11. PRODUCTION OF THE TYCHO CATALOGUE

The principal stages of the Tycho Catalogue production are outlined. The chapter is divided into three parts: the astrometric part, production of the Tycho Epoch Photometry Annex, and production of photometric mean values. The astrometric analysis was decisive in the determination of the stellar contents of the Tycho Catalogue, the quality of solutions, merging criteria etc. The Tycho Catalogue of mean values was constructed in the course of astrometric adjustments and transformations of the calculated data, while the photometric data were computed in a separate process.

11.1. Production of the Astrometric Catalogue

The routine astrometric reductions were carried out as a series of iterative updates of a working catalogue, called the Star Constants Catalogue (SCC). In the main processing the Star Constants Catalogue contained more than 1 200 000 entries, including all the TICR (Tycho Input Catalogue Revision) entries and hexagon points (see Section 7.4); it contained some auxiliary information and the following data:

1. Identification number from the input catalogue.
2. Coordinates from the input catalogue.
3. Combined T magnitude from the input catalogue.
4. Accumulated number of accepted observations.
5. Current Cholesky triangle matrix of 15 elements and the right-hand part.
6. Current solution for astrometric parameters.
7. Condition number of solution.
8. Square norm of residual vector.
9. Corrections to astrometric parameters.
10. Corrections to the tangential coordinates 'H30 – TICR' (where H30 was the preliminary 30-month Hipparcos Catalogue) for monitor stars only.
11. HIP identification number for monitor stars.

The data from the input catalogue (items 1 to 3) stayed unchanged. The proper motions and parallaxes of the input catalogue were not present in the Star Constants Catalogue, but in annexes to TICR. These values were exactly the same as those used in the prediction of transit times. The data of items 4 to 8 were updated with an observation equation for a given star when an observation of this star was encountered and had been accepted for the astrometric solution. The number of accepted observations $N_{\rm astrom}$ then increased by 1, the Cholesky factor and the right-hand part were updated by Givens rotations, and the condition number was updated. The square norm of the residual vector ρ was increased by the newly calculated residual:

$$||\rho||^2 = \sum_{n=1}^{N_{\text{astrom}}} (\Delta u / \sigma_{u,n})^2 \qquad [11.1]$$

Solving for astrometric parameters each time a new observation was obtained, was superfluous but it cost relatively little in computing time when compared with the time spent on disk input/output operations.

The corrections to astrometric parameters (item 9) were updated after each complete iteration for all but the monitor stars, which were a subset of the Hipparcos intermediate 30-month catalogue 'H30' (see Section 7.2). For the 105 000 monitor stars only the corrections to tangential coordinates were updated, while the relevant fields for proper motion and parallax contained differences 'H30 – TICR', calculated once and forever as soon as the preliminary 30-month Hipparcos Catalogue H30 had become available from NDAC. The corrections to positions were however stored separately (item 10). This introduced an important difference between the monitor stars and the rest: For an ordinary star, the corrections to the proper motion and parallax were updated as many times as the number of iterations (5 in the main processing and 3 in the reprocessing). For a monitor star, however, these corrections have effectively been updated only once, when the final parameters were derived. This most probably accounts for a difference in precision between the positions and the other parameters in the Tycho Catalogue, when compared with the Hipparcos Catalogue. This is described in Chapter 18.

When all observations were reduced and the final solution was achieved, the 5 astrometric parameters were derived from the input catalogue data, the current solution and the previously accumulated corrections. At this stage, the on-ground proper motions and parallaxes had to be taken into account again. Finally, several distinct transformations had to be carried out on data in the Star Constants Catalogue.

- the final astrometric parameters were computed by adding the final solution and the accumulated corrections to the input catalogue values. For positions the final equatorial coordinates were derived from the local plane (tangential) coordinates and the input catalogue positions by Equation 1.2.23 of Volume 1;
- the Cholesky triangle matrix was transformed into a covariance matrix, and the formal errors of the solution were derived;
- the formal errors in the Star Constants Catalogue were multiplied by the standard error of unit weight $\sigma_{\text{u.w.}}$, that is:

  $$\sigma_{\text{u.w.}} = \sqrt{||\rho||^2 / (N_{\text{astrom}} - 5)}. \qquad [11.2]$$

  This factor was usually slightly larger than 1.0, but could be much larger for very disturbed stars, double stars and entirely false stars. The resulting internal standard errors are discussed in Chapter 18;
- the position and proper motion, and the covariance matrix were transformed from the epoch of Tycho Input Catalogue J1990.0 to the standard Hipparcos-Tycho Catalogue epoch J1991.25. The covariance matrix was transformed by the simplified treatment in Section 1.5.4 of Volume 1. The position and proper motion were transformed rigorously as described in Section 1.5.5 of Volume 1, assuming $V_R = 0$ since the radial velocity was always unknown;
- auxiliary parameters of the solution, e.g. the signal-to-noise ratio F_s, were calculated.

11.2. Merging

The two runs of Tycho data reductions, the main processing and the reprocessing, were quite independent of each other, and the merging of the two resulting catalogues is described here. The reductions were based on two different input catalogues (TICR and TICU) with different stellar contents, and the positions for common stars could also disagree. The two data reductions were implemented separately, and some of the principal stages were significantly updated for the reprocessing, e.g. the prediction. A few off-line tasks were accomplished in the course of reprocessing, such as close double star treatment and astrometry and photometry of solar system objects.

As an intermediate astrometric result of the two processing runs, two Star Constants Catalogues were constructed, called respectively SCC and SCU. The structure of the catalogues was similar, as described in the previous section. They were transformed into so-called CUO_CAT provisional catalogues, namely CUO_CAT_f for the main processing and CUO_CAT_u for the reprocessing, containing 1 150 157 and 289 158 entries respectively.

The general strategy of 'merging' for a star contained in both catalogues was strictly to take only one of the alternative solutions; a combination or a mixture of the data from the two sources was never allowed. A cross-identification list of common stars in TICR and TICU (see Section 10.2) was used to infer the identity of stars since many of them had received different identification numbers in TICU. A sorted *ad hoc* lookup table was produced, based on this list, to facilitate quick and automatic identification of stars. The list contained, however, a few errors of the two following kinds:

- stars supposed to be identical but having considerably different positions;
- stars not given in the cross-identity list but being in fact identical.

The latter kind of inconsistencies was taken care of in a series of redundancy analyses. The former inconsistency was resolved by way of position comparison for supposedly identical stars in the two solutions. The stars were accepted as identical if the positions agreed within 1 arcsec, otherwise both stars were kept in the merged catalogue CUO_CAT_1, representing possibly a double or multiple system. In fact, only 57 such pairs were found.

All entries of very low astrometric quality in both catalogues were rejected at this stage of catalogue construction. Since too many stars should not be rejected before a more careful analysis was undertaken, a rather loose criterion was adopted to define a low astrometric quality. A solution was considered to be of no value for further processing if the number of accepted transits was below 25. The total set of stars in the two catalogues could be divided into 3 groups:

- approximately 207 000 stars in common between the two solutions;
- 943 000 stars represented only in the main processing;
- 82 000 stars given only in the reprocessing.

The corresponding numbers of low-quality stars were 46 000, 21 000 and 78 000. The large fraction of low-quality solutions in the reprocessing was related to the so-called serendipity stars, the vast majority of which were proved to be non-existing stars, false entries. It should be noted that many of the 21 000 bad stars in the second group were later reintroduced in the final catalogue, but without astrometric solution, for the sake of their photometry.

The remaining 926 000 stars of reasonable quality in the two last groups were all adopted for CUO_CAT_1. The 161 000 stars with redundant solutions of the first group required a careful consideration. At this stage, a proper choice had to be made between the two alternative solutions.

