Progress on the Tycho-2 Catalogue from the Hipparcos Mission†

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Abstract.
A progress report for the Tycho-2 project is presented. A new reduction of the original Tycho photon counts obtained with the ESA Hipparcos satellite is being carried out. This will improve the astrometric and photometric precision of the fainter part of the one million stars in the Tycho Catalogue, and increase the total number of stars to about 2.5 million. The original Tycho reduction was done by detecting a significant signal whenever the stars of an input catalogue crossed a slit system in the focal plane of the Hipparcos telescope. The improvement in the new reduction is achieved by making a superposition of the photons that were counted during all the about 130 observations per star obtained during the mission.

Keywords: reference catalogues, astrometry, photometry

1. Introduction

The ESA satellite Hipparcos carried out astrometric and photometric observations from 1989 to 1993 resulting in the Hipparcos and Tycho Catalogues (ESA 1997). The satellite obtained very high accuracy astrometry for 120 000 stars, the Hipparcos Catalogue. These stars plus an additional 935 000 stars were observed with a more modest accuracy by the satellite's star mapper slits resulting in the Tycho Catalogue, sometimes abbreviated to Tycho-1. This catalogue contains astrometry and two-colour photometry (B_T, V_T) for all stars.

The Tycho-2 project consists in a new reduction of the original Tycho observations which will improve the astrometric and photometric precision of the stars in the original Tycho Catalogue (ESA 1997, Høg et

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al. 1997) and increase the number of stars by a factor of about 2.5. Such improvements have become possible with the much better computer facilities available today, using the Hipparcos and Tycho Catalogues and the calibration data from the first Tycho reduction, and by combining several new catalogues into a new Tycho Input Catalogue.

In the original Tycho project astrometric and photometric data for 1 052 000 stars to a limit of V_T =11.5 mag were derived. The brightest 99 per cent of the stars obtained magnitudes in two passbands B_T and V_T. A precision (median internal standard error) of 7 mas was achieved in astrometry (positions, annual proper motions and parallaxes) for stars with $V_T < 9$ mag, and 25 mas for all stars. The median precision in photometry was 0.012 mag for V_T of the bright stars and 0.06 mag for the whole catalogue. Double stars with separation larger than 2 arcsec were resolved, and duplicity down to 0.4 arcsec was sometimes detected. The results were obtained by appropriate treatment of the continuous data records generated by the Hipparcos satellite's star mapper (Fig. 1) which provided simultaneous measurements in two spectral channels. The processing was based on predicted star transits using a dedicated 'Tycho Input Catalogue'. The data treatment was carried out by the Tycho Data Analysis Consortium (TDAC), using calibration and satellite attitude information from the Hipparcos data reduction consortium, NDAC, and photometric standard stars from the FAST Consortium. A detailed description of the data reductions and of the astrometric and photometric results has been given (ESA 1997, Volume 4).

The processing of Tycho observations for the first Tycho Catalogue was based on detections of each slit group transit above a certain signal to noise ratio (1.5 or 1.8).

An improvement of the limiting magnitude of the first Tycho Catalogue by about 0.4 mag could have been obtained by superposition of the photon counts for each star from two consecutive transits in the preceding and following fields of view. This was beyond the available capabilities with respect to software development and computing facilities when discussed in 1991.

For the Second Tycho Catalogue a much better solution, namely *a photon superposition for the whole mission* has been realised. This idea was proposed in principle by Høg et al. (1982), but had to be abandoned at that time in favour of the more modest approach. The photon superposition gives better astrometric and photometric values for the fainter half of the original one million stars. A major reason for the improvement is that an astrometric estimation based on very few photons does not achieve the Cramér-Rao limit (see Yoshizawa et al. 1985). An estimation based on all photons from many transits comes

