14. SPECIAL TREATMENT OF DOUBLE AND MULTIPLE SYSTEMS

Stars with separations closer than 3 arcsec were usually not separated in the star recognition process (as described in Chapter 5). The limit of resolution was mainly determined by the slit width of 0.9 arcsec, and not by the much smaller optical resolution of the telescope. In the reprocessing, a particular effort was made to apply an adequate treatment to known double stars and suspected double stars. The close double stars were eventually detected in two different ways, depending on their separations. Between 1.5 and 3 arcsec, both components could be detected separately, and the individual positions could be derived. When the separations were between 0.4 and 1.5 arcsec, the duplicity was detected on the basis of a correlation between the measured magnitude and the position angle of the star mapper slits on the sky.

14.1. Introduction

The observation of components of double and multiple systems was already treated in Chapter 5. All stars closer than 6 arcsec to the entries of the Tycho Input Catalogue were searched in the star recognition process. The components were numbered in sequence of magnitude, with the brightest coming first. Then the selection area was extended from 6 to 20 arcsec in radius for the search of the so-called 'wide companions'. These processes ran satisfactorily for finding components brighter than $T = 10.5$ mag and with separations between 3 and 20 arcsec (see Section 5.7). Positions and photometry were derived for these stars as for single stars, and they were included in the Tycho Input Catalogue Revision.

A separation limit of 3 arcsec is large compared to the diffraction limit of the Hipparcos telescope. With an aperture of 29 cm, and an effective wavelength (in the V_T filter) of 532 nm, the radius of the first dark diffraction ring is only 0.38 arcsec. The wide separation threshold in Tycho was indeed not determined by the optics of the telescope but by the detection and star recognition processes. The detection algorithm was optimized for faint stars in order to obtain a catalogue containing as many stars as possible. A model curve corresponding to a single star was fitted to the photon counts (see Sections 4.3 and 4.4). Since the path of a star across each slit of the star mapper is 0.9 arcsec long, the components of double stars were distinguished only when the projection of the separation vector along the scan direction was about twice as large.

In practice, stars as close as 1.2 arcsec were sometimes separated, but the components were safely distinguished only when the projected separation was larger than 2 arcsec. As explained in Section 5.7, a limit of 2 arcsec in the detection process corresponds to a separation limit of 3 arcsec in the star recognition process because detections collected at different scan directions are necessary for finding a star.

Close double stars with separations of less than 3 arcsec were treated in dedicated processes. The components with separations between 1.5 and 3 arcsec were distinguished on the basis of double detections. Stars closer than 1.5 arcsec were also found since their detections have statistical properties different from those of single stars.

The close double star processing consisted of several tasks, shown in Figure 14.1. The processing was controlled by two object lists called 'stars flagged in reprocessing' and 'stars brighter than $V_T = 10.5$ mag', respectively (the second row of boxes in Figure 14.1).

The former object list formed part of the Tycho Input Catalogue Update, the input catalogue for the reprocessing (see Section 10.2). The selection was based on the double stars already known (Section 14.2), but also on a search for possible double stars performed at roughly midway through the mission (Section 14.3). New candidate double stars emerged from an analysis of the raw photon counts, and from the residuals of a preliminary astrometric reduction. All these possible double stars received two sorts of special treatment in the reprocessing, in order to confirm their duplicity. These treatments were supplements to the astrometric analysis (Section 14.4) and to the detection process (Section 14.5).

The second star list, essentially the brighter half of all Tycho stars, was submitted to a special photometric analysis (Section 14.6). It was based on the fact that the detection algorithm provided a signal with a larger amplitude when the components of a double star were aligned on the slits of the star mapper than when they were perpendicular to the slits. As a consequence, duplicity mimicked variability. However, double stars could be distinguished from true variable stars since their brightness was correlated with the position angle of the slits.

14.2. Close Double Stars from Catalogues

The first source of close double stars to be selected for the reprocessing was constituted by the ground-based catalogues of visual double or multiple stars. The double stars relevant for Tycho were selected and cross-matched with the Tycho Input Catalogue Revision. Systems with separations larger than 3 arcsec were ignored, since it was assumed that they had been properly separated in the Tycho Input Catalogue Revision. Components closer than the diffraction limit were also ignored. The list was thus restricted to separations between 0.35 arcsec and 3 arcsec.

