# 5. RECOGNITION OF STARS

*The observations of the first year of mission of the Tycho program were used for revising the Tycho Input Catalogue in the process called 'recognition of stars'. The Tycho Input Catalogue Revision essentially defined the list of objects in the final Tycho Catalogue. The stars were searched with three different processes, according to their distances from the positions in the Tycho Input Catalogue. The main process concerned stars closer than 6 arcsec. Stars with separations between 6 and 20 arcsec were searched too, but the threshold in detection was slightly brighter than in the main process. Stars absent from the input catalogue were also searched, but with an even higher threshold in detection. At the same time, the mean uncertainty of the positions was improved from about 1 arcsec in the Tycho Input Catalogue to about 0.15 arcsec.*

## 5.1. Introduction

The basic strategy of Tycho required an input catalogue with accurate positions, in order to relate the stars and their signals in photon counts. The Tycho Input Catalogue, presented in Chapter 3, was the first step for this purpose; its accuracy was about 1 arcsec on average, but this was not sufficient. Due to the uncertainty of the magnitudes, it contained slightly more than three million stars, but the Tycho team expected that only about one million stars would be retained in the final selection. Moreover, since the Tycho Input Catalogue was partly based on Schmidt plates, many faint stars were expected to be missing, such as stars close to a bright companion illuminating the plate, or stars lying in a nebulous area. The revision of the input catalogue was done in the process called 'recognition of stars', which is the subject of this chapter. Its aim was to find all the stars lying in areas centered on the positions of the Tycho Input Catalogue entries, and to determine precise positions for them.

## 5.2. General Outlines

The Tycho Input Catalogue Revision was produced from observations with the satellite and the Tycho Input Catalogue. Predictions of the times of star transits were used for selecting the signals from the stars. The discrepancies between predicted epochs and actual ones were converted into offsets in the star positions, taking into account the scanning law of the satellite. This basic principle was used in all the Tycho reductions. The main difference between the recognition of stars and the final astrometric reduction is the length of the time interval around each predicted transit where the signal was searched. In the recognition of stars, the interval corresponds to a wide area on the sky, where several stars may be found.

Before searching stars, the observations around each entry of the Tycho Input Catalogue were gathered (the term ‘entry’ is preferred over ‘stars’, since it refers hereafter to positions and identifications, but not to astronomical objects). The entries of the Tycho Input Catalogue were then treated, one after the other, and the stars were searched. Three different processes were used, differing in the time interval where the signal was searched:

- the search for ‘close companions’ was the first of the three processes. It concerned stars that are closer than 6 arcsec to the positions in the Tycho Input Catalogue. It covered only 0.065 per cent of the sky, since the Tycho Input Catalogue contains 3.15 million entries. This search was performed using a low threshold in the signal-to-noise ratio of the detections;
- the second process was dedicated to the ‘wide companions’, having distances from the positions in the Tycho Input Catalogue between 6 arcsec and 20 arcsec. The detection threshold of the observed transits was taken a bit brighter. This process covered 0.66 per cent of the sky;
- the third process was the search for ‘serendipity stars’, which was based on any bright transits not produced by stars in the Tycho Input Catalogue. These transits were related to a network of points covering the whole sky, in order to be sure that all bright stars missing from the Tycho Input Catalogue could be found in the Tycho Input Catalogue Revision.

Subsequent steps of the recognition process removed the redundant stars and estimated the magnitudes. When a star was found by different processes, a rule of selection was used to decide which solution had to be considered as the most reliable one, and the others were discarded. An estimation of a broad-band magnitude called $T$ was also derived from the added signal amplitudes in the $B_T$ and $V_T$ bands.

## 5.3. Preparation of the Input Data

The input data for the recognition of stars were the ‘transit summary’ file and a corresponding file of updated predictions of group crossings of the first year. These data are denoted ‘TS’ and ‘PGCU-2’, respectively in Figure 1.2.

### The Transit Summary File

The transit summaries are combinations of predictions of the time of transits (the so-called ‘predicted group crossings’) with actually detected transits (for brevity, these will be called ‘detections’ in the following). The predicted group crossings were derived from the on-board attitude of the satellite and from the Tycho Input Catalogue. They were computed at Astronomisches Rechen-Institut in Heidelberg. A prediction consists of:

- the identification of the star in the Tycho Input Catalogue;
- information about the scanning motion of the satellite;
- the position on the star mapper of the transit of the star, assuming the coordinates in the Tycho Input Catalogue;
- the predicted epoch of that transit.

This description of the conditions of observation is completed by the photon noise background level, which was provided by the detection process.

The predictions were sent to Astronomisches Institut of Tübingen. The transits of stars were then searched in the tapes of photon counts around the epochs of the predictions. A detection consists of:

- the offset in epoch between the detection and the prediction;
- the signal-to-noise ratio;
- the photon noise background level.

In the detection process, the detections were related to the predictions according to two modes. The first mode was the search for signals within 'prediction intervals'. A prediction interval is an interval in time centred on a prediction epoch, and having a length permitting the detection of a star as long as the offset in position is not larger than 6 arcsec (this is the limit of the search for close companion stars). This means that when a crossing of the vertical slit group is considered, the length of the interval corresponds to the scanning of $2 \times 6$ arcsec. This corresponds to 71.11 ms when the average scanning velocity of 168.75 arcsec $s^{-1}$ is assumed. For a crossing of the chevron slit group, the size of the interval is $\sqrt{2}$ times larger in time. The detection threshold within the prediction intervals for the signal-to-noise ratio of peaks in the photon counts is 1.5.