It had become clear in the course of practical work and by some provisional checks that the astrometric quality of the reprocessing was inferior to the main processing. The lower quality was so conspicuous that even the error model for single observation had to be adjusted. The variance of the transit time, given by Equation 7.6, was modified to:

$$\sigma^2 = \sigma^2_{\rm ph}(A,B) + (\sigma_{\rm att.1} + \sigma_{\rm att.2})^2 \qquad [11.3]$$

where $\sigma^2_{\rm ph}(A,B)$ is a theoretically derived variance due to photon noise, as a function of the amplitude A and the background B, and $\sigma_{\rm att.2}$ is an empirical correction to the previously estimated attitude error $\sigma_{\rm att.1}$. The total attitude error in the brackets was typically 7 mas and 30 mas in the main processing for vertical and inclined slits, respectively. These values were larger during the reprocessing, and also varied from 12 to 18 mas and from 30 to 37 mas, respectively, at different intervals of the mission. The increase of the quadratic term affected particularly the overall precision of the 5 astrometric parameters for bright stars (brighter than 9 mag), as was shown by comparison with provisional main mission data. For the brightest stars the deterioration of precision was a factor of 1.5 in positions, 2.3 in proper motions and 2.0 in parallaxes.

A small but quite obvious increase of systematic errors was also found in the reprocessing solution by comparison with provisional main mission results. In parallaxes, for example, a negative bias of −2.5 mas was found, meaning that the reprocessing parallaxes were in general 2.5 mas too small. The largest errors appeared however in proper motions. Zonal mean differences of proper motions 'Tycho – Hipparcos' are shown in Figure 11.1 for the main processing (upper plot) and for the reprocessing (lower). The zonal errors of proper motions in the main processing are typically below 2 mas/year, while in the reprocessing a value of 5 mas/year is quite frequent and a smooth geometrical pattern is clearly seen. This pattern becomes even more pronounced when differences 'main processing – reprocessing' are plotted (Figure 11.3, upper plot).

The poor performance of the reprocessing astrometry for both accidental and systematic errors is believed to be caused by an unknown error in the prediction software used for reprocessing. The error was 'minor' in the sense that it could not be visible in the rather rough checks like the 'cloud plots' (Section 4.5) at the early stages of the data processing. It was decided not to make further efforts to locate the error or repeat the data reprocessing, lest an inevitable delay of the Tycho catalogue release should result. This decision was also facilitated by the possibility of diminishing the zonal systematic errors by means of the spherical functions technique described in the following section. Still, the reprocessing solution had to be downweighted in the merging, because the updated error model could perhaps not properly describe the remaining systematic part of the errors. Therefore, a reprocessing solution (u) was preferred instead of the main processing solution (f) only when $s^{\rm f}_{\rm max}/s^{\rm u}_{\rm max} > 1.15$, where $s_{\rm max} = \max\{\sigma_i, i = 1, 2, ...5\}$. Only some 9000 reprocessing solutions survived this strict selection. They belong

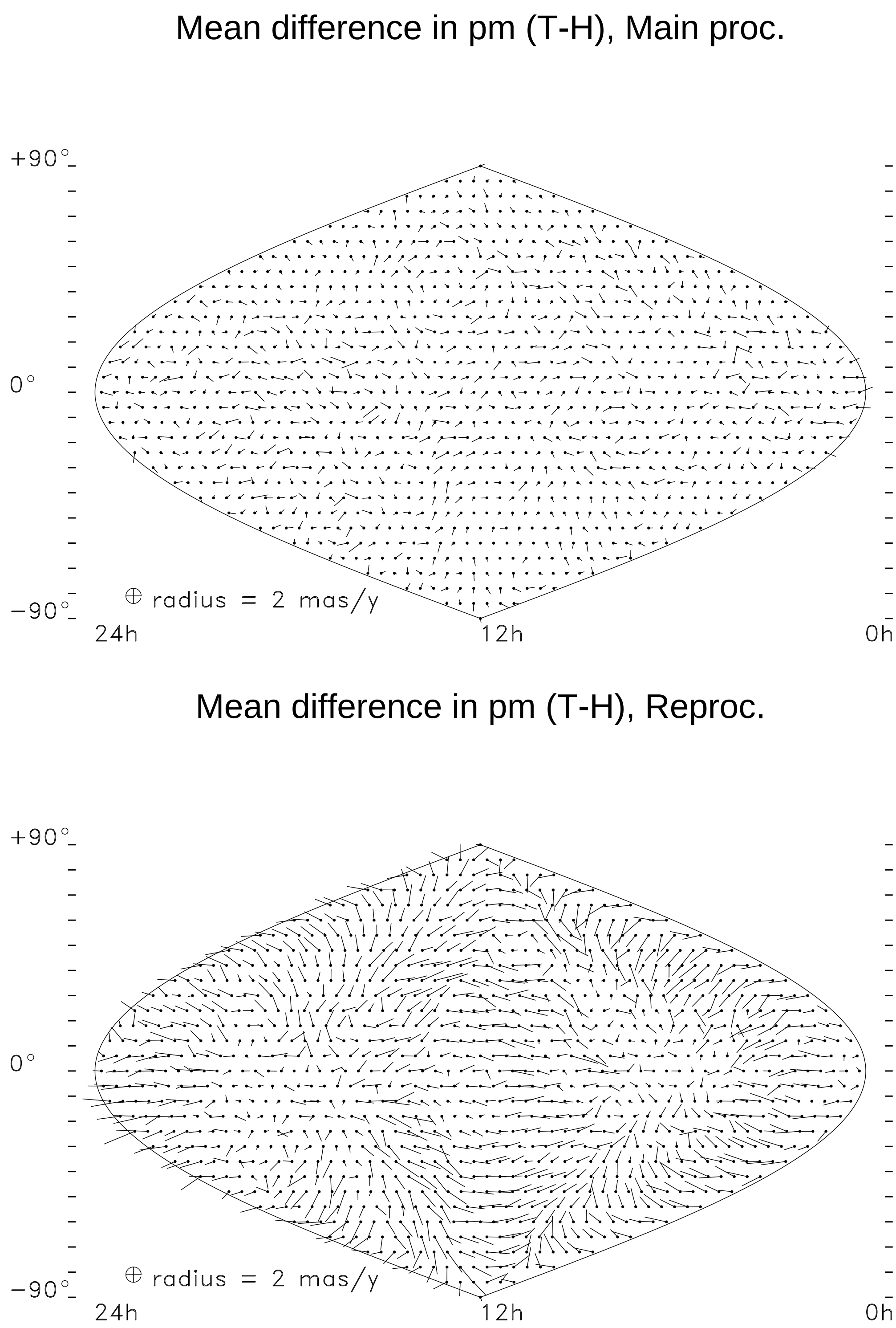

Figure 11.1. *Sky projection of differences 'Tycho – Hipparcos' in proper motions for the main processing solution (upper plot) and the reprocessing (lower). The length of a vector shows the value of the difference in mas/year, and the azimuthal angle indicates its position angle on the sky. The plots are cosine sky projections, in equatorial coordinates, with a cell size of* $6° \times 6°$.

typically to stars of high astrometric quality with perhaps much improved initial positions in TICU.

About 1 070 000 stars were contained in CUO_CAT_1, more than 98 per cent of which had been taken from the main processing. They were subject to several distinct procedures, such as systematic corrections, redundancy analyses, removal of false entries, etc., thus completing the astrometric catalogue production.

11.3. Completing Steps of the Catalogue Production

The fraction of stars in CUO_CAT_1 with solutions from the reprocessing, however small it was, had to be corrected for systematic differences in all five astrometric parameters. Since the final main mission astrometry was not available at that time, the reprocessing part was simply adjusted to the main processing part, leaving the task of final systematic correction, including rotations, to the very end of the catalogue production.

