accuracy of the final Tycho Catalogue. External accidental errors of positions, annual proper motions and parallaxes, are given as function of visual magnitudes, for *bona fide* single stars of $B - V = 0.7$. Systematic errors will be less than 0.5 mas

V	[mag]	2.5-6.0	7.0	8.0	9.0	10.0	11.0	12.0
σ	[mas]	2.5	3.5	5	10	20	50	80

2. Attitude, grid and star catalogues

The satellite attitude data contains the pointing directions of the two optical axes of Hipparcos, as functions of time during the mission. The attitude used in the 'identified transits' was produced by NDAC, based on provisional grid calibration parameters and a Hipparcos catalogue, N18, of positions, proper motions and parallaxes obtained from the first 18 months of the mission.

The grid calibration in Tycho astrometry shall provide corrections to the calibration parameters used in the NDAC attitude so that the corrected identified transits agree with the more accurate Hipparcos catalogue, H30. It is, however, noted that the T30 catalogue discussed here was based on a calibration using the N18 catalogue for positions and proper motions, and only ground-based parallaxes were used. This problem is discussed and probably resolved in Sect. 4.

The star mapper grid consists of accurately etched slits, Fig. 1, on a glass substrate. The light from sky and star(s) passing the slits is collected by two photomultipliers, B and V. The grid geometry, related to the optical axes given by the attitude data, is slowly varying with time due to gradual changes of the mechanical structure of the satellite. In practice, the grid geometry is specified by (a) a table of 'medium scale irregularities', in fact constant for the whole mission, and (b) sets of 11 calibration parameters, each derived from the observations of a period of 24 hours. The calibration parameters are defined as zero-points and orientations of the slit groups, and are in fact corrections to the parameters used in the attitude production.

The final grid calibration shall make use of the H30 catalogue of positions, proper motions and parallaxes of about 100 000 single stars. The calibration provides a data base of parameters covering the mission and supplying the relevant parameters by interpolation for every observation, during the subsequent Tycho catalogue production. This ensures that the positions, proper motions and parallaxes in the final Tycho catalogue are

obtained in the coordinate system of the Hipparcos catalogue, with systematic deviations less than about 0.5 mas, as we shall demonstrate in the following.

A number of consecutive or 'iterated' Tycho catalogues have been produced so far:

(1) The Tycho Input Catalogue of 3 million stars (Egret et al. 1992) was obtained from ground based catalogues, with position errors about 1 arcsec;

(2) the Tycho Input Catalogue Revision of one million stars (Halbwachs et al. 1992 and 1994) was obtained from analysis of the first 12 months of the Tycho mission, with position errors about 60 mas;

(3) the T30a of one million stars, obtained from 30 months of the mission and containing positions with typical errors of 30 mas;

(4) the T30b, an iteration of T30a to make sure that all positions have converged;

(5) the T30c, an iteration of T30b, for the first time including proper motions and parallaxes; and

(6) the T30d, the first iteration of proper motions and parallaxes. This is the catalogue discussed presently and it is briefly called T30.

The four catalogues T30a-d are iterative improvements of the Tycho Input Catalogue Revision by means of the first 30 months of observations. Thus, all about 100 million observation equations are calculated in each iteration, corrected for improved astrometric parameters from the previous solution. The observation residual relative to the previous solution is also calculated and is used to reject outlying observations, with residuals larger than about $3\sigma_{\text{obs}}$.

3. Comparison with the Hipparcos catalogue, H30

The T30 catalogue has been compared with the H30 catalogue, by way of the 98 000 stars in common. The latter catalogue has standard errors less than 2 mas for all astrometric parameters, i.e., negligible compared to the errors of the T30, except for very bright stars. Therefore, *external* systematic and accidental errors of T30 can be derived directly from the differences. Before differences T30−H30 are formed the T30 positions and proper motions are rotated (by about 60 mas and 1 mas/yr) to coincide with the H30 system.

The differences for positions and parallaxes are plotted versus declination and magnitude in Figs. 2-4. Plots of annual proper motions are numerically very similar to the Fig. 2a of positions, and are therefore not included. Plots of the differences as function of right ascension and plots on two-dimensional sky maps were also studied, but are not included because no new information was obtained. The Hipparcos magnitude, Hp, is related

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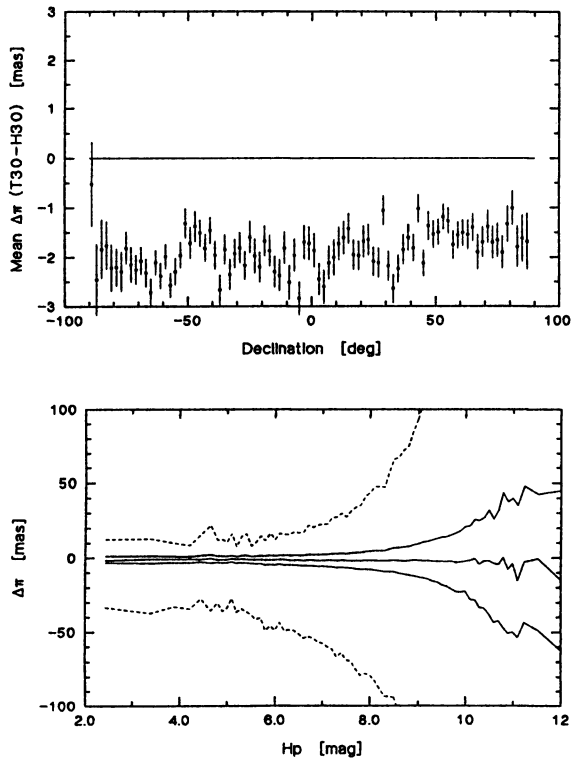