All the detections found were related to the current prediction. When two prediction intervals were overlapping, detection was processed twice in the overlapping part, and the detections in that part appeared in duplicate in the transit summary file, since they could belong to either of the two predictions. If no detection was found, the prediction was still transmitted to the transit summary file, in order to count the predictions of each entry of the Tycho Input Catalogue.

The second mode of detection concerned the observations done outside the prediction intervals. The detection threshold for these was set to 1.8, and the detections were related to the first prediction that followed.

The recognition of stars was based on the observations collected during the first 368 days of the scientific mission, beginning the end of November 1989. The transit summary file prepared at Astronomisches Institut of Tübingen corresponded to 310 full days of observation. The 3.15 million entries of the Tycho Input Catalogue received 244 million predictions, and the transit summary file was written on 152 high-density magnetic tapes. These tapes were sent to the Centre de Données astronomiques de Strasbourg (CDS) to be used for the star recognition process.

### Updating and Selection of the Predictions

The prediction updating process performed a re-calculation of the predictions using on-ground determinations of the attitude of the satellite and of the star mapper calibration. The updated predictions became available about one year later than the on-board attitude, and it was therefore not possible to use them in the detection step. The accuracy of the updated predictions was around 0.2 arcsec instead of 1 arcsec for the original predictions used for detection. For the recognition of stars, Astronomisches Rechen-Institut at Heidelberg prepared 44 high-density magnetic tapes of updated predictions (PGCU-2) that were sent to the star recognition task at the Centre de Données astronomiques de Strasbourg.

The predictions in the transit summary file were replaced by the updated predictions, and the differences of epochs between the predictions and the detections were recomputed. The transits getting an updated prediction with an uncertainty larger than 1 arcsec were discarded from the process. The predictions corresponding to a large background could not help for the detection of faint stars, but might well have added false detections. For that reason, transits having a background larger than 20.7 counts per sample were also discarded. The remaining data contained 155 million predictions and the related detections, giving an effective rate of 53 per cent of the covered time of satellite flight. On average, each entry of the Tycho Input Catalogue received 49 predictions. However, the actual number was highly variable from one entry to another: 2091 entries got less than 4 predicted group crossings, and no search for stars was performed around them. At the other extreme, one entry got 322 predicted group crossings.

## 5.4. The Search for Companion Stars

As explained above, the so-called ‘companion stars’ are the stars searched around the entries of the Tycho Input Catalogue. Close companions are closer than 6 arcsec from them; wide companions have distances between 6 and 20 arcsec, the latter being searched with a brighter threshold for the detections. The searches for the close and for the wide companion stars were processed together.

### Gathering the Transits Related to the Same Entry of the Tycho Input Catalogue

In the original transit summary file, the detections were related to predictions within intervals corresponding to the search for close companion stars. This assignment was reconsidered in the recognition of stars, taking into account the updated epochs of predictions. The detections with signal-to-noise ratios between 1.5 and 1.8 which fell outside the prediction intervals were discarded.

On the other hand, detections with signal-to-noise ratios larger than 1.8 were related to the predictions whenever they were within a ‘wide companion interval’. Since the wide companion stars were to be searched within areas of 20 arcsec radius instead of 6 arcsec for the close companions, the wide companion intervals had to be chosen 20/6 times larger than the original prediction intervals.

On average, every prediction finally received 6 detections, although only one third of the Tycho Input Catalogue entries actually corresponded to detectable stars. As expected, the vast majority of all detections were due to noise: Poissonian fluctuations in the photon counts, spikes, background stars, and ghost detections due to the side lobes generated by bright stars. The rate of true detections per prediction was 0.3. The distribution of the detections around the positions in the Tycho Input Catalogue is shown in Figure 5.1. It appears that the standard deviation of the true detections from the prediction corresponds to 0.5 arcsec. The total amount of data was 991 million 24-byte records, or 23.8 Gigabytes. This file was stored with a cartridge system on the IBM-3090 computer of the Centre de Calcul CNRS de Strasbourg-Cronenbourg. For gathering the transits of each entry in the Tycho Input Catalogue, it was sorted according to the star identifications, with a method perfected by the Centre de Calcul CNRS.

### The Search for Stars around the Positions in the Tycho Input Catalogue

The searches for the close companion and for the wide companion stars were processed in two steps: a preliminary search in a digital map and an iterative least-squares computation. The input data were the transits, converted to detection lines (Figure 5.2). A detection line is the position of the slit group relative to the predicted group crossing at the time of the actual detection (the detected star can be anywhere on this line). The detection lines were calculated in a cartesian coordinate system with the origin at the Tycho Input Catalogue position. The parameters of each detection line were derived from the scanning direction and from the offset between prediction and detection epoch, assuming that the scanning velocity is 168.75 arcsec $s^{-1}$. Each detection line received a weight equal to the square of the signal-to-noise ratio of the detection. In order to avoid false stars generated by detections due to bright stars outside the map, the weights were limited to 9 and 12.25 for the close companions and for the wide companions, respectively. The weights of the brightest detections were thus only about 4 times larger than those of the faintest detections.

Digital maps were built in order to determine approximate positions of the stars. A digital map is a grid of 0.5 arcsec-sized pixels, with sides of 13 arcsec in the search for close companions and 41 arcsec for the wide companions. Since stars were to be searched in circular areas, only the pixels covering a disc inscribed in the square grid were considered. Each pixel received the sum of the weights of the detection lines crossing a diamond having its corners in the middles of the sides of the pixel. In the case of the wide companions, only the detections having a signal-to-noise ratio larger than 1.8 were taken into account. The grid points, i.e. the intersections of the lines that define the pixels, were considered next. Each grid point received the sum of the weights of the four surrounding pixels. The position of the intersection getting the largest weight was finally taken as input for an iterative least-squares computation.

