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Results on Tycho photometry ⋆

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Abstract. The final Tycho database will contain astrometric and photometric data for about 1 million stars. Here we discuss the results of the Tycho photometric calibration for about 80% of the data acquired by the star mapper of the Hipparcos satellite and estimate the photometric precision in the final Tycho photometric data base. For a non-variable star of 7th (10th) magnitude with $\approx$ 100 observations a precision of better than 10 mmag (40 mmag) can be expected in the Tycho star catalogue. The precision on $(B-V)_\mathrm{T}$ depends only slightly on the colour and is exptected to be better than 20 mmag (60 mmag) for the same number of observations. These results will be representative of the final Tycho photometric quality.

Key words: stars: photometry - catalogues - data analysis - Hipparcos

1. Introduction

The Tycho experiment, using the star mapper from the ESA Hipparcos satellite, has provided a unique possibility to compile a large photometric catalogue covering both the southern and the northern hemisphere while using measurements from one single instrument. The Tycho experiment, especially the geometry of the star mapper grid, the processing of the raw photon counts, and the background determination have been described in detail in Høg et al. (1992) and references therein. The scientific results for about 1 million stars will enter into two catalogues: The star catalogue will list the astrometric results (Høg et al. this issue) for each single star, together with mean magnitudes given in quasi B and V passbands and one broad-band T magnitude. A second catalogue will contain individual transits gathered during the 36 months data acquisition of the Hipparcos satellite and enable a future user of this huge data base to carry out his own studies.

The number of transits of a given star depends directly on the scanning motion of the satellite. Due to the nearly constant rotation rate of $168\farcs75/s$ and the fact that the star mapper consists of an inclined and a vertical slit group, the shortest time difference between two consecutive transits will be between 0.3 s and 7.4 s with the first one being the inclined transit. Because of the simultaneous observation of two fields of view, separated by 58°, a star can be expected to be visible again after $\approx$ 21 minutes. A continuous slight precession of the rotation axis of the satellite allowed for the observation of the whole sky. Due to the scanning law the coverage of the sky is however not uniform.

In this paper, results of the Tycho photometric calibration are presented for 833 days of mission, i.e. $\approx$ 80 % of the total observing span, and estimates of the photometric precision of the single transits and the median values in the star catalogue are given. For this purpose a comparison between the Tycho observations and mean ground-based magnitudes derived from the Geneva catalogue of photoelectric observations (Grenon et al. 1992) is carried out. In the following we briefly summarize the photometric calibration process and put emphasis on the results. For details of the calibration process itself the reader is referred to Scales et al. (1992).

2. Calibration

2.1. The Tycho Passbands

The Tycho system consists of two passbands named the B_T and V_T channel hereafter, with effective wavelengths of λ = 428 nm and λ = 534 nm, respectively. We note the approximate

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⋆ based on observations made with the ESA Hipparcos Satellite

relation $(B-V)_{\mathrm{T}} \simeq 1.1(B-V)_{\mathrm{J}}$ between the Tycho and Johnson colour indices, correct within 0.1 mag in the range $-0.3 < (B-V)_{\mathrm{J}} < +1.5$. Detailed information on the passbands and on the relationships to the Johnson B and V bands has been given by Scales et al. (1992). Recently the definition of especially the B_{T} band was slightly modified (M. Grenon, priv. comm.). The calibration carried out for the data shown in this paper refers however to the old definition of the passbands (Grenon et al. 1992). This is justified because the passband redefinition will not imply significant changes on the results presented here: The passband changes affect almost exclusively the B_{T} band and will affect the observed V_{T} of a star in the final Tycho data base only via the colour term (see next section). This will not alter resulting magnitudes by more than $\approx$ 10 mmag. The photometric calibration will be run again using all transits of the standard stars in the new system and will be applied to all stars in the final catalogue.

A third broadband magnitude T is defined from the added countrates in both channels in the way that $T = 0$ for $B_{\mathrm{T}} = V_{\mathrm{T}} = 0$:

$$T = V_{\mathrm{T}} + 2.5\log(1+\mathrm{C}) - 2.5\log\left(10^{-0.4(B_{\mathrm{T}}-V_{\mathrm{T}})} + \mathrm{C}\right) \quad (1)$$

with the constant C = 0.749342 which expresses the relative sensitivity in the B_{T} and V_{T} channel. A similar definition has been used in the recognition process (Halbwachs et al. 1992). The use of this quantity is justified for faint stars not estimated in either the B_{T} or the V_{T} channel. Less than 10% of all Tycho stars are expected to yield only T magnitudes.