From the statistics of the Tycho Input Catalogue Revision it was clear that the fraction of stars represented in the Tycho Catalogue would drop rapidly for combined T magnitudes between 10.7 and 12 mag. For that reason, only double stars with both components brighter than 12 mag were selected. Moreover, whenever the components were too close to be separated, the contribution of the secondary to the total luminosity was required to be above a certain level, i.e. to make it detectable in the raw Tycho signal. Double

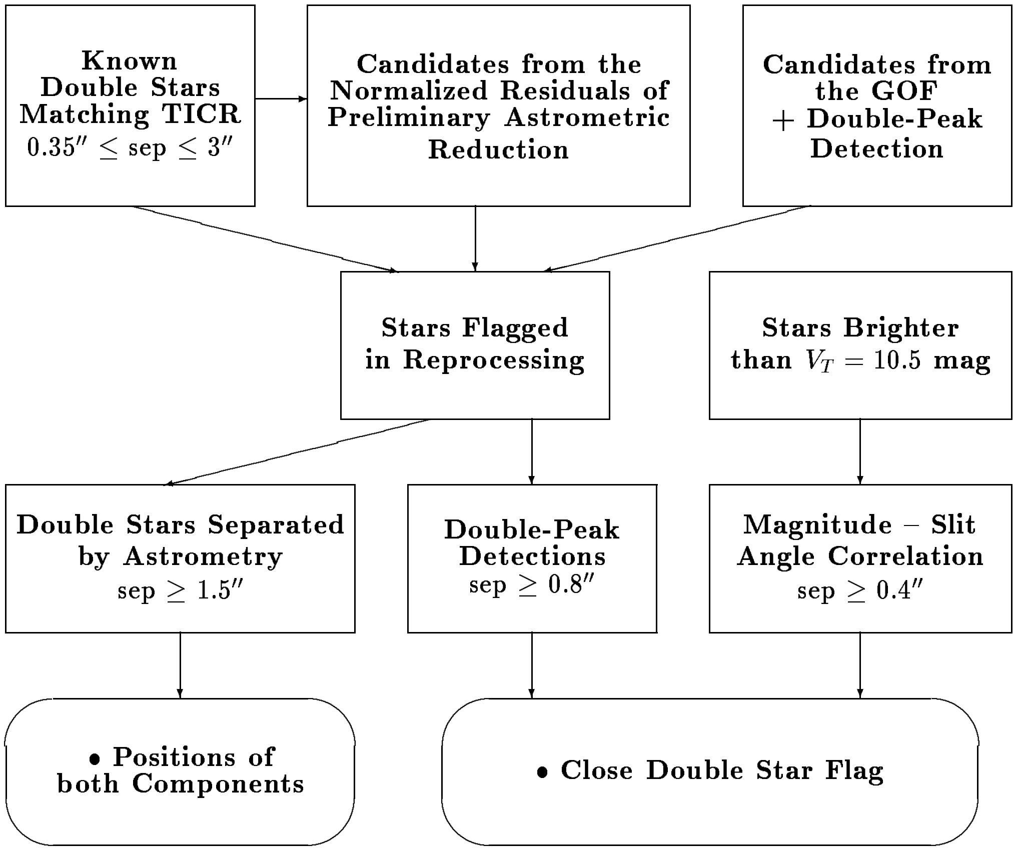

Figure 14.1. *The data flow in close double star processing. The rounded boxes refer to the results in the final Tycho Catalogue. TICR is the Tycho Input Catalogue Revision; GOF = goodness-of-fit.*

stars with magnitude differences larger than 3 mag and separations less than 1.5 arcsec were discarded.

Catalogues

The known visual systems were found in three different sources. Most important was the Washington Double Star Catalogue (‘WDS’, Worley & Douglass 1984). The WDS is virtually complete for stars with separations larger than about 1 arcsec, but some new double stars closer than this limit have been discovered since its publication. Apart from incompleteness, another drawback of the WDS is the very poor accuracy of the coordinates: they are provided with last digits corresponding to 0.1^{m} for right ascension, and 1 arcmin for declination.

The second source was a part of the Catalogue of Components of Double and Multiple Stars (‘CCDM’, Dommanget 1983, 1989b), which was published as an Annex of the Hipparcos Input Catalogue (Turon *et al.* 1992, 1993). This catalogue provides positions with an accuracy of some arcsec, which is much better than the WDS.