The purpose of the least-squares calculation is to find the point which minimizes the weighted sum of squares of orthogonal distances to the detection lines. Let $x$ and $y$ denote the coordinates in the cartesian reference system, $a_i$, $b_i$, and $c_i$ the parameters of the detection lines, and $w_i$ the corresponding weight. The equation of a line is: $a_i x + b_i y = c_i$. Then the position (X, Y) of the star is given by the normal equations:

$$\begin{pmatrix} \sum a_i^2 w_i & \sum a_i b_i w_i \\ \sum a_i b_i w_i & \sum b_i^2 w_i \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} \sum a_i c_i w_i \\ \sum b_i c_i w_i \end{pmatrix} \qquad [5.1]$$

where the left-hand matrix is the normal-equation matrix.

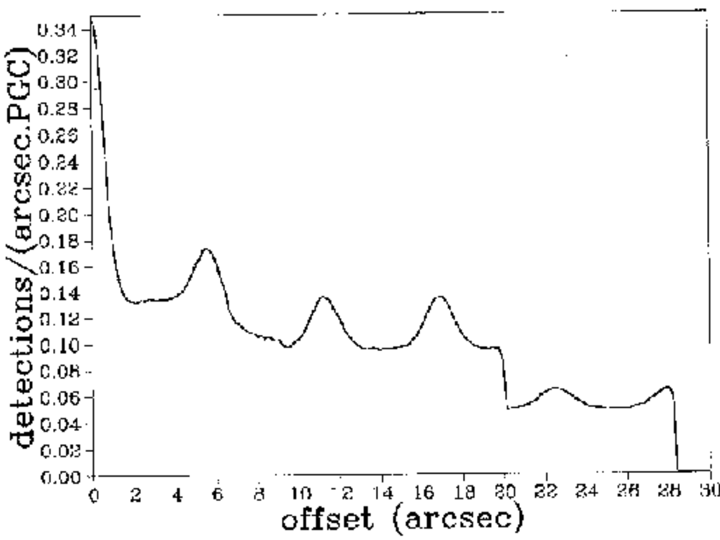


***Figure 5.1.*** *Frequency of detections according to their distances from the positions in the Tycho Input Catalogue. The ordinate is the number of detections per arcsec and per predicted group crossing. The figure is derived from a subsample of 6.5 million detections related to 1.1 million predictions. The main peak contains the detections of the stars of the Tycho Input Catalogue. The secondary peaks are due to side lobes as expected from the configuration of the slit groups.*

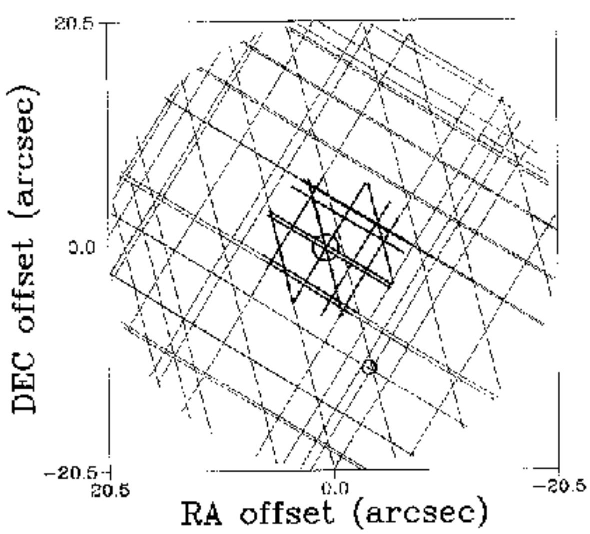


***Figure 5.2.*** *A map of detection lines. The central area has a diameter of 13 arcsec, and the diameter of the large circular area is 41 arcsec. The thick lines interrupted at the border of the central area correspond to detections taken into account in the search for close companion stars. The circles indicate the positions of the stars selected by the computation. The central star is ADS 13 909 C (magnitude: 9.60). The wide companion is the D component (magnitude: 11.25). For clarity of the figure, the number of predicted group crossings is only 6, instead of 49 on average. The significance of the two circled points is therefore not apparent to the eye.*

The weight $w_i$ of each line was set to be the product of the weight coming from the signal-to-noise ratio and of a weight coming from the distance between the line and the input position. This last weight was set to $1/(1+d^4)^2$, where $d$ is the orthogonal distance of the line in arcseconds. The calculation of the position of the stars was repeated iteratively. Each time a position had been derived, it was used for determining the weights of the detection lines for the next iteration. The calculation stopped as soon as one of the two following conditions was satisfied: (a) the new position is closer than 0.03 arcsec to the preceding one, or, (b) the number of iterations is 6.

When a star was found, it was verified that at least 3 detection lines were closer than 0.5 arcsec from its position; otherwise the star was assumed to be false. Other false stars were generated by intersections between closely parallel detection lines produced by a star outside the map and a single background line having a different slope. These were eliminated by rejecting the solution when the condition number of the $2 \times 2$ normal-equation matrix, $\mathbf{A}$, was greater than 7:

$$\mathrm{cond}(\mathbf{A}) = \frac{\|\mathbf{A}\|^2}{\det \mathbf{A}} > 7 \qquad [5.2]$$

Many false stars were still generated by background detection lines, but they were removed by considering the total weights of the detection lines closer than 0.5 arcsec from the solution (only the weights derived from the signal-to-noise ratios of the detections were considered here). These weights were compared to thresholds depending on the numbers of predicted group crossings. The initial thresholds had deliberately been chosen too small, their refinement will be discussed further below. When the weight of a star was above the threshold, the star was provisionally recorded, otherwise it was rejected.