Correction of Systematic Differences 'Reprocessing – Main Processing'

A rather conventional technique of spherical functions representation was used to carry out this task. The original method applied to astrometry was proposed by Brosche (1966), and further developed by several other authors. The differences in astrometric parameters were represented by the expansion:

$$\Delta a_i = \sum_{j=0}^{J} c_j^i \, Y_j(\alpha,\delta) + \epsilon \qquad [11.4]$$

where Y_j are spherical orthogonal functions, $\Delta a_i = (\Delta\alpha \cos\delta, \Delta\delta, \Delta\pi, \Delta\mu_\alpha \cos\delta, \Delta\mu_\delta)$ are the astrometric parameter corrections, and ϵ is the random component of the differences. The spherical harmonics Y_j are orthogonal for different j, and they can be normalized as:

$$\int_0^{2\pi} \cos\delta \, \mathrm{d}\alpha \int_{-\pi}^{\pi} Y_j(\alpha,\delta) Y_l(\alpha,\delta) \, \mathrm{d}\delta = \delta_{jl} \qquad [11.5]$$

where δ_{jl} is the Kronecker symbol. The spherical harmonics are related to associated Legendre polynomials by the equation:

$$\begin{aligned} Y_{nms} &= R_{nm} P_{nm}(\cos\delta) \, \sin m\alpha \qquad \text{or} \\ Y_{nmc} &= R_{nm} P_{nm}(\cos\delta) \, \cos m\alpha \end{aligned} \qquad [11.6]$$

where:

$$\begin{aligned} R_{nm} &= \sqrt{\frac{(2n+1)}{4\pi} \frac{2(n-m)!}{(n+m)}} \qquad m \neq 0 \\ &= \sqrt{\frac{1}{4\pi}} \qquad m = 0 \end{aligned} \qquad [11.7]$$

the index $m = 0, 1, ..., n$, and $n = 0, 1, ..., N$. The index j counts all different spherical orthogonal functions from 0 to $J = (N + 1)^2$. An easy way to compute the associated Legendre polynomials is to use the following expression (Press *et al.* 1986):

$$P_{mm}(\cos\delta) = (2m-1)!! \cos^m \delta \qquad [11.8]$$

and the recurrences:

$$P_{(m+1)\,m} = \sin\delta(2m+1)P_{mm}$$
$$(n-m)P_{nm} = \sin\delta(2n-1)P_{(n-1)\,m} - (n+m-1)P_{(n-2)\,m} \qquad [11.9]$$

Equation 11.4 could not be directly used for the whole set of stars in a simple way. Apart from the necessity of re-normalising the basic functions due to the uneven distribution of Tycho stars over the sky, any attempt to introduce statistical weights for individual stars would require also a re-orthogonalisation. In principle, this could be achieved by Gram-Schmidt orthogonalisation, with computational difficulties. A new approach was used instead, in order to avoid weighting of individual stars. The sky was divided into a number of cells of $6° \times 6°$ size. Weighted mean differences of the astrometric parameters of stars within each cell were computed and assigned to a reference point in the centre of the cell. The statistical weights of the reference points were fairly uniform and could therefore be neglected in the following computations. The orthogonality and normalisation of the basic functions were proven to hold within the relative precision of 10^{-4} over the set of the reference points by direct calculation. The expansion corresponding to Equation 11.4 was sought then for the reference points, disregarding individual stars. The method is fast and convenient for big catalogues. It is quite justified for the determination of large-scale systematic distortions.

For each astrometric parameter, 81 terms of Equation 11.4 ($N = 8$) were calculated. As expected, the largest terms were found in proper motion differences, i.e. in $\Delta\mu_\alpha \cos\delta$: $-3.55\ Y_{11s}$ mas/year, and in $\Delta\mu_\delta$: $2.10\ Y_{21s}$ mas/year, where $Y_{11s} = \sqrt{0.75/\pi}\cos\delta\ \sin\alpha$ and $Y_{21s} = \sqrt{1.25/\pi}\cos\delta\ \sin\delta\ \sin\alpha$. The standard errors of the coefficients c^i_j were typically 0.05 to 1.00 mas(/year). The dominating term for parallax was $1.37\ Y_{00c}$ mas, where $Y_{00c} = \sqrt{0.25/\pi}$.

Before deriving a spherical function representation, it had to be ensured that the rotation (relative orientation) between coordinate systems or the spin between proper motion systems is negligibly small. Alternatively, a method exists to derive the rotation and the spin, when statistically significant, by means of a spherical function representation, where they appear at certain terms (Vityazev 1994). A more traditional way of rotation and spin determination was chosen, since no computational limitation was experienced for the rather small number of stars (about 200 000). The rotation and spin turned out to be very small, as expected.

The resulting systematic corrections were applied individually to each of the reprocessing stars in CUO_CAT_1. The vector plots in Figures 11.2 and 11.3 show the great improvement of the reprocessing solution after this correction. All smooth variations of both position and proper motion differences were removed by spherical harmonics, leaving only some small-scale disturbances. The negative bias of reprocessing parallaxes also disappeared. The result seems satisfactory enough to consider the merged catalogue as a uniform astrometric solution, called CUO_CAT_2.

Redundancy Analysis #1

Due to imperfections of the input catalogue and some errors in the TICR–TICU cross-identification list a small number of stars could appear two or even three times, under different identification numbers, in CUO_CAT_2. Such redundancies had to be eliminated. The astrometric solutions could of course be different for redundant entries. An entry was considered to be redundant if the position at J1991.25 was within 1 arcsec of

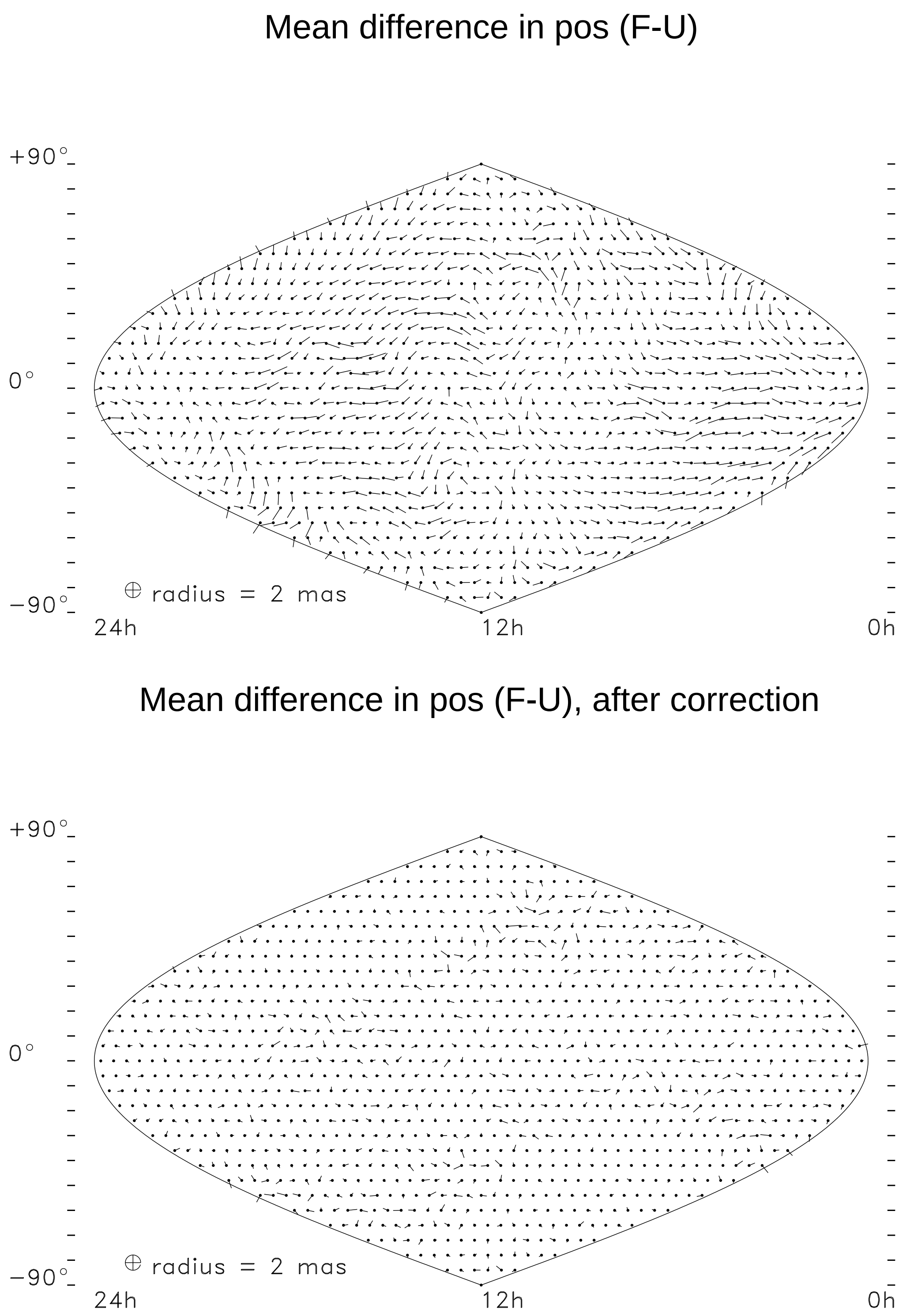

Figure 11.2. *Sky projection of differences 'Main processing – Reprocessing' in positions. The length of a vector shows the value of the difference in mas, and the direction indicates its position angle on the sky. Cosine sky projection in equatorial coordinates, cell size* $6^\circ \times 6^\circ$.