2.2. The Calibration Process

For the current calibration process a carefully selected sample of confirmed photometric standard stars from the Geneva data base was used. This data base was compiled from about 267000 measurements (Grenon et al. 1992) and cross-referenced with the Tycho Input Catalogue to give 65058 stars (Egret et al. 1992). This sample was further restricted to confirmed photometric standard stars with B_{T} or V_{T} magnitudes between 4.5 and 9 mag. Brighter stars are excluded because of saturation effects of the photomultipliers, fainter ones because of the detection limit problem (cf. paragraph 3). Stars which are close pairs or members of multiple systems were not used in order to avoid confusion with the standard stars. The resulting number of standards used in the given magnitude range was then almost 10000. Only transits with background countrates below 10800 counts/s entered into the calibration.

The calibration process (cf. Scales et al. 1992) computes solutions in the magnitude space for six parameters: zero-point, colour $c = B_{\mathrm{T}} - V_{\mathrm{T}} - 0.7$, slit coordinate z, quadratic terms of c and z, and one mixed term cz. Thus, each amplitude estimate a given by the detection process (Bässgen et al. 1992) is converted from a countrate to a magnitude before the observation equations are solved. This conversion to a raw magnitude already contains a magnitude offset. Thus, the zero-point calibration parameter shown in Fig. 1a only informs on the relative change with time. The six parameters - together with the slit coordinate z and the observed colour - are later used to compute the reduced observed magnitudes.

The calibration is done separately for the three bands, both fields of view, upper and lower parts of the grid, and inclined and vertical slit groups resulting in 24 possible combinations. The parameters are computed independently for a period of time called a photo set. This span of time is however not kept constant but is adapted automatically to yield a minimum of 4500 calibration transits. This is necessary in order to avoid large differences of the parameter errors due to sky regions with varying star densities. As a result, the length of the 132 individual photo sets covering 833 days varies between 2.6 and 11.9 days.

The computed parameters are shown in Fig. 1a for one of the 24 possible combinations: B_{T} channel, vertical slits, lower grid part and following field of view. Whereas the parameters depending on slit coordinate and colour show no significant variations (cf. Fig. 1b) and no long term drifts, the zero-point, or offset, exhibits a clear change with time. This effect is also present in the other 23 combinations not shown here. The amount of change is roughly 55 mmag over a period of 600 days. This corresponds to a decrease in sensitivity of ≈ 5 %.

2.3. Errors of single transit observations

The most important errors for the Tycho photometry are the errors resulting from the computation of the six parameters (called hereafter 'parameter error') and the photon noise.

Due to the varying length of the photo sets the parameter errors σ_{par} are almost constant (cf. Fig. 1b). They depend however on the slit coordinate z and the colour index c. A star may cross the inclined or vertical slit group at z coordinates between $z = 0'$ and $|z| = 20'$ at the upper or lower part of the grid. For both extreme values the parameter error will be at maximum, the minimum will be attained for a crossing at $z = 10'$. The errors on the colour dependent parameters attain their minimum values for $B_{\mathrm{T}} - V_{\mathrm{T}} = 0.7$ mag. As a result, parameter errors on single transits can be expected to vary between $\approx$ 10 mmag and $\approx$ 100 mmag. It is being considered to reduce the parameter error further by a smoothed interpolation over, say, five photo sets, at least for the parameters appearing to be constant.

The second error source, the photon noise, is described in detail by Scales et al. (1992). It is given by: $\sigma_{pn} = \sqrt{\gamma a + \delta b}/a$ with a being the estimated amplitude and b the background countrate in a given channel, γ and δ are constants different for each passband and the inclined or vertical slit group. Due to the smaller collecting surface of the inclined slits compared to the vertical slits, σ_{pn} is always smaller for vertical transits (by $\approx$ 15 % or $\approx$ 30 % for a 6th or 11th magnitude star, respectively). Whereas the background countrate in the V_{T} channel, $b(V_{\mathrm{T}})$, varies between $\approx$ 500 counts/s up to some million counts/s (Wicenec & Bässgen 1992) detection of star transits was done for a background below $\approx$ 97000 counts/s (Bässgen et al. 1992). Thus only transits with a background

Fig. 1a and b. Results from the calibration for 833 days of mission. **a** The six calibration parameters calculated as a function of time for the $B_{\rm T}$ channel using the vertical slit system, the lower part of the grid and the following field of view. Note that $c = B_{\rm T} - V_{\rm T} - 0.7$. All parameters are given in mmag. The time axis gives days since the launch of Hipparcos. **b** Errors in mmag of the six parameters shown in Fig. 1a

below this threshold will be recorded in the photometric transit catalogue. Out of these, best photometric results for stars fainter than 5th or 6th magnitude will be attained for $b(V_{\rm T})$ $\lesssim$ 12000 counts/s. Such a criterion will be applied to the data shown in the next section. A background variation in this range, i.e. within 500 to 12000 counts/s, will not increase $\sigma_{\rm pn}$ for stars brighter than 9th magnitude. Values for $\sigma_{\rm pn}$ ($V_{\rm T}$) computed for vertical and inclined transits can be found in Table 1.

