8. PHOTOMETRIC ANALYSIS OF TRANSIT DATA

The purpose of the photometric calibration, described in this chapter, was to derive an accurate transformation from the signal amplitudes estimated in the B_T and V_T channels, by the detection process, into magnitudes in the Tycho B_T and V_T system. This was done for each channel separately by allowing for six independent instrument calibration parameters. Only one of these parameters was found to vary significantly during the mission.

8.1. Theoretical Basis

Input data to the photometric calibration were the estimated background count rate and the estimated signal amplitudes in the B_T and V_T channel. The signal amplitudes, a (reckoned in counts per sample), came either from the main processing or from the reprocessing data stream (see below), resulting in two independent calibrations. Because calibration was done in magnitude space, the signal amplitudes were first transferred to observed raw magnitudes:

$$m_{\text{obs}} = -2.5 \log(a) + m_{\text{off}} \qquad [8.1]$$

The constants m_{off} are given in Table 8.1.

The functional relationship between the observed raw Tycho magnitude m_{obs} and a ground-based magnitude from the standard star catalogue m_{standard} has the following form:

$$m_{\text{obs}} = m_{\text{standard}} + \sum_{i=1}^{6} c_i X_i \qquad [8.2]$$

where the c_i are the unknown calibration parameters and the X_i are the variables listed in Table 8.2.

During pre-launch simulations, time-dependent terms and higher-order mixed terms like $(B - V - 0.7)^2 z$ and $(B - V - 0.7) z^2$ had been included in the list of variables, but extensive tests on real data showed that they were not significant.

In order to ensure the statistical independence of the chosen variables and to add to the stability and reliability of the solution, the variables were not simply taken in their basic form but were changed to a Legendre polynomial representation. This included proper scaling of the range and units of the variables.

Table 8.1. Calibration constants for the photon noise. The constants γ and δ, and the magnitude offsets m_{off} for the preceding and following fields of view (FOV), are described in the text.

Channel	γ	δ	m_{off} Preceding FOV Lower	Preceding FOV Upper	Following FOV Lower	Following FOV Upper
inclined B_T	0.12419	0.13003	11.430	11.309	11.504	11.400
vertical B_T	0.13223	0.11538	11.761	11.662	11.795	11.701
inclined V_T	0.11337	0.11115	11.071	11.046	11.028	10.998
vertical V_T	0.11444	0.11308	11.458	11.446	11.377	11.384

Table 8.2. Photometric calibration variables.

Index	Variable	Physical Meaning
1	1	zero point
2	z	slit abscissa
3	z^2	
4	$(B - V - 0.7)$	colour index
5	$(B - V - 0.7)^2$	
6	$(B - V - 0.7)z$	mixed term

The calibration was done separately for the B_T and V_T bands, both fields of view, upper and lower parts of the grid, and inclined and vertical slit groups, resulting in 16 possible combinations. The full set of parameters was computed independently for a period of time called a photoset (see Section 8.2).

Each single observation was described by the functional relationship given in Equation 8.2, relating the catalogued standard star magnitude with the observed magnitude and the unknown six calibration parameters. The catalogue error was assumed to obey a Gaussian distribution with a standard deviation equal to an adopted mean error for the particular magnitude range of the star. Using a normalisation with the standard errors of the observed magnitudes $\sigma_{m_{\mathrm{obs}}}$, Equation 8.2 can be rewritten as:

$$r = p\, m_{\mathrm{standard}} + \sum_{i=1}^{6} q_i X_i \qquad [8.3]$$

with $p = 1/\sigma^2_{m_{\mathrm{obs}}}$, $q_i = c_i/\sigma^2_{m_{\mathrm{obs}}}$, $r = m_{\mathrm{obs}}/\sigma^2_{m_{\mathrm{obs}}}$. Note that in Equations 8.2 and 8.3 the noise terms have been omitted for brevity.

This equation must be valid for each single observation and for all standard stars observed. From Equations 8.3 the design matrix of the least-squares problem was constructed, which was then multiplied by its transpose to give the normal equation matrix. Solving the normal equations gave the calibration parameters c_i. Numerically, this was done by Cholesky decomposition (Seber 1977).

Reduction of Transit Data to the Tycho System and Error Assignment

The computed parameters c_i were used to derive magnitudes in the Tycho photometric system by inversion of Equation 8.2 for each single transit depending on field of view, part of the grid, and slit group.