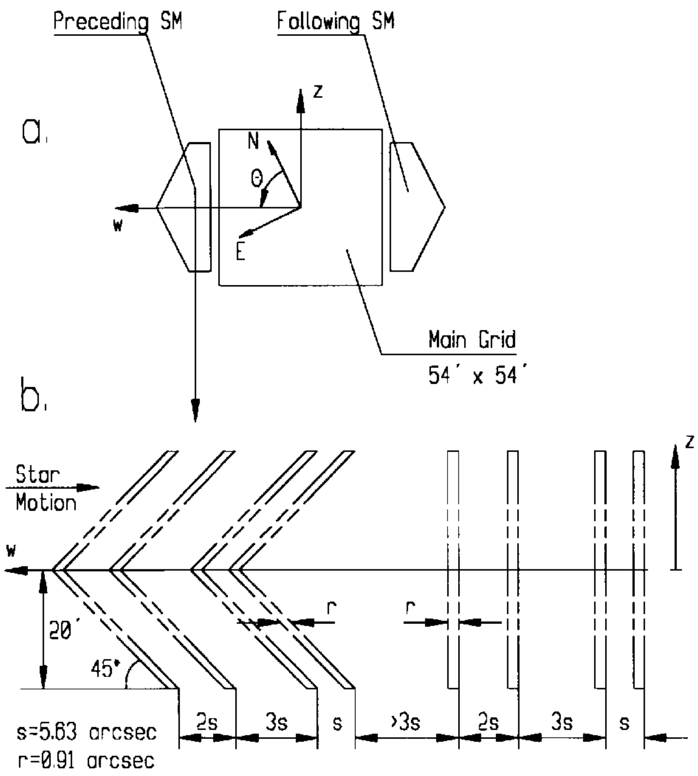

Figure 1. The slit systems at the focal plane of the Hipparcos telescope. The telescope superposes two fields on the sky separated by 58 deg. (a) Arrangement of the star mappers and the main grid. Only the preceding star mapper was used during the mission, the following one being provided for the sake of redundancy. (b) The star mapper. The 'vertical' slits of the star mapper are perpendicular to the motion of the stars, while the 'chevron' slits are inclined by 45 deg. The light from the whole star mapper area is divided by a dichroic beam splitter onto two photomultiplier tubes which count the photons simultaneously in two bands: B_T and V_T.

much closer to that limit. Furthermore, many transits of the faint stars were below the limit of signal-to-noise ratio for the detection and were thus completely lost. Figures for the number of lost Tycho transits are given in Volume 4, Section 20.4 of ESA (1997).

2. Data reduction

The second Tycho processing of all raw counts is based on the available satellite attitude, available astrometric and photometric calibration parameters from the first processing, and an input catalogue of 4.35 million stars.

The two photomultiplier tubes, one for each passband, register light from the four vertical and the four inclined slits shown in Fig. 1. Two fields of view, 58^{o} apart, are superposed in the focal plane.

A star crossing a slit group, either vertical or inclined, produces a signal with four peaks at known distances. By applying the so-called *four-peak non-linear filtering* as described in Volume 4 of ESA (1997), the signal was folded to produce only one peak for each slit group transit. This folded signal is used in all the further data reductions.

Because each of the slits covers 0.9 arcsec by 2400 arcsec, it happens quite often that more than one star crosses one of the slits at nearly the same time. If the star under study is badly affected by such a disturbing star the transit in question may be rejected. If the disturbance is smaller and from a known star, the disturbing signal can be subtracted.

The basic idea of the data reduction is illustrated in Fig. 2. The $8{\times}8$ arcsec^2 maps are centered on the predicted star position on the sky, including the assumed proper motion and parallax. Each of the 31 counts extracted from a transit cover a strip of the sky 40 arcmin high and 0.2–0.3 arcsec wide. The width depends on whether the transit occurred in the inclined or the vertical slits. The corresponding width of 6–9 arcsec covered by the stretch of 31 counts is sufficient to include the star and the immediate surrounding. On the maps in Fig. 2 the counts are added to the relevant pixels, any particular count being added to all pixels corresponding to the relevant strip of sky. Vertical and inclined slits scan the sky in directions 45^{o} apart, and over the three year observing period many different directions are covered. At the position of a star a stronger signal will accumulate than at other positions. Fig. 2a shows the accumulation of the first six transits of the 8th magnitude star HIP 56829. Displaying so few transits makes it possible to distinguish the scan directions and individual counts. Being a Hipparcos star, the prediction is very accurate and no correction to the predicted position is seen. Fig. 2b shows the accumulation of all 164 transits for the star HIP 24697, centered on the predicted position of the B component. Such a double star with 1.2 arcsec separation is easily resolved in Tycho-2, whereas the first Tycho Catalogue did classify it as double, but failed to resolve it. Finally Fig. 2c shows the much fainter star LHS 2056, serendipitously included in the input catalogue by combining GSC and USNO–A positions. While the B_T signal is very faint, the star is clearly visible in the V_T and the combined signals.