The combined error of a single transit is then given by $\sigma_{\rm t} = \sqrt{\sigma_{\rm pn}{}^2 + \sigma_{\rm par}{}^2}$. For faint stars the dominant error source is the photon noise, for bright stars the parameter error dominates (cf. the discussion in the following section). For a 7th (10th) mag star with $B_{\rm T} - V_{\rm T}$ = 0.7 mag crossing the vertical slits at $z = 10'$, the error of a single transit $\sigma_{\rm t}$ is about 0.05 (0.30) mag.

Further error sources not included in $\sigma_{\rm t}$ may however become important for certain observations. An additional error is introduced during the data transmission from the satellite: because countrates were compressed by a semi-logarithmic algorithm the resultant magnitude has an uncertainty. This 'digitization error' yields errors of several mmag and is therefore of importance for the brightest stars only. For all other stars the photon noise error is larger. Countrates for faint stars were not compressed at all. Other errors are due to variations of the scanning velocity of the satellite (Scales et al. 1992). We therefore presently only speak of the 'precision' of Tycho photometry while the term 'accuracy' would be premature. This latter term indicates according to practice in modern statistics that all kinds of errors are included in the error figures given.

3. Reduced Observations

3.1. Single transits

The calibration parameters derived in Sect. 2 were used to reduce all transits for 833 days of mission. Thus, about 150 million transits of the $\approx$ 1 million stars contained in the Tycho Input Catalogue Revision (Halbwachs et al. 1994) were processed. From this huge data base and the reprocessed data (cf. Sect. 4) the Tycho transit catalogue will be constructed.

To show some results we present data for all stars with ground-based photoelectric observations in a sky region in the southern hemisphere. The ground-based data are from the same data base as used in the calibration (see Sect. 2.2). Figure 2 compares the reduced Tycho observations of 937 stars with the ground-based magnitudes. Because each point corresponds to one transit all observations for a single star are on one line with a constant $B_{\rm T}$ (cat).

While observations of most stars are located within the 3 r.m.s. photon noise error, several clearly fall outside. These observations indicate either variable stars, close binaries or stars with a differing ground-based magnitude. There is however another effect for stars fainter than $\approx$ 9 mag: these stars seem to be observed brighter compared to the ground-based data. Because the expected number of transits of a star is known from the predicted group crossings (Høg et al. 1992), it is also known that a certain fraction of transits for a given star is missing. This fraction increases when fainter stars are observed and is due to the detection limit. The detection limit is a lower limit of the SNR with which transits are accepted. Due to photon noise a fraction of transits of faint stars has an SNR lying below this limit and is lost. In the final star catalogue this effect of missing transits will be corrected for using a "survival analysis" method (see e.g. Feigelson 1990) yielding unbiased magnitudes for the faint stars.

To compare the achieved precision with the error sources described above, a cleaner sample of stars is needed than the one shown in Fig. 2. For this purpose all transits of 14265 photometric standard stars over a time span of $\approx$ 290 days were analysed, separately for inclined and vertical transits. This number of stars exceeds the number of stars used in the calibration process which used stars between 4.5 mag and 9.0 mag only. Table 1 gives the measured standard deviations separately for the inclined and vertical $V_{\rm T}$ channel for intervals of 1 mag width. About $\approx$ 150000 vertical and $\approx$ 100000 inclined transits were used. Columns (3) and (5) give the

Fig. 2. Reduced Tycho observations for 937 stars with ground-based magnitudes in a given sky region. Each point represents one observation and gives the difference between the reduced and catalogued $B_{\rm T}$ magnitude for a single transit. Thus, transits for a given star show up on a line with constant $B_{\rm T}$ (cat). The solid curves indicate the 3 r.m.s. limits from photon noise for a background of 3600 counts/s