To each magnitude measured in a single transit, a mean error:

$$\sigma_t = \sqrt{\sigma_{pn}{}^2 + \sigma_{par}{}^2} \qquad [8.4]$$

was assigned. Here, σ_{par} is the parameter error resulting from the uncertainty of the calibration and σ_{pn} is the photon noise. The latter is given by:

$$\sigma_{pn} = \sqrt{\gamma a + \delta b}/a \qquad [8.5]$$

with a being the estimated amplitude and b the background count rate in a given channel (both in counts per sample; 1 sample = 1/600 s). The constants γ and δ are different for each passband and slit group. They are given in Table 8.1, which also lists the constants m_{off} for the conversion from count rates to magnitudes given in Equation 8.1. Note that m_{off} depends on the field of view (preceding/following field of view) and the branch of the slit groups (lower/upper).

The values of σ_t for each observed magnitude are published in the Tycho Epoch Photometry Annexes A and B, for two selections of stars. For bright stars σ_t is dominated by the parameter error, for faint stars by the photon noise. While the Tycho Epoch Photometry Annex gives only one value σ_t per magnitude, it should be noted that the photon noise σ_{pn} is in fact not symmetric for faint stars, as can be seen in Figure 8.2. The limits of a $\pm 1\sigma$ interval in magnitudes must be calculated by computing Equation 8.5 in terms of count rate, and transforming:

$$a \pm \sqrt{\gamma a + \delta b} \qquad [8.6]$$

to the magnitude scale, using Equation 8.1. More details are given in Chapter 9.

Further error sources not included in σ_t became important for certain observations. One such additional error was introduced during the data transmission from the satellite to the ground. Count rates were compressed by a semi-logarithmic algorithm; therefore the resultant magnitudes got an additional scatter. This 'digitisation error' had a size of several millimag. It was of importance for the brightest stars only, since for all other stars the photon noise error was much larger. Count rates for faint stars were not compressed at all. Other errors were due to variations of the scanning velocity of the satellite (Scales *et al.* 1992 and Section 8.3).

Median Magnitudes and Standard Errors

For the analysis and verification methods described below, median magnitudes were computed. The mean error of the median magnitude is estimated by:

$$\sigma_m = s/\sqrt{2N/\pi} \qquad [8.7]$$

In this formula N is the number of individual measurements, and s is a measure of the scatter of them, defined as half the difference between the 15.85th and the 84.15th percentile. For a Gaussian distribution s is equal to the standard deviation, the two selected percentiles being at ± 1 standard deviation from the mean.

8.2. Instrument Calibration

The Tycho photometric system consists of two channels, B_T and V_T, described in Volume 1, Section 1.3.3. During the data reductions a third broadband magnitude T was defined from the added count rates (see Großmann *et al.* 1995). The Tycho Catalogue and the Tycho Epoch Photometry Annex contain magnitudes almost entirely in the B_T and V_T photometric system.

Selection of Standard Stars

A selection of about 30 000 standard stars was prepared in the Tycho photometric system. But the standard stars entering the observation equations were restricted to the magnitude range 4.5–9.0 mag. Brighter stars were excluded because of saturation effects of the photomultipliers, fainter stars because of the censoring problem (see Chapter 9). Members of close double stars or multiple systems were not used in order to avoid confusion. The resulting number of standards actually used in the given magnitude range was almost 10 000 for the main processing, and 13 600 for the reprocessing.

Selection of Transits

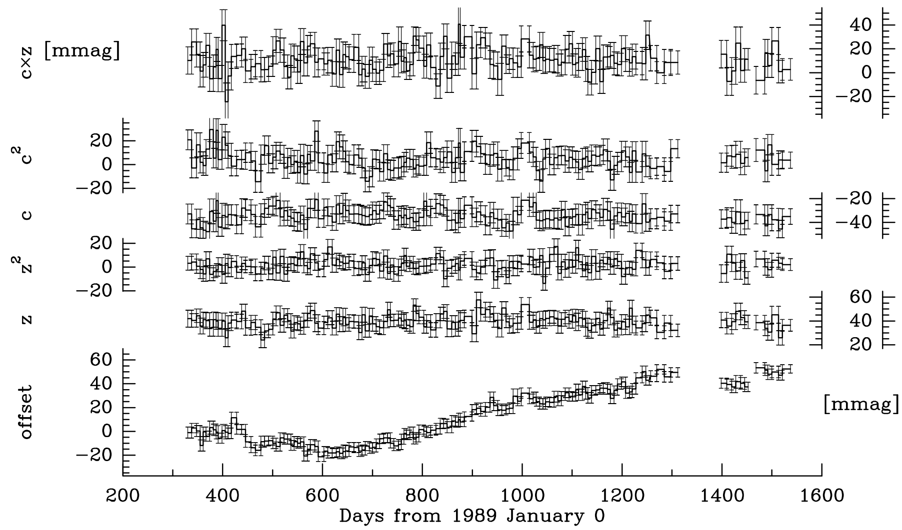
Contrary to the case of the final selection of transits used to compute median or corrected mean magnitudes in the Tycho Catalogue, no astrometric residuals were available at the processing stage of calibration: transits were accepted according to a probability measure depending on the squared difference $m_{\rm obs} - m_{\rm standard}$ and the squared difference $t_{\rm obs} - t_{\rm predicted}$, i.e. between observed and predicted transit times. Transits within 10 arcsec of the top or bottom slit ends were rejected, as were transits within 30 arcsec of the apex of the inclined slits. In addition, transits near jet-firings were not used (see Section 8.3). In order to avoid a background dependence of the calibration parameters, only transits having background count rates below 18 counts per sample entered the calibration.