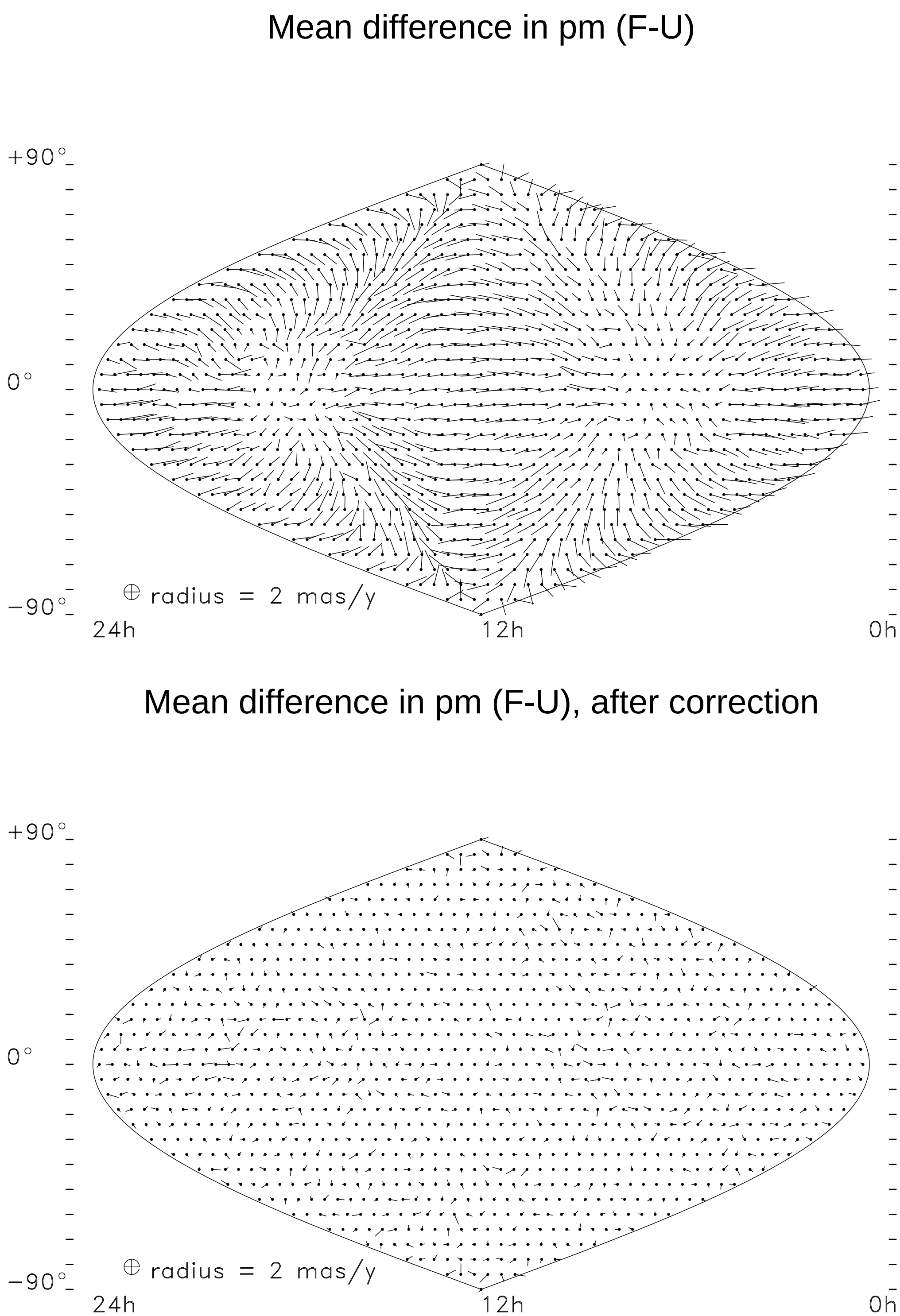

Figure 11.3. *The same as Figure 11.2, but for proper motions.*

another entry. That was the only criterion of redundancy adopted, reliable photometric data not yet being available. The limit of 1 arcsec was approximately the angular resolution of the Tycho instrument, being at the same time at least an order of magnitude larger than the expected error of positions. 1348 pairs of redundancies were found, some of them triple.

Selection of stars in the redundant pairs to be retained in the catalogue was made according to the following rules, in order of decreasing priority:

- if two stars in a pair have solutions from different sources (main processing and reprocessing) then the main processing solution is preferred, unless $s^f_{\max}/s^u_{\max} > 1.15$ (see Section 11.2);
- if two stars in a pair belong to different quality classes then the star of higher quality is preferred;
- the solution with highest F_s is preferred.

Some 792 redundant entries were discarded in this analysis, the rest was referred to as the CUO_CAT_3 catalogue.

Discarding Artefacts and Side Lobes

At this stage, the catalogue still contained quite a few spurious entries, i.e. non-existing stars. Two kinds of spurious entries could be distinguished, depending on their origin:

- intrinsic artefacts of the Tycho Input Catalogue;
- false components introduced by the recognition processing (see Chapter 5), usually closer than 20 arcsec to a bright real star.

The former kind were mostly identified with bright galaxies and planetary nebulae, confused in the Guide Star Catalog with stars, and stars with unknown or erroneous proper motions. The latter comprised chiefly so-called side lobes, i.e. parasitic signals due to interference of photon counts from different slits of the star mapper. Side lobes appeared at certain distances from sufficiently bright stars, and their presence is clearly seen in a pair statistics like that in Figure 16.16 where peaks at 5.6 and 11.3 arcsec are visible.

There was no certain criterion to distinguish false entries, due to a random excess of counted photons, from entries due to real stars. Only rather general statistical characteristics, available in the catalogue, could be used in practice, allowing few real stars to be lost, but never reaching a complete cleanness. With respect to side lobes, a satisfactory pair statistics was achieved only after some 23 600 components of multiple entries having quality flags Q above 5 had been discarded.

The intrinsic artefacts of the input catalogue were more difficult to recognize. It was noticed, however, that a specific group of so-called 'COMPI 10' entries was especially abundant with them. The 'COMPI 10' stars were included in TICR at positions where the Tycho Input Catalogue had a rather bright object which was, surprisingly, not found in the Tycho recognition processing. This fact was already a hint that there might be no star at the place, or it might be an extended object. A dedicated study revealed that only about 30 per cent of 'COMPI 10' stars were true. In the study, a total of 29 such objects were identified in a collection of 31 photographic prints, 55 arcmin in diameter, obtained with the Danish 1.5 m telescope at La Silla around 1990 for another purpose. The sample was classified into galaxies (8), false stars (11), and true stars (10) by visual inspection. Even true stars might, however, be too faint for Tycho to contain other than spurious information. Since detected transits at galaxies and at empty spots do not concentrate towards the estimated position, the signal-to-noise ratio F_s is always small. It was therefore decided to discard 23 100 'COMPI 10' stars with Q above 6 ($F_s < 5$).

Such rejections and cleaning procedures resulted in a series of catalogues, up to CUO_CAT_6.

Additions to the Catalogue and Redundancy Analysis #2

A few special groups of stars were included in the catalogue after dedicated treatments and analyses. Firstly, the result of double star reduction in astrometry (Section 14.4) was merged with the catalogue. There were two kinds of output from that reduction:

- 517 stars failed to be resolved into separate entries, but were found to be missing in the catalogue, at the same time. Such lost stars were mainly caused by the parasite recording, which rejected too many proper transits, when TICR contained a few (often false) nearby components;
- 1657 pairs of resolved double stars, to be merged with the catalogue.

Among the 3314 resolved components, 2232 had already been present in the catalogue. These were basically components successfully resolved by the recognition processing. A decision was taken to prefer always the solution from the double star reduction, since a much more careful selection of transits had been made, where the misleading parasite recording did not affect the result. The merging was carried out in a second redundancy analysis.