Whenever the least-squares calculation yielded a star that could not be accepted, the four pixels that had provided its preliminary position were set to zero. On the other hand, when a star was accepted, the detection lines closer than 1 arcsec to the calculated position were removed from the digital map and were discarded from the computations of the positions of more stars. This was done to avoid false stars generated by intersections between detection lines related to a star and background detection lines. The search for stars was processed again until the weight of the subsequent preliminary position became less than 1.6 times the acceptance threshold of the least-squares solution.

False stars could have appeared if the close companions and the wide companions had been searched independently: the detection lines of a close companion star might then have generated false stars in the surrounding area where wide companions were searched, and vice versa. This possibility was largely avoided by the following rule: The search for close companions was processed first, and the detection lines closer than 1 arcsec to the stars were discarded. The wide companions were searched afterwards, on the basis of the detections with signal-to-noise ratios larger than 1.8 that were not discarded previously. When one or more wide companions were found, the search for close companions was completely carried out again, discarding all the detection lines that were closer than 1 arcsec to the wide companions.

This process, based on preliminary selection thresholds, provided 1.31 million stars: 1.23 million close companions, and 76 000 wide companions. The next step was to redetermine the acceptance thresholds in order to remove most of the false stars. For that purpose, it was first necessary to remove the redundant stars.

### Search for the Redundant Companion Stars

The Tycho Input Catalogue contains some components of double or multiple stars whose separation is smaller than the size of the digital maps. A component of such a multiple system could then appear in several maps, and it could be recorded several times as close or as wide companion stars, that were in fact redundancies of the same object.

For searching redundancies, the equatorial coordinates of the stars were derived by adding the coordinates in the Tycho Input Catalogue to their positions relative to the map centres. The selection of the redundant entries was based on the following algorithm:

- when two stars were closer to each other than the 'redundancy threshold', one of them was flagged as redundant; the rule was to flag the star with the largest distance from the centre of the map where it was found; the redundancy threshold was chosen as the closest separation between two stars found in the same map: 1.22 arcsec;
- when a star had been flagged as redundant, it was no longer considered for searching other redundant stars; but,
- when a star became redundant, the redundancy flags of the stars that it had made redundant before were reconsidered.

This iterative process converged rapidly. About 27 000 stars were discarded from the determination of the definitive thresholds because they were redundant.

### The Definitive Selection of Companion Stars

The choice of the selection thresholds depended on the number of false stars that was considered acceptable in the Tycho Input Catalogue Revision. It was decided that the search for close companions and the search for wide companions may each generate about 60 000 false stars, corresponding to a proportion of 2 per cent of the entries of the Tycho Input Catalogue. The number of false stars was crudely estimated, assuming that it corresponds to the number of stars more than 2 arcsec from the positions in the Tycho Input Catalogue. The thresholds were determined in order to get, for each process, about 2 per cent false stars among the entries of the Tycho Input Catalogue having the same number of predicted group crossings. The total number of stars having weights above the thresholds finally adopted was 1 166 500.

This amount was further reduced by applying a final criterium: the maximum number of stars found in the same map was 21, but it was not considered realistic that so many stars could be correctly found within a 40 arcsec diameter area; therefore only the 8 brightest stars were kept. This resulted in a final file of 1 163 399 stars, among which 26 356 stars were still redundancies. When these are not counted, 1 078 889 close companions remained. 61 973 of them were between 2 and 6 arcsec from the positions in the Tycho Input Catalogue. The number of wide companions was 58 154. These numbers are both reasonably close to the target of 60 000 'false stars' introduced in the preceding paragraph. The distribution of the close companion stars as a function of their distances to the positions in the Tycho Input Catalogue is presented in Figure 5.3. The stars having the most accurate positions in the Tycho Input Catalogue are the astrometric standards. The uncertainty of their positions is 0.14 arcsec on average, and the distance from the stars actually found is on average 0.16 arcsec. This similarity indicates a very good accuracy for the revised positions. A comparison with the positions derived from Hipparcos provided an average offset of 0.07 arcsec for the Hipparcos stars (which are brighter on average, and thus measured more precisely than a ‘typical’ Tycho star).

The final Tycho Catalogue contains 6920 stars that were found by the search for companion stars at more than 3 arcsec away from any entry of the Tycho Input Catalogue. This number looks small when compared to the whole catalogue, but the importance of the companion processes appears when the double stars are considered: about 20% of the Tycho double stars with separations closer than 20 arcsec have at least one component among the 6920 stars above. Moreover, the entries of the Input Catalogue that were split into two close companion stars are not counted in this statistic. In fact, half of the Tycho Catalogue double stars closer than 10 arcsec and with unbiased ($B_T$, $V_T$) magnitudes have a component that was added in the companion processes.

## 5.5. The Search for Serendipity Stars

The vast majority of detections in the transit summary file were not related to companion stars. While the detections with small signal-to-noise ratios were generally not due to stars, but to noise or to artefacts, the bright ones could possibly be due to stars missing in the Tycho Input Catalogue. These bright detections are called ‘serendipity detections’, and they were processed to search for the ‘serendipity stars’.

### The Network of Serendipity Points

As with the other modes, the search for the serendipity stars was based on predictions of group crossings of positions in an input catalogue, and on detections in the photon counts around the predicted epochs. The fundamental difference is that the input positions now are no longer positions of stars, but positions arbitrarily chosen, hereafter called ‘serendipity points’. These points were used as the centers of big square maps of detection lines that cover the whole celestial sphere. Since the vertical slit group of the star mapper is 40 arcmin long, it was decided to use maps with 40 arcmin sides. To make sure that no stars be lost at the boundaries, the 40-arcmin maps were chosen to have overlaps of at least 6 arcsec. The serendipity points were arranged on 273 parallel circles on the sphere, the median one being the equator. The total number of serendipity points was 94 575.