Length of the Photosets

Independent sets of calibration parameters were computed for certain periods of time called photosets. Their length was chosen such that the calibration parameters could reasonably be assumed to be constant over the period. Keeping the length constant would, however, have resulted in large variations of the parameter errors $\sigma_{\rm par}$, due to sky regions with varying star densities.

For this reason the length of the photosets was adapted automatically to yield a minimum of 4500 accepted calibration transits. Thus the length varied between 3.4 and 18.0 days. Due to the higher number of stars available in reprocessing, the number of photosets covering the whole mission for this data stream was 165 compared to 138 in the main processing.

a



b

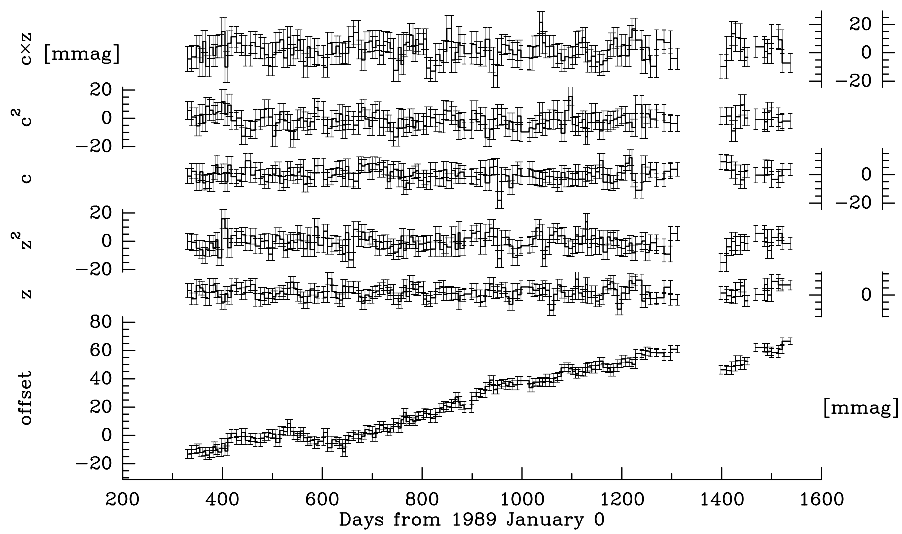


Figure 8.1. *Results from the calibration for the whole mission, comprising 1190 days of measurements. The six calibration parameters and their mean errors are shown as a function of time: (a) for the* B_T *channel, and (b) for the* V_T *channel. The example parameter sets displayed here are for the main processing, vertical slit group, lower branch of the grid and following field of view. Note that* $c = B_T - V_T - 0.7$*. All parameters are given in millimag. The time axis gives days since 1989 January 0.*

Calibration Results

The computed parameters and their errors are shown in Figure 8.1, for two of the 16 possible combinations: vertical slits, lower branch, following field of view, for the B_T channel and V_T channel, respectively. Whereas the parameters depending on slit coordinate and colour showed no significant variations and no long-term drifts, the zero-point, or offset, exhibited a clear change with time. This effect was also present in the other 14 combinations not shown here. There was a monotonous change of roughly 55 millimag over the period between day 600 and day 1300, corresponding to a decrease in sensitivity of 5 per cent. The first three months of observations behaved differently in the two channels, without a continuous increase; this was possibly due to the many changes of instrument focus during this time. The offset also changed after three months of sun-pointing (the gap after day 1300) and again after a shorter gap near day 1470. All other parameters remained constant within their limits of uncertainty.