The reduction method is described in Sect. 2.3.

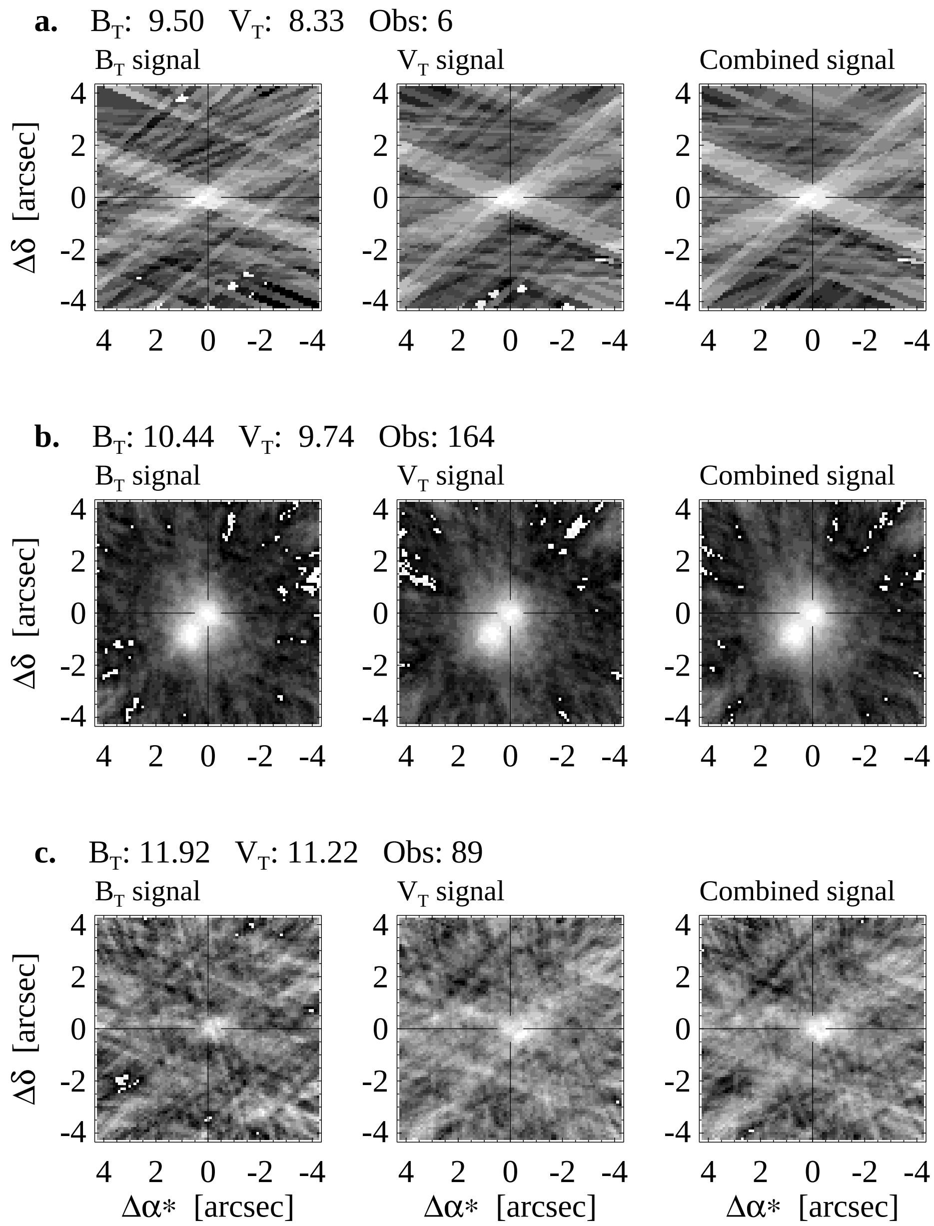

Figure 2. Superposition of photons in maps of 8×8 arcsec^2, centred on the predicted position. An offset from the centre thus determines a correction to the input catalogue. (a) Only six observations were included in order to show the principle, therefore only a few position angles. (b) A double star with 1.2 arcsec separation and clearly resolved in 164 observations although the observed slit response function has FWHM = 1.0 arcsec. (c) A faint star, very faint in the B_T signal, but clearly detectable in the V_T and the combined signals.