### The Predictions in the Serendipity Process

The updating and selection process of the predictions, described in Section 5.3, provided 4.6 million predictions of transits of the serendipity points. Contrary to the search for companion stars, these predictions were not sufficient for collecting all the star detections in the 40-arcmin maps: the maps were now as large as the star mapper slits, but the predictions referred only to their centers; a star somewhere in a map could yet have been detected when the slit group was scanning a strip that did not contain the center. In order to take into account the scanning of any part of the maps, additional predictions were calculated, assuming that the slits are lengthened by $\sqrt{2} \times 20$ arcmin at each extremity.

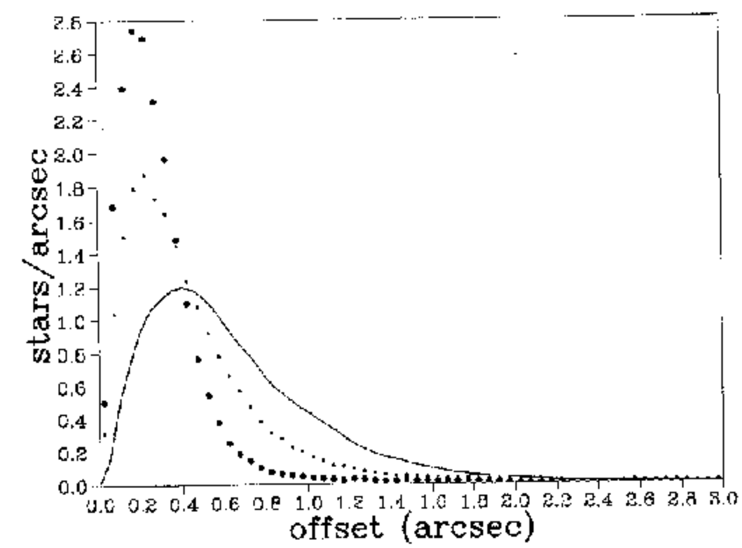


***Figure 5.3.*** *Frequency of the accepted stars as a function of distance to the Tycho Input Catalogue positions. The large dots refer to the astrometric standard stars in the Tycho Input Catalogue, the small dots refer to the stars of the Hipparcos programme, and the line refers to all the accepted stars. The frequencies are normalized in order to facilitate the comparison.*

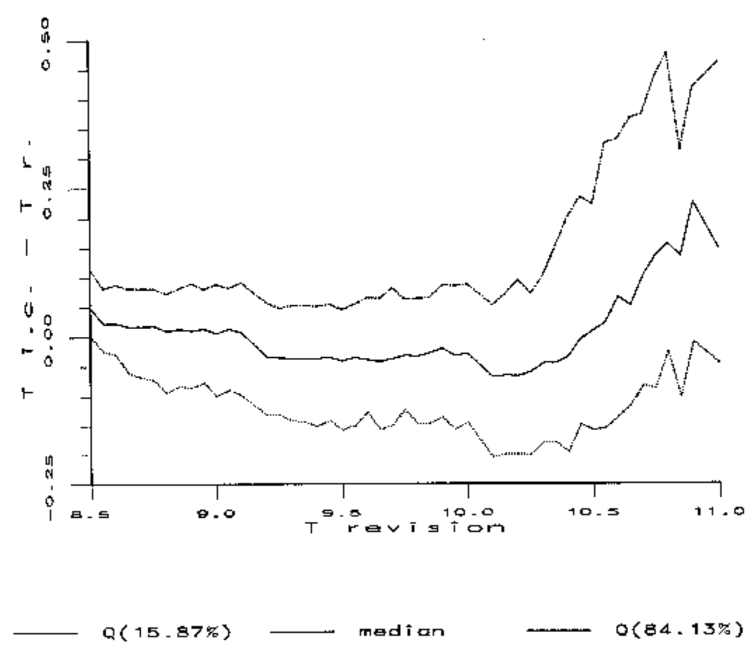


***Figure 5.4.*** *Relation between the T magnitudes estimated in the Tycho Input Catalogue Revision, and their offset with respect to the magnitudes in the Tycho Input Catalogue. The solid line indicates the median of the difference between the magnitudes derived from the Tycho Input Catalogue and the magnitudes obtained from the observations. The dotted line refers to the quantile 15.87 per cent, and the dots and dashes to the quantile 84.13 per cent. Only the photometric standards with known B and V are considered.*

This computation was done by interpolating the predictions for the centers of the maps as long as the rotation of the satellite was not affected by jet firings. Whenever a jet firing occurred between two original predictions, the computation was an extrapolation from the unaffected side. The result was then less accurate, but this concerned only 3 per cent of the additional predictions.

The additional predictions were slightly less accurate than the original ones: for 5.8 million predictions derived by interpolation, the standard deviation is about 1.2 arcsec instead of 0.2 arcsec. The computation of the additional predictions was carried out at the Centre de Données astronomiques de Strasbourg. The final number of predictions was 10.6 million.