Main Processing and Reprocessing Calibration

The motivation for distinguishing between these two processing chains in photometry was the usage of different single-slit response functions in the detection process (see Chapter 10). In the main processing, observations of bright stars were severely affected by the non-linearity of the photomultipliers at high count rates, yielding too faint magnitudes. During the reprocessing estimation the amplitudes for bright stars were obtained from the wings of the signal where the count rates were lower and the photomultipliers behaved linearly. As a consequence, observations of stars brighter than $V_T = 3$ mag in the Tycho Catalogue and the Epoch Photometry Annex were taken from reprocessing photometry. Regarding the calibration parameters c_i there was no significant difference between main and reprocessing calibration. Thus, Figure 8.1 is not repeated for reprocessing.

8.3. Verification Methods

The present section deals with the comparison of the observed median and the ground-based standard magnitudes of the stars in the Tycho internal transit data base (TPOC, see Chapter 11). Overall properties of the published catalogues are discussed in Chapters 16 and 19.

Verification took place at different levels of processing, starting from immediate comparisons of observed magnitudes of standard stars with the standard star catalogue. More crucial comparisons were done at the level of the Tycho internal transit data base. This data base served as a basis to construct the Tycho Epoch Photometry Annex and Tycho Catalogue, as described in Chapter 11.

Verification During Processing

As soon as the calibration parameters had been computed for a given photoset, they were applied to all observations of selected stars (the selection for this purpose being larger than the set of standard stars). The resulting calibrated transit data entered into

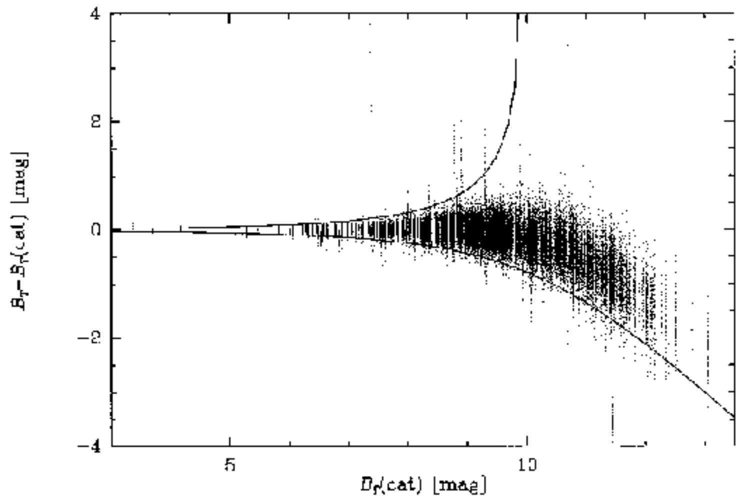


Figure 8.2. *Reduced Tycho observations for 937 stars with ground-based magnitudes in a given sky region. Each point represents one observation and gives the difference between the reduced and ground-based magnitude for a single transit. Thus, transits for a given star show up on a line with constant ground-based B_T(cat). The solid curves indicate the 3σ limits from photon noise for a background of 18 counts per sample as given by Equation 8.6.*

a gradually increasing transit catalogue. This catalogue allowed a crucial external verification of the data. A completely independent calibration of the star mapper (including a different background and signal amplitude estimation) was carried out by the NDAC consortium. Calibrated magnitudes and error estimates were checked to be consistent between these two data streams. This was done for star mapper data from the start of the mission, using a sample of up to 30 000 stars.

Effects of Jet Firings

Early investigations showed that the estimated signal amplitudes were affected by errors in the assumed instantaneous scan speed. For instance, an error of 0.2 arcsec s^{-1} could change the measured magnitude by about 0.010 mag. This led to the exclusion of all transits within about 2.1 s following a jet firing of the satellite attitude control system.

Recalibration of Passbands

During the mission the Tycho spectral passbands were redetermined (see Chapter 13). This necessitated a revision of the standard star magnitudes, which in turn resulted in changes of the instrument calibration parameters. A direct comparison between calibrated transits from the old and the new system showed that only few of the calibration parameters had actually changed. In the B_T channel, the offset and colour term were affected, while in the V_T channel only the colour term had changed. This was consistent with the fact that mainly the B_T passband had been redefined. The change in the B_T offset was of the order of 20 millimag. It can directly be seen when comparing Figure 8.1(a) with Figure 1 in Großmann *et al.* (1995).