Secondly, 33 567 low quality stars ($Q = 9$ in Field T40, see Volume 1, Section 2.2) mainly in clusters or other dense regions were inserted in the catalogue. These stars had previously been rejected, but were re-introduced with the positions of TICR, without proper motions and parallaxes, because they could be of interest for photometry. Only 13 077 of them survived the following rejection and cleaning procedures, and some of them may still be false.

Finally, a dozen serendipity stars were re-introduced after a dedicated study at Strasbourg, based on inspection of Digital Sky Survey maps. The resulting catalogue CUO_CAT_11 contained 1 074 030 stars.

Redundancy Analysis #3

A search for internal redundancies was repeated because of the recent additions. The same limit on distance of 1 arcsec was adopted. 9593 pairs of redundancies were found, with at least one of the components being a $Q = 9$ star. As a result, 9530 entries were deleted.

Rotation and Systematic Corrections

The rotation and spin between the current Tycho and the final Hipparcos coordinate and proper motion systems were determined and corrected in Tycho as soon as a nearly complete version of the Hipparcos Catalogue became available. Just over 96 000 single reference stars, common to Tycho and Hipparcos and for which the relevant astrometric parameters in the two catalogues agreed within 3σ, were selected. Each star provided two equations for the rotation, and another two for the spin, as described in Section 1.5.7 of Volume 1. The equations were solved by the least-squares method iteratively, adjusting each time the selection of stars.

The astrometric Tycho processing was tied to a preliminary coordinate system, N18 (see Volume 3, Chapter 11), which was consistent with the first version of attitude parameters, used throughout the data reduction, and supplied with a consistent main mission astrometric solution, based on 18 months of the mission. The rotation between this system and the final ICRS system was found to be $(+40.04, +41.54, -67.60) \pm 0.01$ mas. The spin between the two proper motion systems was, as expected, much smaller, only about 1 mas/year.

After the rotations had been determined and applied to all positions and proper motions in TYC, large-scale zonal errors were corrected. The same technique of spherical harmonics (Section 11.2) was used again. The set of data was reduced by means of computing weighted mean differences in cells of $6^\circ \times 6^\circ$, and then 81 coefficients c_j of Equation 11.4 were determined for each astrometric parameter. The appearance of the differences is shown in Figures 11.4 before and after the corrections. It is clearly seen how the spherical functions remove extended features like the broad 'streams' in position in Figure 11.4(a), the upper plot. The degree of improvement can be expressed through median absolute differences over the sample of cells. The values were, before and after the correction respectively 1.25 and 0.83 mas for positions, 1.22 and 0.93 mas/year for proper motions and 0.64 and 0.57 mas for parallaxes. It was concluded that the systematic errors of the Tycho Catalogue with respect to the Hipparcos Catalogue are within 1 mas(/year), when the weighted mean differences are considered.

The systematic differences Tycho–Hipparcos are most probably due to systematic errors in the preliminary N18-NDAC attitude used in the final Tycho processing. The N18 catalogue was based on an early sphere solution in which some distortions due to the Hipparcos Input Catalogue still remained. These distortions could only partly be compensated by the instrument calibration parameters because the latter represented an average of about 10 satellite revolutions, rather than being related to zones on the sky. The remaining zonal errors thus provide an indirect view of the intricate influence of the attitude errors on the distortions of resulting astrometric parameters.

Cross-Identification and Merging with the Hipparcos Catalogue

Ideally, the cross-identification of stars in the Tycho and Hipparcos Catalogues with a limit of 1 arcsec on the position difference should be straightforward and unambigous due to the following circumstances:

- the combined formal error of a position is at least ten times smaller than the limit of 1 arcsec;
- Tycho astrometry never resolves components of double stars closer than 1 arcsec to each other.

For the vast majority of stars this criterion of identity was in fact sufficient and ample. Only a handful of stars required special consideration. In some cases positions in the Tycho and Hipparcos Catalogues disagreed by more than 1 arcsec, but the identity of

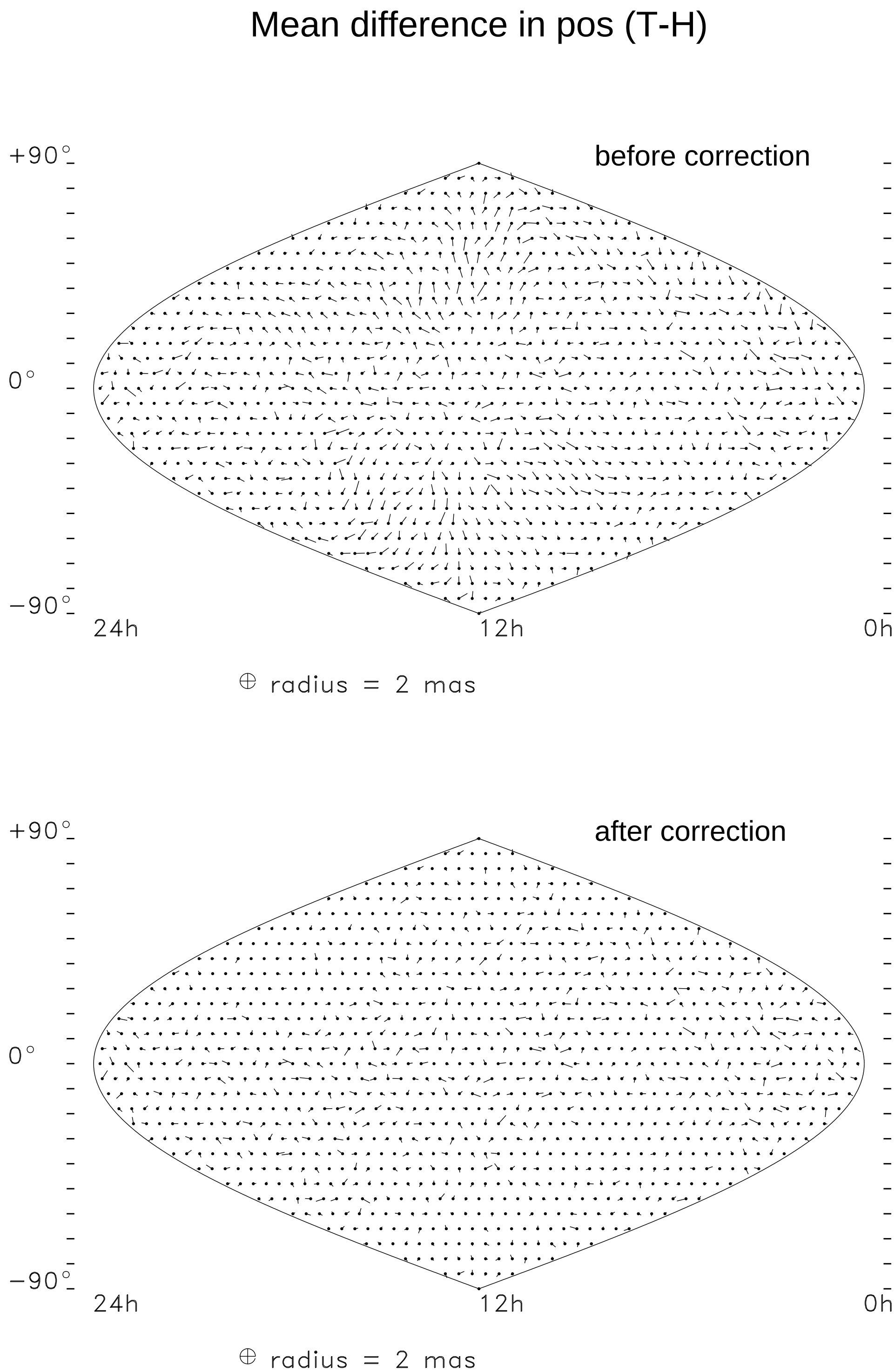

Figure 11.4 *(a) Sky projection of differences 'Tycho – Hipparcos' in positions. The length of a vector shows the value of the difference in mas, and the azimuthal angle indicates its position angle on the sky. Cosine sky projection in equatorial coordinates, cell size* $6^\circ \times 6^\circ$.