### The Serendipity Transits

The 'serendipity transits' were extracted from the transit summary file, and related to the predictions for the serendipity points, calculated above. Only detections with signal-to-noise ratios larger than 3.5 were taken into account. Moreover, detections closer than 3 arcsec to the entries of the Tycho Input Catalogue were discarded, since they were probably due to the stars already found with the close companion process. The remaining serendipity detections (9.4 million) were then assigned to the 10.6 million predictions. Each assignment was accepted only when no jet firing modified the rotation velocity of the satellite between the detection and the prediction. Each detection was related to several predictions, since it might have come from the preceding as well as from the following field of view, from the chevron as well as from the vertical slit group, and since the slit groups were usually crossing more than one digital map at a time. For these various reasons, the final file of serendipity transits contained 94.1 million records, i.e. ten times the number of detections. These records were sorted in order to gather the transits of each serendipity point.

### The Mapping Process in the Search for Serendipity Stars

Since the size of the digital maps in the serendipity process was much larger than in the search for companion stars, the preliminary positions of the stars were derived in two steps:

- the 40-arcmin map was digitized in $50 \times 50$ square pixels of 48 arcsec size. For each transit, the position of the related slit group was recorded on the map. The calculation was different from the case of the companion stars, since the detections were no more represented by a single line crossing the whole map; the extremities now had to be taken into account, as well as the shape of the chevron slit group. The detections received a weight equal to the square of the signal-to-noise ratio, as in the search for companion stars. The value of the weight was limited to 36. The map was used for a rough localisation of a possible star, with the method of the grid points already described in Section 5.4;
- the selected grid point was used as the centre of a second $50 \times 50$ pixels map, but now with a pixel size of 2 arcsec. This map corresponds to the four pixels of the first map that were around the selected grid point. The detection lines were recorded in the second map, and the position of the star was searched again.

The preliminary position derived in this way was used as input for an iterative least-squares calculation based on the detection lines of the second map. This calculation was similar to that of the positions of companion stars, with some adaptations, since the uncertainty of the transits was a bit larger still. The weight of each line was again multiplied by a term depending on the orthogonal distance from the input position, but this distance was now reckoned in units of 2.3 arcsec. The total weights of the stars were derived from the lines closer than 1.15 arcsec to the derived positions (the limit was 0.5 arcsec for the companion stars). When a star was found, the detections closer than 3.45 arcsec were discarded (instead of 1 arcsec in the companion processing).

The preliminary selection threshold for the serendipity stars was quite underestimated, since somewhat more than half a million stars were found. It was obvious that the large majority of these objects could not be stars missing in the Tycho Input Catalogue, but were only false alarms.

### Final Stages of the Search for Serendipity Stars

As for the classes of companion stars, the number of serendipity stars to be selected was arbitrarily fixed to 60 000, i.e. 0.63 star per serendipity point. Again, the minimum weight of the stars to be selected was a function of the number of predicted group crossings, in order to obtain a constant rate. The redundant stars in the overlapping parts of the maps were removed assuming a redundancy threshold of 2 arcsec. The serendipity stars closer than this limit to companion stars were also considered as redundancies and were discarded.

The final file of serendipity stars contained 57 933 stars. In the end, only 162 of these were later found to be true stars which were retained in the Tycho Catalogue, see Chapters 10 and 11. This small number is in no way to be regarded as a failure of the serendipity recognition but, on the contrary, as indicative of a highly successful Tycho Input Catalogue.

## 5.6. Estimation of the Magnitudes of the Stars

The last step in the recognition of stars was the evaluation of the magnitudes of the stars from a rough photometric reduction. Each time a star was found, the related detections were used to derive the average amplitude of the photon counts. Since the photon counts used in the process were the sum of those obtained through the $B_T$ and the $V_T$ filters, the resulting magnitude, called $T$, refers to a combination of $B_T$ and $V_T$. The transformation of the averaged amplitudes to $T$ magnitudes was calibrated using the photometric standard stars in the Tycho Input Catalogue.

### Calibration of the Magnitudes using Standard Stars

The Tycho Input Catalogue does not provide the $T$ magnitudes of standard stars, but only $B$ and $V$ magnitudes. These magnitudes are even different from $B_T$ and $V_T$, but this difference is neglected here. $T$ was defined such that $T = B_T = V_T$ when $B_T - V_T = 0$. The $T$ magnitudes of standard stars were thus derived applying this constraint and using star mapper count rates estimated before launch:

$$T = V - 2.5 \log(0.74 + 10^{-0.4(B_T - V_T)}) + 0.6 \qquad [5.3]$$

(This formula is practically equivalent to $T = (B_T + V_T)/2$, if the colour index $B_T - V_T$ is not extreme, but the mathematical mean of two magnitudes is in fact meaningless.)

The relation between the average amplitudes of the detections and $T$ was derived from the above-defined $T$ magnitudes of the standard stars. Stars brighter than 8.5 mag were not taken into account, since the available amplitudes were truncated. For the others, a least-squares calculation gave the relation:

$$T = 12.30 - 2.65 \log\langle S \rangle \qquad [5.4]$$

where $\langle S \rangle$ is the average amplitude of the star (in Tycho-internal units). This calibration is rather rough, but it was sufficiently accurate for the purpose of the Tycho Input Catalogue Revision. It appears in Figure 5.4 that, for stars brighter than 10.2 mag, the true relation is perfectly linear with the slope −2.5. This confirms that the amplitudes are proportional to the fluxes. The estimation of magnitudes fainter than 10.2 leads to underestimations: faint stars are not detected at every predicted group crossing, and the missing detections are not taken into account in the calculation. The 11 mag stars therefore appear about 0.2 mag brighter than they are.

### Calculation of the Magnitudes of Bright Close Companion Stars

The calibration, Equation 5.4, was used to compute the magnitudes of the stars. However, due to the truncation of amplitudes, no magnitude brighter than 8.5 could reliably be derived. Whenever a magnitude brighter than 8.5 was found for a close companion, it was investigated whether it might be preferable to keep an estimation of the magnitude derived from $B$ and $V$ in the Tycho Input Catalogue. In these cases an alternative magnitude was derived from Equation 5.3 (when only one of the magnitudes $B$ and $V$ was available, the color index $B - V = 0.7$ was assumed) and compared to that derived from the calibration, Equation 5.4. The brightest was kept in the Tycho Input Catalogue Revision.