Table 1. Measured standard deviations $\sigma_{\rm meas}$ and photon noise $\sigma_{\rm pn}$ for the $V_{\rm T}$ channel, vertical and inclined slits. Only photometric standard stars are used. Units are [mag]

	vertical		inclined	
$V_{\rm T}$	$\sigma_{\rm meas}$	$\sigma_{\rm pn}$	$\sigma_{\rm meas}$	$\sigma_{\rm pn}$
(1)	(2)	(3)	(4)	(5)
4	0.022	0.012	0.023	0.015
5	0.026	0.020	0.028	0.024
6	0.034	0.032	0.040	0.038
7	0.053	0.051	0.063	0.062
8	0.094	0.086	0.109	0.105
9	0.148	0.152	0.166	0.191
10	0.221	0.294	0.246	0.386
11	0.327	0.633	0.347	0.857

predicted photon noise computed for a constant background of 3600 counts/s, columns (2) and (4) give $\sigma_{\rm meas}$ i.e. the observed width of the distribution which includes all possible error contributions. $\sigma_{\rm meas}$ is derived from transits with a range in the background of up to 12000 counts/s with the median near $\approx$ 3600 counts/s.

Results for $\sigma_{\rm meas}$ confirm the values found by Scales et al. (1992) for vertical transits from a much smaller data set. Thus we can restrict the discussion to the following points:

1. $\sigma_{\rm meas}$ is smaller for the vertical than for the inclined slits
2. $\sigma_{\rm meas}$ is similar to $\sigma_{\rm pn}$ for stars of 6th to 8th mag
3. For the brightest stars $\sigma_{\rm meas}$ is larger than $\sigma_{\rm pn}$
4. For the faintest stars $\sigma_{\rm meas}$ is smaller than $\sigma_{\rm pn}$

(1) is due to the smaller collecting surface of the inclined slits. This behaviour is as expected from the predicted photon noise error $\sigma_{\rm pn}$. Fact (3) is attributable to the parameter error with values in the range between 0.01 mag and 0.10 mag (cf. Sect. 2.3), thus the dominant error source for transits of bright stars. (4) is a consequence of the facts that most of the very faint stars are detected only at a lower background than 3600 counts/s, and that some transits are missing as discussed above.

3.2. Precision of median magnitudes

As estimators for the "mean" Tycho magnitudes derived from all retained transits of a given star, we use the median values of $B_{\rm T}$, $V_{\rm T}$ and T. The achievable precision on the median magnitude is estimated using the error on the median given by:

$$\sigma_{\rm m} = s/\sqrt{2{\rm N}/\pi} \qquad (2)$$

In this formula s is a measure of the scatter, i.e. it is here defined as half the difference between the two points with 15.85% of the observations below and 15.85% above it, respectively. For a gaussian distribution s is equal to the standard deviation.

The number of observations N is the number of accepted transits for photometry. Transits are rejected:

1. if the background countrate is above 12000 counts/s
2. if disturbed by other star transits

Condition (1) ensures good quality photometry especially for stars fainter than 6th magnitude. Throughout the following discussion these two criterions have been applied and the number of observations N counts only these accepted transits, which are called 'observations' below.

To estimate $\sigma_{\rm m}$, observations in a test sky region collected during $\approx$ 800 days are used. For non-variable stars in the magnitude range 6.5 to 7.5 mag (285 stars) and 9.5 to 10.5 mag (359 stars) the resulting $\sigma_{\rm m}$ is shown in Fig. 3 as a function of the number of observations (both inclined and vertical). With $\approx$ 100 transits as an average number of usable observations, a precision of $\lesssim$ 10 mmag for a 7 th magnitude star and $\lesssim$ 40 mmag for a 10 th magnitude star can be reached. For some stars even several hundreds of observations were possible. Table 2 gives $\sigma_{\rm m}$ for three different colour ranges as a function of $V_{\rm T}$ using 828 photometric standard stars with 80 to 120 observations. The precision is only slightly dependent on the colour range chosen. The biggest values of $\sigma_{\rm m}$ are achieved for red stars. This is due to the fact that the photon noise is larger in the $B_{\rm T}$ channel when studying a star with a given $V_{\rm T}$ and a high $(B-V)_{\rm T}$ value.