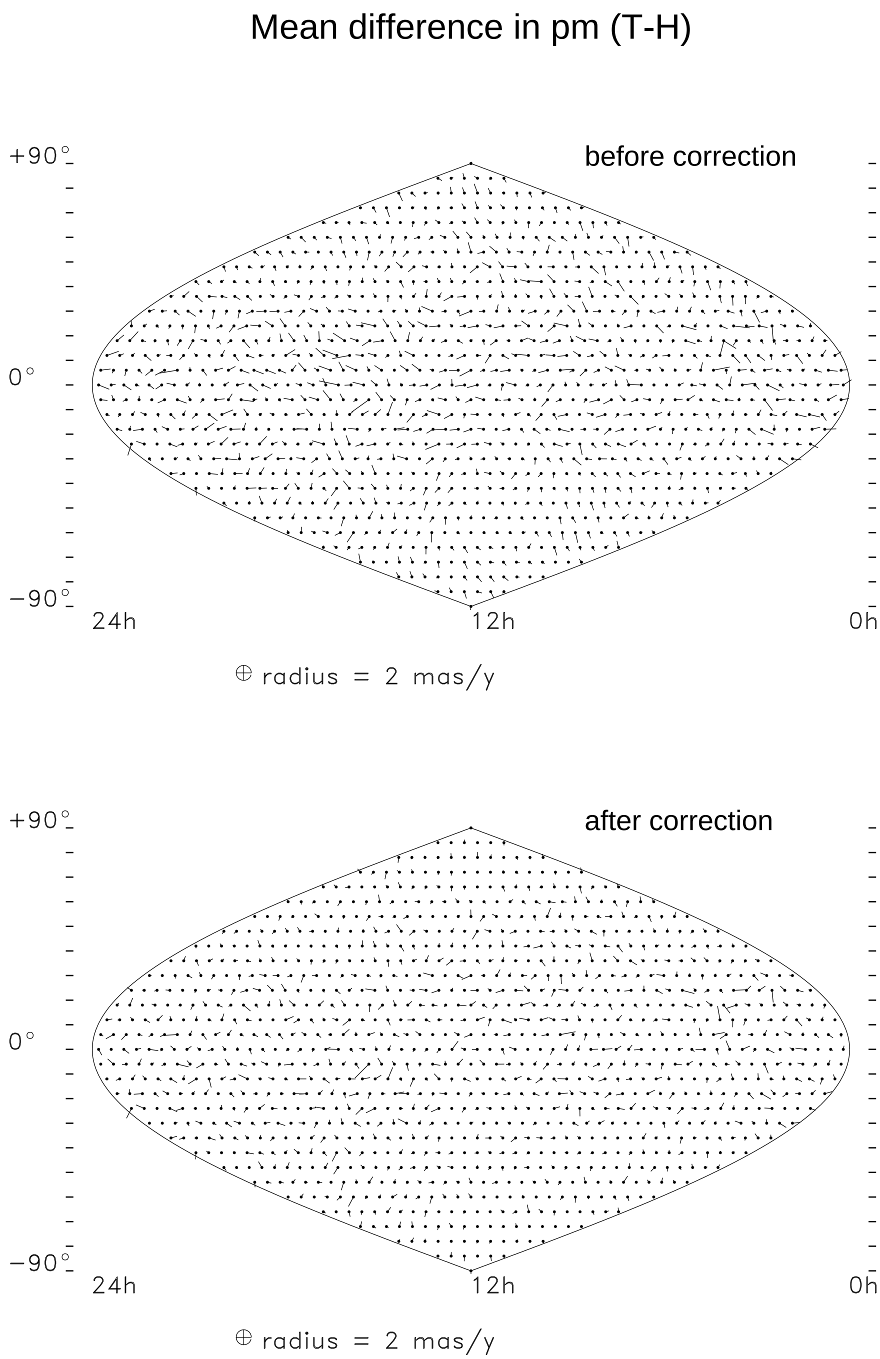

Figure 11.4 *(b) Sky projection of differences 'Tycho – Hipparcos' in proper motions. The length of a vector shows the value of the difference in mas, and the azimuthal angle indicates its position angle on the sky. Cosine sky projection in equatorial coordinates, cell size* $6^\circ \times 6^\circ$.

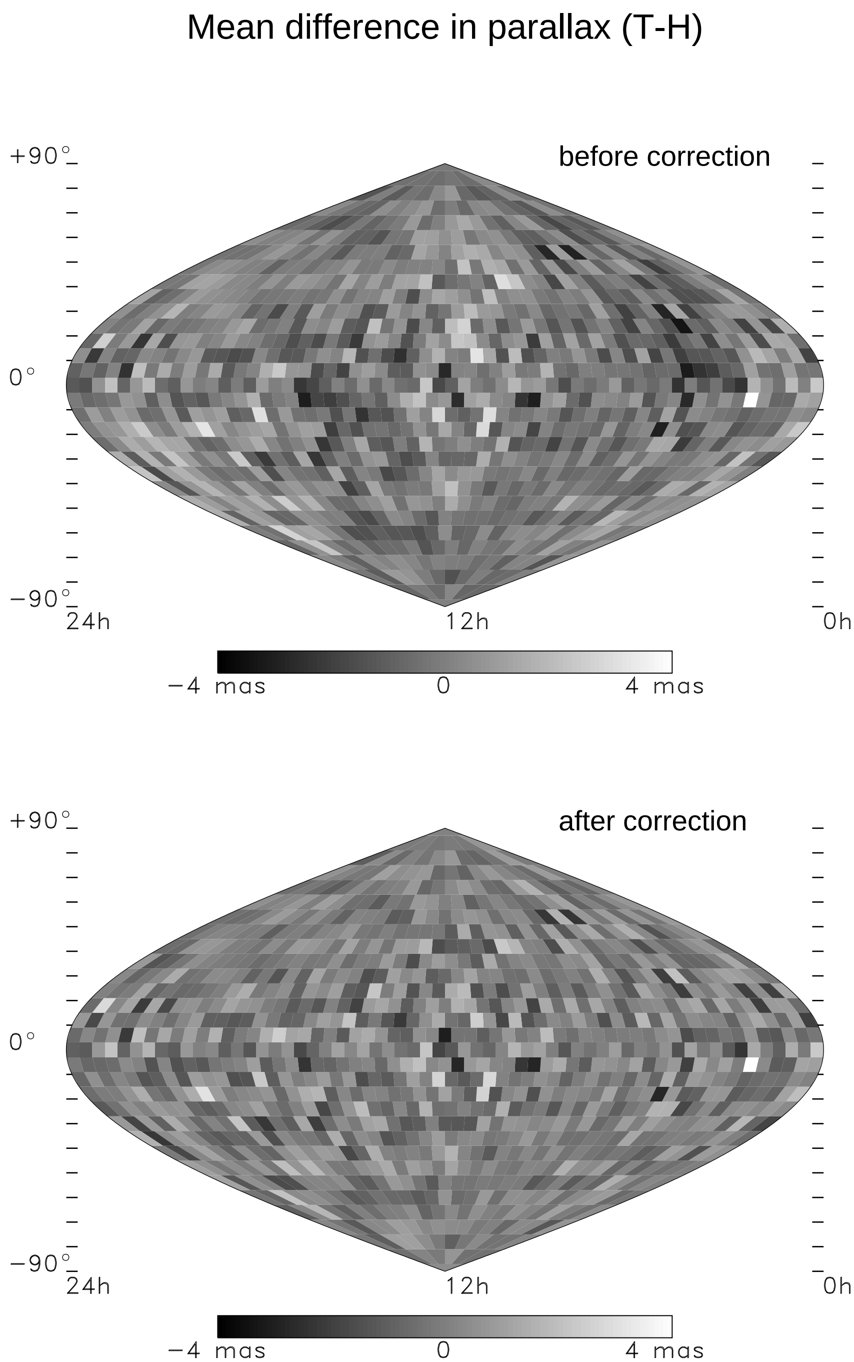

Figure 11.4 *(c) Sky projection of differences 'Tycho – Hipparcos' in parallaxes. Cosine sky projection in equatorial coordinates, cell size* $6° \times 6°$.

the entries was quite clear. These were the cases of so-called grid-step errors in the Hipparcos Catalogue, where a position could be wrong by a multiple of 1.2 arcsec. In order to get rid of most uncertainties clearly due to the grid-step error, the limit was extended up to 2.0 arcsec for 57 entries.