### Distribution of the Magnitudes

The cumulative frequencies of the stars found with the different processes are shown in Figure 5.5. In a logarithmic plot a straight line would be expected for the distribution when the sample is complete. It appears that the limits of completeness are about 10.7, 10.6 and 10.2 mag for the searches of close companion, wide companion and serendipity stars respectively (the differences reflect the different thresholds in detection, since the wide companions and the serendipity stars are generally not stars but false alarms).

The Tycho Input Catalogue contains about 590 000 stars brighter than 10.725 mag, among which 44 786 have no companion star closer than 3 arcsec. Some of these stars probably have erroneous positions in the input catalogue, others are probably variable stars, but still others could have been missed due to inhomogeneities in the observations: some stars got only very few predicted group crossings, or have observations disturbed by spikes or high background. For these reasons, the 44 786 entries not found, but brighter than 10.725 mag were kept in the selection and included into the Tycho Input Catalogue Revision.

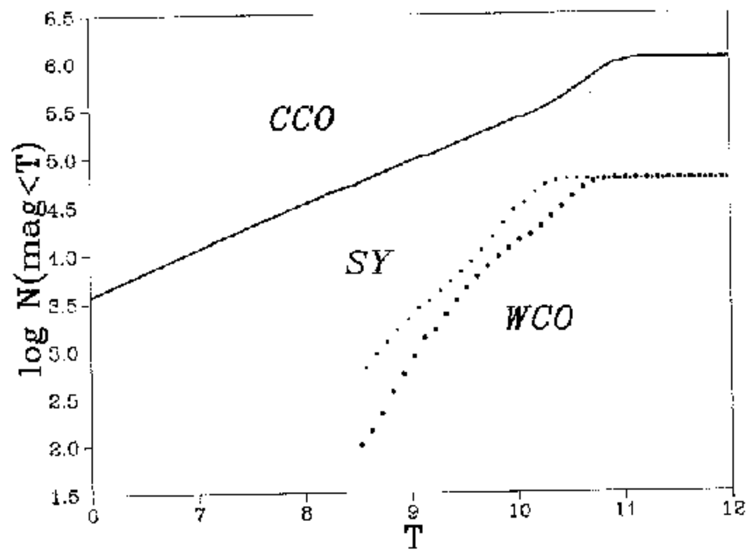


*__Figure 5.5.__ The cumulative distribution of T magnitudes of the non-redundant stars. The upper line is the distribution for the close companion stars. The large dots refer to the wide companion stars, and the small dots to the serendipity stars.*

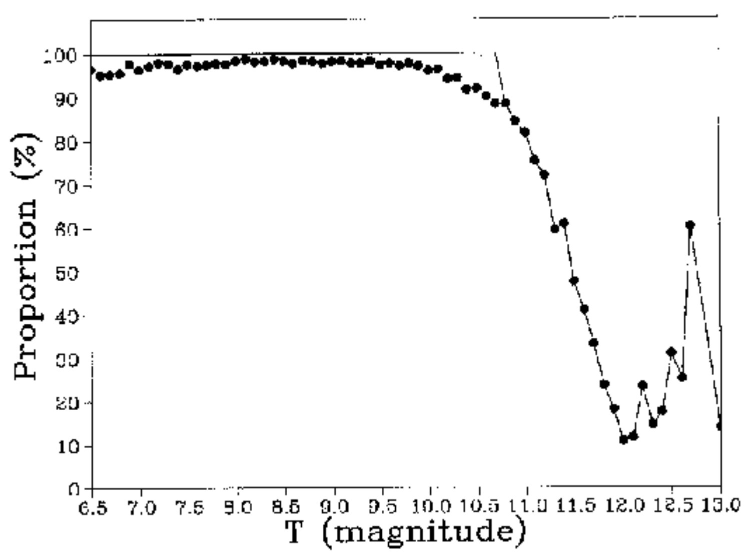


*__Figure 5.6.__ Proportion of Tycho Input Catalogue entries found with the close companion process, versus the T magnitude. Only stars with accurate data in the Tycho Input Catalogue are considered. The dots give the success rate of the process proper; the line refers to the proportion of stars finally selected for the Tycho Input Catalogue Revision (the stars brighter than 10.725 mag in the Tycho Input Catalogue were kept even when they were not found in the process).*

## 5.7. Properties of the Tycho Input Catalogue Revision

### Content of Tycho Input Catalogue Revision

The Tycho Input Catalogue Revision finally contains:

- 1 078 889 non-redundant stars found by the search for close companions. Among these stars, 1 016 916 are closer than 2 arcsec to positions given in the Tycho Input Catalogue, and are very probably true stars;
- 58 154 non-redundant stars found by the search for wide companions. An undetermined proportion of these are in fact false stars, generated by background detections (actually, this proportion was subsequently determined by the final steps of the Tycho data reductions described in Chapters 7 and 11);
- 26 356 redundancies, due to overlapping between maps centered on closely neighbouring Input Catalogue entries;
- 57 933 serendipity stars, with a large proportion of false stars among them;
- 44 786 entries of the Tycho Input Catalogue, corresponding to stars brighter than 10.725 mag that were not found in the search for close companions.

The total number of entries is 1 266 118, including 178 060 candidate new stars. The efficiency of the search for new stars is investigated hereafter, based on our knowledge shortly after the recognition process had been carried out. The final stellar content of the Tycho catalogue will be discussed in Chapters 17 and 19.