2.1. Input catalogue

The second Tycho Input Catalogue (TIC2) was constructed by including stars brighter than $V \simeq 12.5$ mag from a hierarchy of large catalogues. We had estimated that with this limit nearly all stars would be included for which significant results could be obtained, and that the size of the catalogue would not be too large for our processing capabilities. Most of the stars were obtained from the Hipparcos and Tycho Catalogues giving 1.1 million stars, the STARNET (Röser 1995) giving 2.4 million, the Guide Star Catalog version 1.2 (Röser et al. 1997) giving 0.5 million and the USNO–A version 1.0 (Monet et al. 1996) giving 0.3 million. While Hipparcos and STARNET provide proper motions of sufficient precision, the Tycho proper motions needed improvement and the other catalogues contain no proper motions at all. For Tycho stars precise proper motions were taken from a preliminary version of the Tycho Reference Catalogue (Høg et al. 1998) and the ACT (Urban et al. 1998b). Both these catalogues combine the Tycho positions with positions from the Astrographic Catalogue to derive the proper motions. For the remaining stars proper motions could be constructed for 0.3 million stars by combining GSC and USNO–A positions with sufficiently large epoch differences. In the end 0.5 million stars were left without proper motions. For the Hipparcos stars the parallax was also included. The positions in TIC2 have an accuracy about 0.25 arcsec at the observation epoch as required for the processing.

2.2. Extraction of identified counts

The so-called prediction processing, generally described in Vol. 4 of ESA (1997), was performed for all the stars. The purpose of the prediction is to provide expected times of programme star transits in terms of the on-board clock, which allows to find and identify them in the telemetry data files. The identified photon counts are then extracted from the original data files and all necessary corrections are made. This preparatory stage of the data reductions consists of two major processes:

- prediction of transit times using the available satellite attitude parameters and auxiliary data catalogues;
- identification and extraction of photon counts.

The prediction algorithms are adopted from the first Tycho processing with minor updates. An important simplification of the data processing scheme with respect to the first Tycho reduction is that no detection of transits is required any more.

The second step is in fact quite complex. It includes the following procedures:

- correction of predicted times for instrument calibration parameters of different kinds adopted from the first processing;
- recording disturbing stars crossing the slits nearly at the same time;
- four-peak non-linear filtering folding the signal from a transit over four slits to produce a single-peak signal;
- calculation of the exact position of the predicted crossing time within the extracted series of the folded consecutive counts.

A large-scale sky background based on 11-second stretches of samples was used in the first Tycho processing, but not here. Instead, a local background was determined (by a trimmed median method) from the extracted 31 samples and used in astrometry and photometry.

The four-peak folding determination algorithm of the first Tycho processing were used with only minor changes while the rest had to be written from scratch. The input for this stage of processing is 16 Gbyte of predicted slit crossings files and 90 Gbyte of photon counts files. The output is over 60 Gbyte of identified counts files. The records in the latter are mostly in chronological order, following the sequence of predicted crossings. They have to be thoroughly re-sorted providing so-called sorted counts files, which constitute the only input for the following astrometric and photometric reductions.

In principle, the prediction stage could have been skipped in the second processing, and all the photon counts projected directly onto the sky producing a sort of global digital map. This was reckoned possible, but not practical as an input catalogue of sufficient quality could be constructed from the fairly complete and accurate on-ground catalogues, thus utilizing a sizable part of the existing reduction software, and obtaining a much faster computation.

2.3. Astrometry and photometry

The basic principles of the present reductions and how they differ from the first Tycho processing are briefly described in this subsection.

Disturbing star transits are troublesome in the Tycho observation reductions. In the first processing, an observation was simply ignored if the recorded disturbing transit, a "parasite", was too close and too bright. A more sophisticated and apparently successful treatment of disturbing signals is implemented now. The closest and brightest parasites still lead to a rejection of the observation, but the fainter and more distant ones in time, are *subtracted* from the observed counts. Not all the parasitic stars are liable to subtraction, but only those flagged in the input catalogue as having sufficiently reliable B_T and V_T magnitudes and coordinates.