Finally, 102 096 main Hipparcos Catalogue entries and 20 892 components of the Double and Multiple Star Annex C were cross-matched and merged in the Tycho Catalogue. 2887 Hipparcos stars and 3694 components were not found in the Tycho Catalogue and were added for the sake of completeness. Less than 20 of these can still be due to grid step errors (see Chapter 18). This constituted the 'maximum' catalogue CUO_CAT_19, from which entries could only be deleted.

Refinement of the Catalogue

A few further attempts were made to refine the catalogue as soon as provisional B_T and V_T magnitudes had become available for most of the stars. Some 13 000 entries were gradually deleted after dedicated analyses of the stellar contents, involving available photometric data, pair statistics and comparison with the Guide Star Catalog (GSC):

- 783 entries with $Q = 9$ for which the photometric reduction did not converge to a definite result;
- 11 700 entries of low quality which were in disagreement with GSC. About 10 000 of them were $Q = 9$ stars with a difference in position between the Tycho Catalogue (TYC) and GSC larger than 3 arcsec, and with $V_T > 9$ mag. Another 1700 stars of $Q = 5 - 8$ were rejected if the difference in positions was larger than 1.5 arcsec and/or the difference in magnitudes was larger than 1.5 mag, and the star was in a pair with another TYC star, closer than 36 arcsec. This rejection was based on the finding that for bright double stars GSC provided very often the position of a photocentre, or of a spike, which resulted in a TYC solution of low quality with $V_T \simeq 11$ mag. The criteria that were used for rejection were shown to be reliable through visual inspection of a large number of maps, obtained with the Digital Sky Survey. This rejection also improved the appearance of pair statistics;
- a handful of stars of $Q = 7 - 9$ were removed from the catalogue, if they appeared in close pairs with Hipparcos stars, and the Hipparcos entries did not bear any indication of duplicity.

These rejections and other minor improvements led to the catalogue CUO_CAT_25, which was transformed into the Tycho Catalogue format, supplemented with magnitudes and other photometric data, and with subsidiary information, such as proximity flags, notes, etc.

11.4. Production of the Tycho Epoch Photometry

Tycho photometry for individual transits is contained in the Tycho Epoch Photometry Annexes, divided into two parts, A and B. The smaller one (TEPA A) includes transit data for 34 446 stars and is delivered on the ASCII CD-ROM set along with the main Hipparcos and Tycho catalogues. The larger one (TEPA B) will be available from CDS, Strasbourg, and provides epoch photometry for 481 553 stars, including all TEPA A stars.

The final internal data base and the derived catalogues were sorted according to star number (i.e. to the TYC identifier) and the transits belonging to one star were sorted in time. However, the starting point was a data base in the chronological observing sequence of stars as specified by the scanning law of the satellite, comprising 432 million transits of 1 208 168 stars in the TICR catalogue (main processing) plus 103 million transits of 306 766 stars in the TICU catalogue (reprocessing).

Thus, more than 500 million transits had to be sorted according to star number and the time. This huge process was split into several steps as shown in Figure 11.5. The figure also illustrates the calibration process and the construction of the photometric mean catalogues preceding the production of the final Tycho Catalogue. Figure 11.5 shows only the part of the TDAC data flow related to photometry and catalogue production. A comprehensive overview of the data flow is given in Chapters 1 and 12.

The main features of Figure 11.5, as discussed below, are:

- physical sorting;
- calibration and reduction to the Tycho photometric system;
- assignment of astrometric information to single transits;
- computation of photometric mean values;
- construction of the Tycho Epoch Photometry Annex.

Other points to be mentioned are the computation of Barycentric Julian Date and the selection of stars for TEPA A and TEPA B. The latter process is described in Section 2.6 of Volume 1. The selection between photometric data from the main processing and reprocessing is discussed in Section 11.5.

All data base names and processes appearing in Figure 11.5 are abbreviated throughout the remaining part of this chapter as follows:

Transit data:

PGCU	Predicted Group Crossings Update
ITDB	Identified Transits Data Base
TPOC	Tycho Photometric Observation Catalogue
TPOC1/2	different stages of sorting in the TPOC
AT files	All-Transits files: containing astrometric residuals for single transits
TPOC A/B	the TPOC subsets (still binary) preceding the Tycho Epoch Photometry Annex files TEPA A and TEPA B

Star catalogues:

TPMC	Tycho Photometric Mean Catalogue
TYC(internal)	A complete Tycho Catalogue containing additional information for each star.

Physical Sorting

Due to the huge amount of data the sorting according to star number and the sorting of the transits according to time was split into several steps. The boxes at the right in Figure 11.5 give the physical sorting status (together with some other information) of each transit data base.

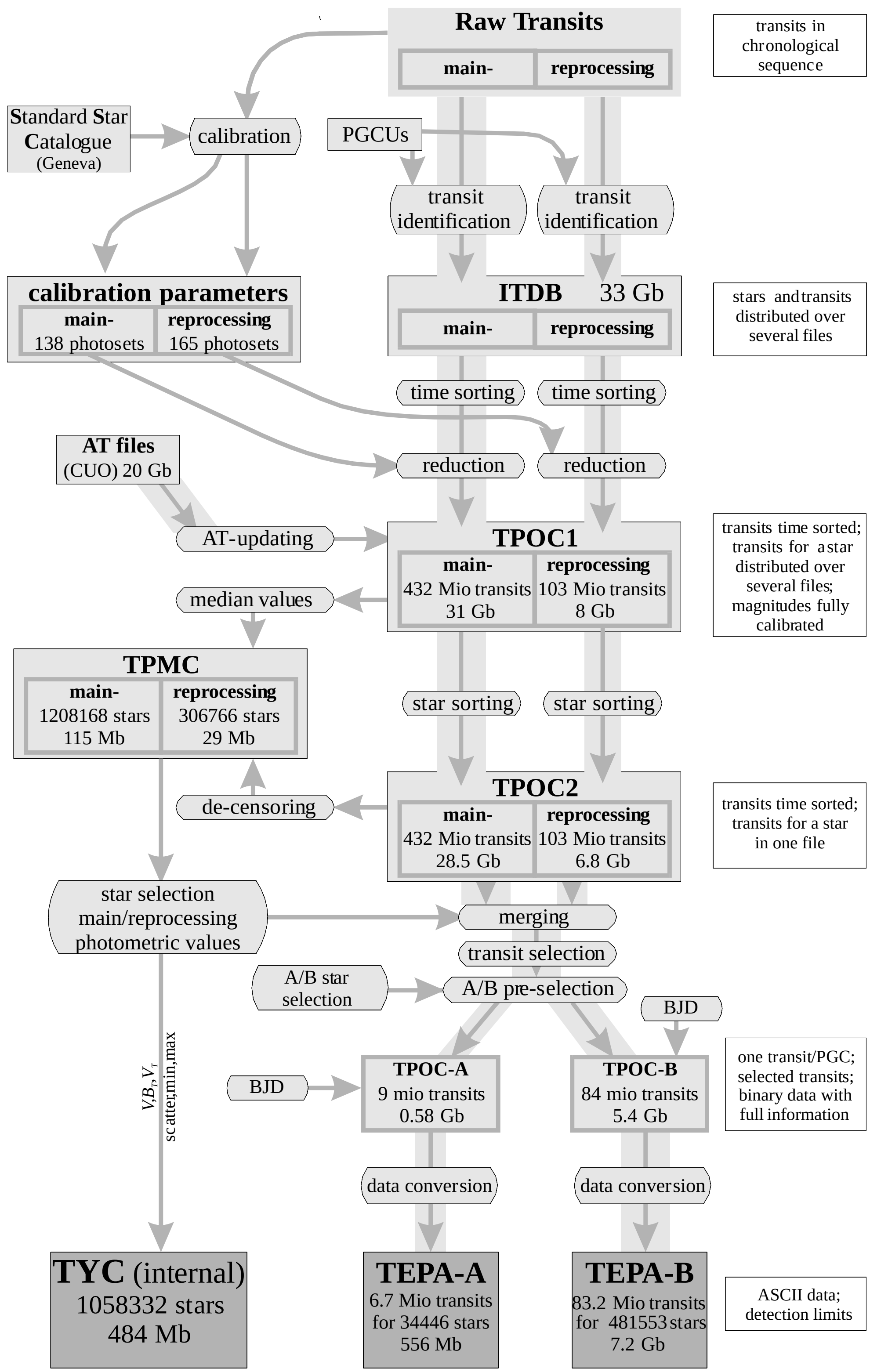

Figure 11.5. *Data flow for the production of Tycho epoch photometry. Shaded rectangular boxes show data bases while rounded boxes show programs. To the right the main properties of each data base is given. Abbreviations are explained in the text.*

Starting from the ‘raw transits’ data stream, the ‘transit identification’ process led to a data base (the ITDB) with transit data of one star distributed over many disk files and even the single transits distributed inside one file (though logically connected by means of pointers).