### Efficiency of the Close Companion Process

The efficiency of the search for close companion stars was investigated on the basis of the stars having the most accurate data in the Tycho Input Catalogue: stars from the INCA Data Base that are not members of binary systems, and for which the $B$ and $V$ magnitudes are known. The proportion of entries for which a companion star was found closer than 2 arcsec is given in Figure 5.6. This proportion is close to 100 per cent for stars brighter than 10 mag, and still larger than 90 per cent for stars brighter than 10.725 mag.

### Efficiency of the Wide Companion Process

Although the wide companion process produced a lot of entries that must be assumed to be false alarms but not stars, it had to be verified that the stars actually missing in the Tycho Input Catalogue were effectively found. The efficiency of the process could be estimated thanks to a bug in the operational version of the Tycho Input Catalogue: some stars having large proper motions received positions corresponding to an erroneous epoch (this bug is corrected in the published version). The efficiency of the wide companion process was estimated from the stars for which the positions at the epoch of the observations were between 6 and 20 arcsec from the positions used for the search. It is assumed that a star was correctly found when a companion star is less than

3 arcsec from the correct position. Results are given in Table 5.1. This statistic refers to stars with proper motions between 0.4 and 2.9 arcsec/year, that are not easily found since their transits are scattered. It is an underestimation of the efficiency of the search for the missing stars with the wide companion process.

**Efficiency of the Serendipity Process**

The case of the search for serendipity stars was investigated with the same method as for the wide companions. 47 stars have proper motions so large that their actual positions would be more than 20 arcsec away from their positions in the operational version of the Tycho Input Catalogue. 28 serendipity stars were found closer than 3 arcsec from these 47 actual positions. Results are given in Table 5.2. As for the wide companions, they give an underestimation of the efficiency of the process, since these stars have proper motions larger than 1.3 arcsec/year and their transits are scattered.

**The Search for Secondary Components with the Companion Processes**

The companion processes were dedicated to the search for stars missing in the Tycho Input Catalogue which are close to a brighter star that is included. For evaluating how well this goal was achieved, the double stars of the INCA Data Base were considered. The pairs with secondary components fainter than 10.5 mag were discarded from the statistic, since such stars were incompletely found even when they are single. The proportion of secondary stars for which a companion star was found closer than 3 arcsec is given in Table 5.3.

The small proportion of secondary components that were found when the separations are closer than 3 arcsec comes essentially from the limit in detection. In this process, two stars could be separated with certainty only when the projection of the position difference along the scanning direction was larger than 2 arcsec. Since several detection lines with different directions are necessary for a successful recognition, the effective limit for separating two stars is $\sqrt{2} \times 2 = 2.8$ arcsec. Some pairs closer than this limit were separated however, since stars as close as 1.2 arcsec were sometimes separated by detection. On the other hand, things are worse when the scattering of the predicted group crossings is large. Under these conditions, the detection lines of two close components, when they are reported on a digital map, do not reveal two stars but only a large patch roughly corresponding to the photocentre of the system.

When the separation is large, the search for the secondary star is even less efficient than the search for a single star. This is due to the detection threshold of the wide companion process, but also to another reason: bright primary components generate side lobe transits with distances equal to harmonics of the basic step of the slit groups, which is 5.625 arcsec (see Figure 5.1). The intersections of these side lobe lines with the detection lines of the secondary components sometimes generate a false star that looks brighter than the secondary. When such a false star is found and accepted by the reduction algorithm, the neighbouring detection lines are discarded, including those coming from the true star. The remaining detection lines may then be too few to permit the selection of the secondary star. For these reasons, an off-line treatment of double stars was added to the Tycho data reduction scheme. This process is described in Chapter 14.

**Table 5.1.** The stars with erroneous positions in the operational version of the Tycho Input Catalogue (the so-called 'TIC stars' here) which were found with the wide companion process.

| T magnitudes | <10.5 | 10.5–11.0 | 11.0–12.0 | >12.0 |
|---|---|---|---|---|
| TIC stars | 134 | 21 | 60 | 13 |
| Companions | 111 | 9 | 10 | 0 |
| Proportions (per cent) | 83 | 43 | 17 | 0 |

**Table 5.2.** The stars with erroneous positions in the operational version of the Tycho Input Catalogue (the so-called 'TIC stars' here) which were found with the serendipity process.

| T magnitudes | <8.5 | 8.5–10.5 | >10.5 |
|---|---|---|---|
| TIC stars | 22 | 8 | 17 |
| Serendipity Stars | 16 | 3 | 0 |
| Proportions (per cent) | 73 | 37 | 0 |

**Table 5.3.** The double stars of the INCA Data Base for which the secondary components were found. Only pairs with components brighter than $T$ =10.5 mag are considered.

| Separations | <3″ | 3–6″ | 6–12″ | 12–20″ |
|---|---|---|---|---|
| INCA double stars | 306 | 799 | 868 | 630 |
| Secondary components found | 64 | 549 | 621 | 490 |
| Proportions (per cent) | 21 | 69 | 72 | 78 |

## Conclusions

The Tycho Input Catalogue Revision contains all the stars of the Tycho Input Catalogue down to a magnitude of $T$=10.7 mag. Any stars brighter than this limit and missing in the Tycho Input Catalogue, but located close to an Input Catalogue entry, were found with a very good efficiency by the companion processes. The serendipity process, in addition, found a significant proportion of such stars even if they were far from any Input Catalogue position. The typical precision of the positions in the Tycho Input Catalogue Revision is about 0.15 arcsec, as shown in Figure 5.3.

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