Figure 3. Differences between parallaxes, T30−H30. (a) Systematic differences versus declination. A plot versus right ascension shows the same systematic difference, about −1.9 mas. (b) The curves mark the sextiles, as explained in Fig. 4. The systematic difference seems to be slightly more negative at faint stars.

to the Johnson and Tycho magnitudes as $Hp = V_J + 0.16 = V_T + 0.08$ for a star of the typical colour index $(B - V)_T = 0.7$.

4. Discussion

The external systematic errors of T30 are simply obtained as the systematic difference T30−H30 because the H30 has a superior accuracy. They appear from Fig. 2 to be less than 0.5 mas for positions. They are in fact also less than 0.5 mas/yr for proper motions. The only systematic feature worth noting is the statistically significant trend in $\Delta\delta_\delta$ (Fig. 2b) from +0.5 to −0.5 mas. This small trend might perhaps be neglected, but it is expected to disappear in the final Tycho catalogue because a new grid calibration will be used, based on the H30 catalogue, instead of the NDAC 18 month Hipparcos catalogue, used in the present calibration.

The systematic error of parallaxes in T30 appears from Fig. 3a to be

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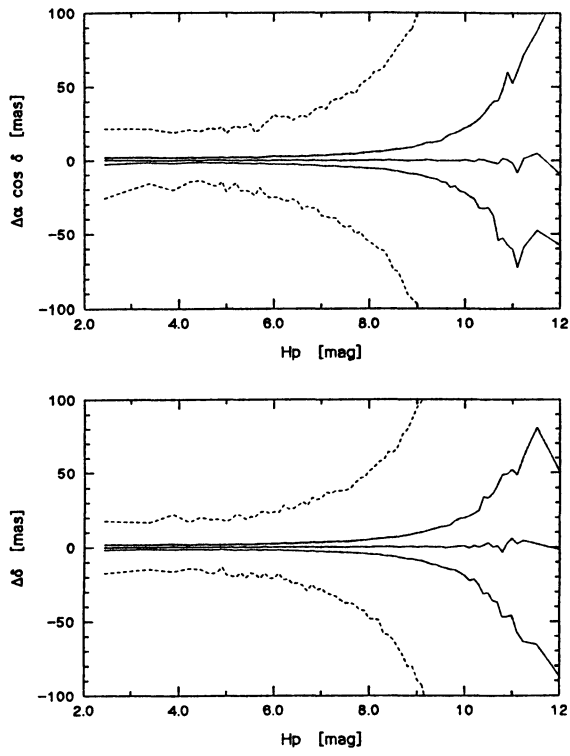

Figure 4. The solid curves mark the 1st, 3rd and 5th sextiles of the differences between preliminary Tycho and Hipparcos positions, T30−H30, of 98000 common stars calculated for bins in Hp of at least 100 stars or of 0.1 mag width (whichever gives the wider bin). The magnitude $V_J \simeq Hp - 0.16$ mag. The dashed curves are the 1st and 5th sextiles in a 10 times expanded scale. *Note*: the 3rd sextile is the same as the median. The 1st and 5th sextiles roughly correspond to −1 and +1 s.d. for a normal distribution.

very significant, equal to −1.9 mas. This error is expected to disappear in the final catalogue because the calculated Tycho parallax will be used to calculate the residual for the subsequent iterative catalogue, and this was not done at present. This means that a zero parallax was in fact assumed, although the parallaxes of the Tycho stars have a median value about +10 mas. This has presumably given a slight bias, resulting in the systematically too small Tycho parallaxes.

The external accidental errors of positions and parallaxes as functions of magnitude can be derived from the 1st and 5th sextiles of the distribution functions in Figs. 3b and 4, as explained in the note to Fig. 4. Corresponding plots for the annual proper motions are nearly identical and are therefore not included. This results in Table 1 giving the expected final Tycho accuracies. The table takes into account the expected improvement

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from 36 months of observations, 6 months more than in the T30 catalogue. It is noted that the errors are only about 2.5 mas for stars brighter than $V = 6.0$, comparable with the Hipparcos accuracy. The external accidental errors of T30 obtained in this paper agree within less than 10 per cent with the formal standard errors, derived from the normal equations and a statistical model of the photon noise plus empirical values for the attitude noise (about 7 mas for vertical slits and 35 mas for inclined, cf. Høg et al. 1994). The photon noise model is derived from basic statistical principles, as discussed by Makarov and Høg (1994).

It appears from the table that the errors of Tycho proper motions for stars fainter than 8 mag are so large that positions calculated for epochs a few years from the mean epoch 1991.25 will be rather uncertain. This problem will be solved by the proper motions with accuracy about 3 mas/yr, expected in the planned Tycho Reference Catalogue (Röser and Høg 1993) obtained after a new reduction of the AC catalogue plates by means of the Hipparcos catalogue.

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