Apart from the advanced treatment of disturbances, a considerable improvement is expected for stars in crowded regions and multiple systems from the way disturbed observations are selected for solution. Once a tentative astrometric and photometric estimation has been made for a given star, residuals are derived for each transit by subtracting the expected signal profile from the observed counts. Observations with χ^2 statistics exceeding a certain limit are neglected in the following iteration. The limit is adjustable, so that not more than 15 % of observations can be rejected for each star. Normally, a much smaller proportion is rejected. Some information on the histogram of χ^2 statistics is kept in the output to be used for flagging highly disturbed unreliable solutions.

A very different approach to weighting observations for astrometric solution was taken. In the first processing, the simultaneous counts in the B_T and V_T channels were simply added together before making an astrometric estimation, and these combined observations were weighted between each other according to estimated signal amplitudes and backgrounds. Here, we weight the B_T and V_T counts before co-adding them. Generally, it puts a relatively higher weight on the observations in the B_T channel, where the star signals are typically smaller, but the backgrounds are even smaller. Then comes another weighting which depends on the background value for each combined observation individually, but the same mean magnitudes are assumed, estimated in the previous iteration. The little harm that it can cause for variable stars is by far outweighted by not permitting the wildly disturbed observations with bright parasites, which somehow have survived the cleaning and rejection, to spoil the solution completely.

Finally, an absolutely different estimation method was taken for the astrometric and photometric solution. Instead of a linear detection filtering and a least-squares solution in the Tycho-1 astrometry, and a maximum likelihood estimation in photometry, both solutions are obtained in one run by a cross-correlation method. Here a cross-correlation is the convolution of a series of photon counts with the average discrete slit response function. It serves as both astrometric and photometric estimators, since the position where it assumes its maximum provides an estimation of the true star position, and the maximum value itself can be easily calibrated into magnitudes. In principle, the

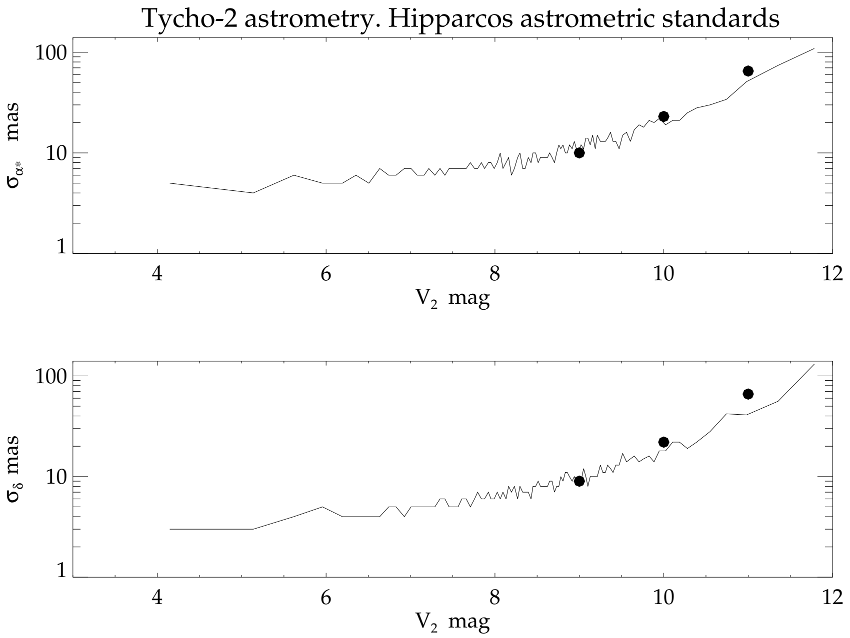

Figure 3. Tycho-2 astrometry. Robust standard errors of the differences between observed equatorial coordinates and those of Hipparcos astrometric standard stars as functions of observed provisional V_T magnitude. The dots show the corresponding standard errors in the first Tycho catalogue for comparison. It appears that the improvement over Tycho-1 is, e.g., a factor of 1.5 at $V_T = 11$ mag.

photometric estimation can be decoupled from the astrometric one with this method, as no residuals analysis is involved. Still, a few iterations are required to solve for each object for the sake of the cleaning and weighting refinement.