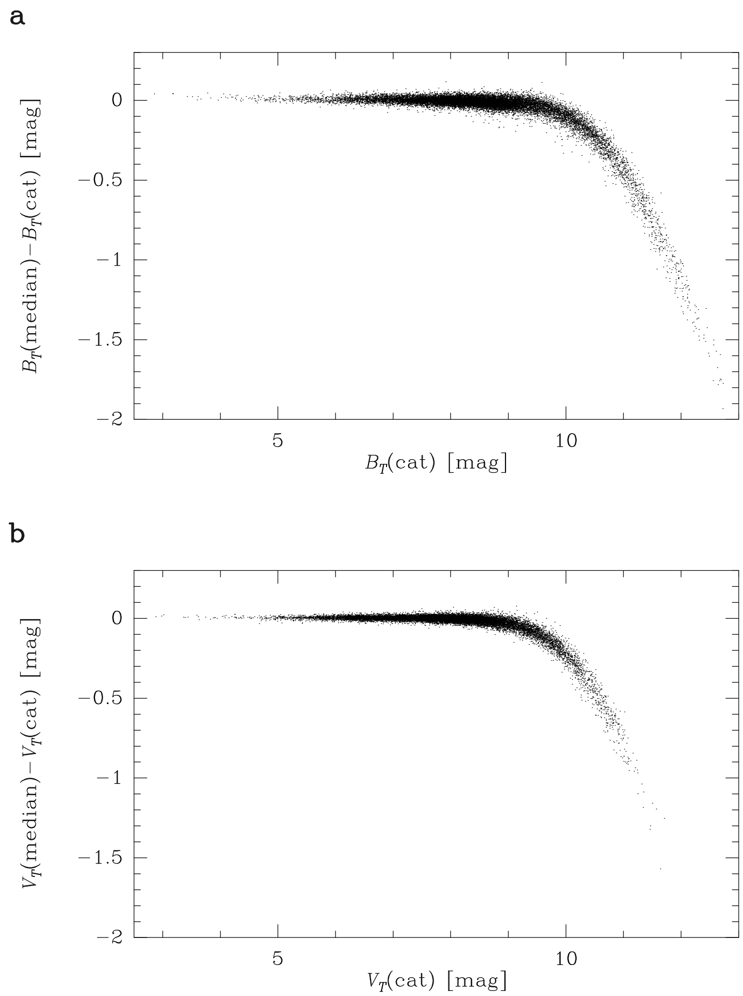


Figure 8.3. *Calibrated Tycho observations of 17 683 standard stars distributed over the whole sky. Each point represents the median magnitude for one star. The figure shows the difference between the observed Tycho median magnitude and the ground-based magnitude: (a) for the B_T channel, and (b) for the V_T channel.*

Modifications of the Standard Star Sample

The redefinition of the passbands did not only lead to changed standard star magnitudes, but also to a change in the sample of standard stars. At the time of the change, existing satellite data could already be used to check the (supposedly single) standard stars for duplicity. In addition, results of an early calibration of 800 days of mission (Großmann *et al.* 1995) were used to cancel variable stars and possible misidentifications from the standard star sample.

The Standard Stars: Catalogued and Observed Values

The original sample of about 30 000 stars with ground-based magnitudes contained many stars which were not usable for the calibration process (see Section 8.2). This is clearly demonstrated in Figure 8.2, showing about 100 000 single observations of 937 stars in a given sky region. While most observations are located within the 3σ photon noise limit, several clearly fall outside. These observations either indicate variable stars, close doubles, or stars with an incorrect ground-based magnitude. Removing these stars restricted the sample to 17 683 stars. However, the sample actually used during main processing and reprocessing calibration was smaller still, because of the magnitude limits imposed in addition (see Section 8.2).

Figure 8.3 compares the calibrated Tycho magnitudes of the 'cleaned' 17 683 standard star sample with the catalogued B_T and V_T magnitudes. For each star the difference between the Tycho median magnitude and the ground-based magnitude is plotted. The strong bias for stars fainter than the 9.0 mag is due to the censoring (i.e. non-detection) of individual transits. It is the reason why standard stars fainter than 9.0 mag were excluded from the determination of calibration parameters, and why the usage of median magnitudes for the Tycho Catalogue was restricted to stars brighter than V_T = 8.0 mag and B_T = 8.5 mag. The fainter stars had to be subjected to the more sophisticated de-censoring treatment described in Chapter 9.

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