Table 2. Error on the median $(B-V)_{\rm T}$ for three colour ranges as a function of $V_{\rm T}$ for 828 photometric standard stars with 80 to 120 observations. Columns (2),(4) and (6) give the number of stars used per magnitude bin. Units are [mag] for $V_{\rm T}$ and [mmag] for $\sigma_{\rm m}$

$(B-V)_{\rm T}$	[-0.2,0.2]		[0.5,0.9]		[1.4,2.0]	
$V_{\rm T}$ (1)	n (2)	$\sigma_{\rm m}$ (3)	n (4)	$\sigma_{\rm m}$ (5)	n (6)	$\sigma_{\rm m}$ (7)
5	7	4	-	-	-	-
6	34	5	7	6	13	9
7	82	9	52	11	25	15
8	80	16	264	18	33	26
9	36	25	105	28	30	42
10	6	41	35	44	9	53
11	2	59	4	60	-	-

As a last estimate on the possible precision of $(B-V)_{\rm T}$ from Tycho photometry, we analysed $\sigma_{\rm m}$ on $(B-V)_{\rm T}$ for 264354 stars with declinations between 0 deg and $\approx$ 35 deg. Transits from $\approx$ 80% of the total observing span were used without restrictions on the number of transits. For most stars the $\sigma_{\rm m}$ on $(B-V)_{\rm T}$ will be around 60 mmag. About 28000 stars will have a $\sigma_{\rm m}$ on $(B-V)_{\rm T}$ of less than 30 mmag. The result shown in Fig. 4 is however preliminary regarding the items (2) and (3) discussed in the conclusions.

As an example of a non-variable star the observations of a photometric standard are shown in Fig. 5a. In order to plot the unevenly distributed observations, the data points were restricted to time intervals when the star is near the scanning node of the satellite, and the time axis has been split. All observations, i.e. from inclined and vertical transits, are shown. The catalogued ground-based values for this star are (Grenon et al. 1992): $V_{\rm T}$ = (6.764 $\pm$ 0.001) mag, $(B-V)_{\rm T}$ = (1.519 $\pm$ 0.006) mag. The 192 Tycho observations of this star yield the following median values and errors $\sigma_{\rm m}$: $V_{\rm T}$ = (6.763 $\pm$ 0.004) mag, $B_{\rm T}$ = (8.279 $\pm$ 0.007) mag, T = (7.368 $\pm$ 0.003) mag, and $B_{\rm T}-V_{\rm T}$ = (1.513 $\pm$ 0.008) mag.

Fig. 3a and b. The error on the median $\sigma_{\rm m}$ as a function of the number of observations for non-variable stars in the magnitude range **a** 6.5 to 7.5 mag (285 stars) and **b** 9.5 to 10.5 mag (359 stars). Each point corresponds to the error $\sigma_{\rm m}$ of the median of one single star

The Tycho data base will also include many known and unknown variable stars (Mauder & Høg 1987). As an example, observations of a known variable are presented in Fig. 5b. The data belong to the irregular red variable and late Carbon star T Lyr. Due to the high $(B-V)_{\rm T}$ the observations in the $B_{\rm T}$ channel are much noisier and not all transits were observed. Examples of new variables found during Tycho processing are shown in a recent publication (Makarov et al. 1994).

4. Conclusions

Results of the calibration of Tycho photometry were presented for 833 days of the mission showing stable calibration parameters except for a decrease in sensitivity of the instrument by $\approx$ 5% during the interval of observation. The calibration was applied to observations of stars with ground-based photoelectric data to estimate the precision of the current photometric data base covering $\approx$ 800 days of the mission. For a non-variable star of 7th (10th) magnitude with $\approx$ 100 observations a precision

Fig. 4. The precision on $(B-V)_{\rm T}$ for 264354 stars using data from $\approx 80\%$ of the total observing span

on mean magnitudes of better than 10 mmag (40 mmag) can be expected. For the same number of observations the precision on $(B-V)_{\rm T}$ depends only slightly on the colour and can be expected to be better than 20 mmag (60 mmag).

Before the compilation of the final transit catalogue and the computation of the mean values in the star catalogue several major improvements will be introduced:

1. All stars newly detected during the recognition process and all solar system objects observable by the star mapper such as the Galilean satellites and minor planets, will be processed.

2. Furthermore a new estimation process will yield better results for stars brighter than 4th magnitude compared to the old one (Bässgen et al. 1992): In the current data base observations of these stars are severely affected by the non-linearity of the photomultipliers at high countrates yielding too faint magnitudes. During the new estimation the amplitudes for bright stars will be obtained from the wings of the signal where the countrates are lower and the photomultipliers behave linearly.

3. In the star catalogue the "mean" magnitudes given for stars fainter than ≈ 9 mag will be estimated by a model taking into account the missing transits.

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Fig. 5a and b. Example observations **a** a non-variable star with observations restricted to time intervals with the star near the scanning node of the satellite (101 observations), **b** the slow irregular variable T Lyr. The time axis gives days since the launch of Hipparcos. For both stars transits with a background exceeding 12000 counts/s and transits disturbed by other stars were excluded

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