The major drawback of the cross-correlation method is that it increases the statistical photometric bias at faint magnitudes. It tends to locate a star at the spot where the signal is strongest, which with noisy data should give systematically too bright magnitude estimations. However, as is shown in Section 4, the photometric bias proves to be tolerable. It can be corrected by simple interpolation in a sample of stars limited to brighter than $V_T \approx 12$ mag.

3. Astrometric results

Only positions of the stars are solved routinely in the present processing. Proper motion components that could be derived from the Tycho observations alone, would be much inferior even to those in the input catalogue. Yet more accurate and consistent proper motions will be obtained for almost all the detected objects by combining the positions in Tycho-2 and AC2000 (Urban et al. 1998a). However, a special solution including proper motion is envisaged afterwards for a much smaller number of stars. Some of the objects, although bright enough, are not found in the AC2000 with the present day positions. They might be new high-proper motion stars, and a Tycho-2 proper motion solution would be desirable as a start-up for cross-identification.

Parallaxes are not solved for either, because of the expected poor quality. A special treatment of a limited number of suspected nearby stars and those without reliable Hipparcos data is possible.

A provisional evaluation of the astrometric performance in the second Tycho processing was made on a sample of 105 000 HIP astrometric reference stars included in the input catalogue with the HIP position, proper motions and parallaxes. These are basically all non-problematic single stars with good astrometry in HIP. The resulting Tycho-2 positional offset for such a star is almost entirely the Tycho-2 external error, since the Hipparcos error is much smaller. Positional corrections were computed for some 35 000 of these stars and the robust percentile estimation of 1σ errors is shown in Fig. 3. The corresponding errors in the first Tycho catalogue are given for comparison. Further improvement of the results in the final Tycho-2 Catalogue is expected for the following reasons:

- the faintest stars in the sample will become fainter than shown in Fig. 3, when the photometric bias of the observed magnitudes is corrected;
- the sample will be cleaned of poor quality and much disturbed solutions;
- the positions of the brightest stars in the sample will improve when global systematic errors are corrected.

It seems from this test that the anticipated improvement of astrometric accuracy for faint stars will indeed be achieved, and the Tycho-2 Catalogue will become an important stage in the succession of big astrometric catalogues.

3.1. Double stars

In the Tycho-2 data reduction, bright double stars will be detected down to separations of about 0.8 arcsec for magnitude differences of less than about 2 magnitudes, and most of them will be resolved. Thus, the resolution is better than the FWHM of the observed slit response function (cf. Fig. 1.3, Volume 4). The corresponding resolution for Tycho-1 was 2 arcsec. At present it is not clear to what extent reliable solutions for separation, position angle and individual photometry can be achieved.

An interesting class of objects is the Hipparcos stars with poor or even no astrometric solution. These stars are often double stars where the input catalogue values used in the Hipparcos data analysis were not sufficiently accurate to allow a solution. Here the Tycho-2 results may provide the required improvement and allow a new investigation of the Hipparcos data. An example is the orbiting triple system HIP 78727 for which no solution was obtained in the Hipparcos Catalogue. Using preliminary Tycho-2 results as input values, the published Hipparcos transit data (ESA 1997) was analysed giving α: 16 04 22.1930, δ: $-11\,22\,23.104$, π: 37 mas, $\mu_{\alpha*}$: -76 mas/yr and μ_δ: -59 mas/yr for the main component. The B component is at a separation of 630 mas, position angle 226.6° and with a relative proper motion of 83 mas/yr in the direction 21°. The C component has not yet been studied. The Hipparcos Input Catalogue is in error by more than 8 arcseconds for this system which is several times more than what could be tolerated in the original data analysis. Further studies of this and other systems are planned.