Third, the Catalogue de 2550 Etoiles Doubles COU ('COU', Couteau 1990) includes several hundred double stars of the northern hemisphere which were discovered by Paul Couteau after the publication of the WDS. In addition it provides recent measurements of the relative positions of components for many of the stars in the WDS. The accuracy of coordinates is the same as in the WDS.

The numbers of double stars satisfying the selection criteria among the WDS, the CCDM, and the COU were 13 826, 3569, and 1394 respectively, but several systems were in duplicate or even in triplicate, since the three catalogues are overlapping (hereafter, a 'double star' is a primary component and a fainter star; a close system of N stars is considered as $N-1$ double stars). The WDS and the COU were merged, and the entries also in CCDM were discarded, since CCDM provides better coordinates than the two other catalogues. For the remaining stars in the merged WDS+COU file, accurate positions were searched in the catalogue of Positions and Proper Motions, or 'PPM' (Röser & Bastian 1991; Bastian *et al.* 1993). The cross-matching with PPM was done in order to increase the probability of selecting the correct double stars afterwards. Whenever a case appeared to be ambiguous, two entries for the double star list were constructed, one from the PPM and one from the WDS+COU file. Finally three lists were obtained: 6980 entries with coordinates from WDS or COU, 4423 entries with coordinates from PPM, and 3569 entries from CCDM.

Cross-Matching the Double Stars with the Tycho Input Catalogue Revision

The positions of double stars from the catalogues were compared with the positions of stars in the Tycho Input Catalogue Revision and a cross-matching was performed. Different selection rules were used, depending on the accuracy of the positions of the double stars.

For the double stars with coordinates from WDS or COU, matching stars were requested to be closer than 3 arcmin and the magnitudes of the primary components to differ by less than 2 mag from the magnitude in the Tycho Input Catalogue Revision. When several stars of the Tycho Input Catalogue Revision satisfied these criteria, a priority selection algorithm was applied. The stars closer than 3 arcsec to the original positions in the Tycho Input Catalogue were selected first, since the stars with large offsets in position were assumed to be false stars (see Chapter 5). When no star satisfied this condition, the stars found at more than 3 arcsec were considered. When no stars at all had been found in the star recognition process, then the stars brighter than 10.725 mag in the original Tycho Input Catalogue that were kept in the Revision were also taken into account. This selection provided a total of 6127 stars from the Tycho Input Catalogue Revision, which matched 5405 objects from the ground-based double star catalogues.

The double stars with coordinates from PPM were selected according to the following rule. Stars in the Tycho Input Catalogue Revision closer than 3 arcsec to the PPM positions were considered, and up to three stars were selected: the closest star, the closest star actually found in the star recognition process, and the brightest star found in the star recognition process. 4405 stars from the Tycho Input Catalogue Revision were thus associated with 4356 double stars with PPM coordinates.

The double stars with coordinates from CCDM were cross-matched using a rule similar to that for PPM coordinates. Since the positions in the CCDM are less accurate than those in the PPM, the selection distance was 20 arcsec instead of 3 arcsec, however.

Table 14.1. Origin of the coordinates of double stars matching the Tycho Input Catalogue Revision, split into classes of separation. The numbers of double stars in the 'Merged' line are different from the sums of the columns since some double stars are common to the PPM and the WDS+COU list.

Separations	0.35" – 1"	1" – 2"	2" – 3"	Sum
CCDM	1581	1189	770	3540
PPM	2156	1416	784	4356
WDS+COU	2250	1674	1481	5405
Merged	5965	4255	3014	13234

3768 stars from the Tycho Input Catalogue Revision were thus associated with 3540 double stars.

In the end a total of 14 237 Tycho Input Catalogue Revision stars had been associated with 13 234 double stars in the WDS+COU and in the PPM lists. The origins of cross-matching and statistics of the separations between the components are presented in Table 14.1. These stars were flagged and added to the Tycho Input Catalogue Update, described in Section 10.2.