The next step, resulting in TPOC1, sorted all stars according to their Tycho Input Catalogue number and all the transits for each star according to time. But stars and transits were still distributed over many disk files. During this step the still growing ITDB and the TPOC1 co-existed.

Production of the TPOC2, completely sorted according to star number and time, had to wait until the ITDB and TPOC1 were completed. The TPOC2 contained all stars and their time-sorted transits in several physical files, each covering 80 Guide Star Catalog regions, i.e. 122 files covering the whole sky in the main processing and (due to a special numbering) 157 files in the reprocessing.

Calibration and Reduction to the Tycho Photometric System

The time-dependent calibration was carried out with the raw transits as input data, using the Geneva Standard Star Catalogue as a reference system (see upper left part of Figure 11.5). The calibration was done separately for the main processing and reprocessing (details can be found in Chapter 8), giving time intervals of varying length (between 3.4 and 18.0 days) with constant calibration parameters, called ‘photosets’. The reduction to the Tycho photometric system was done at the stage of TPOC1 construction for each single transit, with 138 photosets covering the whole mission (165 photosets for reprocessing).

Assignment of Astrometric Information to Single Transits

Because there may be several detections inside one ‘predicted group crossing’ interval (see Section 2.6) it was necessary to select the correct one. Given only photometric information this would have been easy only for bright stars, but quite unreliable for faint stars. The only method to identify ‘correct’ transits unambiguously is to use the information obtained from astrometric processing, i.e. the astrometric residual of a transit Δu and its expected standard error σ_u. Due to their importance both values are also given for each single transit in the Tycho Epoch Photometry Annex.

Therefore, astrometric information for single detections for both the main and the reprocessing (available from CUO as ‘AT-files’) was assigned to detections in TPOC1 by the process ‘AT-updating’.

Computation of Photometric Mean Values

For all stars the median values and percentiles were computed and stored in the TPMC together with the de-censored magnitudes for stars fainter than 5 mag. The de-censoring work on TPOC2 was the most time consuming single process in Figure 11.5.

Both de-censoring and median computations used the astrometric information, but only de-censoring checked for parasites (i.e. possible disturbances of transits by other stars giving too bright magnitudes). The storage of both median and de-censoring values in the TPMC enabled the necessary comparison of the different methods, and it allowed postponement of the decision on the actual limit for the usage of medians as late as just before the final Tycho Catalogue production. The actual limits to use median values and the decision process selecting between main and reprocessing data are described in Section 11.5.

Construction of the Tycho Epoch Photometry Annex

While the TPOC2 data base contained *all* transits measured with the Tycho experiment and in both main and reprocessing, the final catalogue should contain only valid transits:

- there should be only one detection per 'predicted group crossing' interval. If more than one detection was found, the transit with smallest $|\Delta u|$ was chosen;
- the added background in the B_T and the V_T channel was required to be below 100 counts per sample;
- the z coordinate had to fulfil the condition $|z| < 1195$ arcsec, i.e. transits near to the slit edges were ignored;
- for the inclined slits, transits within 10 arcsec of the apex were omitted too;
- transits close to jet-firings controlling the attitude of the satellite were ignored.

This 'transit selection' in combination with the 'A/B star selection' led to the construction of the immediate predecessor catalogues to the Tycho Epoch Photometry Annexes, i.e. to the TPOC A/B data bases. The merging selected the data from either the main or the reprocessing, as described in the next section. Thus, TPOC A/B contained only one solution for a given star.

In the 'data conversion' process the binary TPOC data were rewritten to the ASCII format described in Section 2.6 (Volume 1), and detection limits for not-measured magnitudes were computed, as described in Section 16.4. Furthermore, the star content was reduced to exactly those stars with the Field T50 = A/B flag (see Volume 1, Section 2.2) set in the Tycho Catalogue, (this is the reason for the lower number of transits in Tycho Epoch Photometry Annexes as compared to TPOC A/B, see Figure 11.5).

11.5. Photometric Part of the Tycho Catalogue

The photometric 'mean' values in the Tycho Catalogue were extracted from the two Tycho Photometric Mean Catalogues (TPMC), the one based on the TICR, thus containing mean values from main processing data, the other one based on TICU, containing results from reprocessing data (as described in the preceding section). Both catalogues contained 'mean' data and percentiles derived from median computations and from de-censoring for each star.

For all stars brighter than $B_T = 8.5$ mag and $V_T = 8.0$ mag the mean magnitudes given in the Tycho Catalogue are median values. Down to these magnitude limits there were almost no censored transits, and the median and de-censored magnitudes agreed within 0.005 mag, i.e. within the calibration uncertainties. The number of stars with median magnitudes given is thus only 29 524.

Regarding photometry, the major difference between the main processing and the reprocessing was the usage of different single-slit response functions (see Section 8.3). The reprocessing gave better estimates of signal amplitudes for the very bright stars because estimation was done in the wings of the signal. Thus, 129 stars brighter than $V_T = 3$ mag have reprocessing median magnitudes.

While 1687 stars were available only in the reprocessing, for 133 469 stars a decision had to be made from which processing the mean values and transit data should be taken. The main principle during 'star selection' (see Figure 11.5) was to retain a maximum of information, i.e. to prefer that processing which yielded 'mean' magnitudes in both channels. Because this was the case for most stars, in a second step that processing providing most accepted transits was chosen if the number of accepted transits differed by more than 10 per cent in de-censoring and 20 per cent in median computations. If not, the astrometrically selected processing was chosen for this star. Thus, the processing yielding the maximum number of accepted transits was chosen for 53 620 stars (out of 103 220) with de-censored magnitudes and 1072 stars (out of 27 099) with median magnitudes.

While the flag in Field T36 of the Tycho Catalogue (see Volume 1, Section 2.2) indicates whether median or de-censored magnitudes are given, the selection whether mean values were derived from main or reprocessing data can only be found in the star header flags in the Tycho Epoch Photometry Annexes.

Remarks on Uncertain or Missing Tycho Magnitudes

The flag in Field T57 of the Tycho Catalogue was set equal to 'M' for about 20 000 stars which were suspected to have very uncertain magnitudes, mostly because of a standard error larger than 0.3 mag (see Volume 1, Section 2.2 for details).

This flag was also set in cases where the number of photometric transits $N_{\rm photom}$ was less than 16 since it was realized that some magnitudes with very few transits were wrong especially for faint stars. The minimum number of transits for an accepted astrometric solution was however always equal to 30. The flag was set to 'M' for this reason and in a few other cases when V_T was outside the interval of the 15th and 85th percentiles. In these altogether 896 cases the approximate T-magnitude from the astrometric processing was given, i.e., flag 'T' in Fields T36 and T7, and no B_T, $B_T - V_T$ or percentiles were given. The photometry of all these stars may be studied in detail by means of the Tycho Epoch Photometry Annex B, and the deviation may then sometimes be found to be caused by intrinsic stellar variability.

If B_T or V_T magnitudes fainter than 15.0 mag were computed by the de-censoring analysis the values were replaced by blanks in the main Tycho Catalogue because these faint magnitudes were considered to be unrealistic, see Volume 1, Section 2.2, Fields T32–39 for details.

For such reasons a total of 8753 entries contain no value of the colour index $B_T - V_T$, including the 6301 stars with data only from the Hipparcos Catalogue (see Volume 1, Section 2.2, Fields T37–38).

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