4. Photometric results

The directly derived magnitudes in B_T and V_T were compared with good ground based magnitudes of stars in an appropriate magnitude range. A set of stars from fields at the North Galactic Pole and in SA 80, 81 and 132 observed by Knude (1986, 1993, 1998) in *uvby* was used for this purpose. Only early type dwarf stars were used in order to keep a well defined transformation from the Strömgren system to Tycho. The *uvby* photometry was first transformed to Johnson B and V using transformations by Jønch-Sørensen (1998) and then transformed to B_T and V_T using the transformations in Section 1.3 of Vol. 1 of ESA 1997. An average correction as function of magnitude (see Fig. 4) was applied. The resulting magnitudes appear from the figure to have standard errors at, e.g., V_T= 11.0 and 12.0 mag of 0.085 and 0.14 mag respectively. The standard errors are slightly smaller at the same magnitudes in B_T. We can safely assume that the photometry by Knude is much more accurate than the Tycho-2 magnitudes and the derived errors therefore represent the external errors of the Tycho-2 magnitudes.

A comparison with the first Tycho Catalogue (Table 16.3 and Fig. 19.1 in Volume 4) shows the same precision at $V_T = 11.0$ and that about

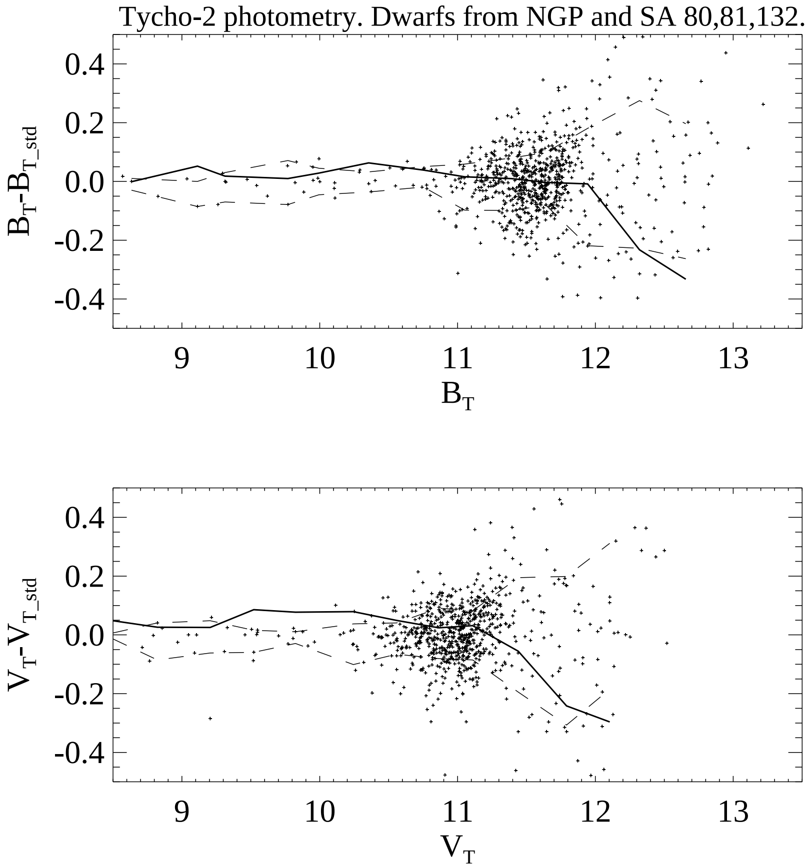

Figure 4. Tycho-2 photometry. Differences between observed corrected magnitudes and those of standard stars: dots for individual stars, dashed curves for the robust 1σ percentiles. The solid line shows the values which were subtracted from the directly derived magnitudes in order to conform on average with the standard stars.

1 mag fainter stars are included in Tycho-2 with a good photometric accuracy.

5. Conclusions

The second Tycho reduction will give good results for about 2.5 million stars, brighter than $V_T \simeq 12.0$ mag. The resulting Tycho-2 Catalogue will be published in 1999. Expected external standard errors at $V_T = 11.0$ and 12.0 mag are respectively $\sigma_{\alpha,\delta} \simeq 50$ and 150 mas and $\sigma_{V_T} \simeq 0.10$ and 0.15 mag. Double stars with separation above 0.8 arcsec will generally be resolved.

When combined with positions from the Astrographic Catalogue, proper motions can be derived for most of the stars with a typical precision of 2.5 mas/yr. The star density for this very large and precise reference catalogue will be 60 stars per square degree on average, but a few times smaller at the Galactic poles and a few times higher in the Galactic plane.

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