14.3. Candidate Double Stars from Tycho Observations

Preliminary Selection from Detection

Double stars closer than about 2 arcsec were usually not separated by the detection algorithm. However, systems with separations of about 1 arcsec still generated transits with the profiles of the four photon peaks differing from those of a single star. This showed up as a 'bad' value of some goodness-of-fit parameter derived in the detection process while fitting slit response functions to the observed photon counts. This property was used as a first step in selecting candidate double stars from the photon counts. As a preparation for this step, the mean goodness-of-fit values and their standard deviations were calculated for different bins of T magnitudes, for photon counts in the B_T, V_T and T bands. The mean values together with the standard deviations were used in a goodness-of-fit check implemented in the transit identification program. For each detection, the appropriate mean goodness-of-fit was derived from the B_T, V_T and T magnitudes. A detection was flagged when its actual goodness-of-fit value differed by more than one standard deviation from the mean values. The detections were assigned to a star in the Tycho Input Catalogue Revision when they were less than 1.4 arcsec from the corresponding predicted group crossing. This procedure was applied to a part of the mission corresponding to 247 full days of observation, between 22 April 1990 and 3 March 1991.

The second step in selecting candidate double stars from the Tycho observations was a 'double-peak test' applied to the photon counts of the transits flagged by the above goodness-of-fit test. The photon counts in the T band were read and folded with the non-linear 4-peak filter. Then a single-star profile was fitted to the folded counts, the initial values for transit time and signal amplitude of the peak being set to the maximum count rate in a 4-sample interval centered on the transit time derived by routine detection and estimation. If the fit was successful, the resulting profile was subtracted from the count rates and a second maximum was searched inside a 20-sample interval (i.e. 5.625 arcsec) centered on the initial transit time. If a second maximum was found, the corresponding starting values were set and a double-star profile was fitted to the initial folded data.

The test was considered to be successful if the signal-to-noise ratios of both peaks were larger than 1.5, if the separation of the peaks was between 0.45 and 2.8 arcsec, and if the secondary peak could not be attributed to another star of the Tycho Input Catalogue Revision. The whole procedure (goodness-of-fit test plus double-peak test) resulted in the flagging of 0.9 per cent of all transits. In order to keep a reasonable number of candidate double stars, all stars having less than 4 transits successfully tested with the double-peak fit were discarded.

For the remaining stars on the list, it was checked whether the double-peak separation was correlated with the slit angle. The stars with the best correlation were selected, aiming at a number of about 10 000. A list of 8687 stars was finally obtained, including 1608 stars matching the list of known double stars.

Preliminary Selection from the First Iteration of Astrometric Reduction

Another selection of candidate double stars was performed on the principle that the (unresolved) detections of double stars should be more widely scattered around the positions derived in astrometric reduction than those of single stars. The parameter describing this statistical property was the normalized residual from the astrometric adjustment, defined as:

$$R = \sqrt{\frac{\|\rho\|^2}{N_{obs} - 2}} \qquad [14.1]$$

where ρ is the normalized residual vector of the individual observed transit times (see Equation 11.1), and N_{obs} is the number of observations.

A first iteration of the Tycho astrometric reduction process was run on the first 17 months of the mission, and the normalised residuals were derived. It appeared that many stars found in the star recognition process at more than 3 arcsec from positions in the original Tycho Input Catalogue had large R, since they were in fact false stars. These stars were discarded from the search for double stars, as were also the stars having a companion closer than 10 arcsec.

The selection criterion for candidate double stars depended on R and on the T magnitude. It was tuned by considering the stars matching known doubles among the stars with large R. Only pairs with separation between 0.8 and 2 arcsec, and with a difference of magnitudes Δm less than 1 mag were taken into account, since they were the easiest to detect. It was assumed that all double stars brighter than $T = 7$ were known. Their intrinsic proportion among stars was thus derived from counts in the Tycho Input Catalogue; the result was 0.78 per cent. Considering, on one hand, the number of stars in the Tycho Input Catalogue Revision, and, on the other hand, the known double stars, completeness coefficients were derived for magnitude bins, and the proportions of stars that should be double were calculated for different intervals of R and T. The selection threshold of candidate double stars was set in order to get an estimated proportion of true double stars (known or not) of at least 20 per cent among the selected stars. All stars fainter than 10 mag were discarded by this criterion, and 1217 stars were finally selected, including 420 stars matching the double stars from catalogues.

When the known double stars from catalogues (Section 14.2) were discarded from the count, the selection from detection and from astrometry finally provided 7846 new candidate double stars. They were added to the 14 237 known doubles, the combined list of 22 083 stars was flagged in the Tycho Input Catalogue Update, in order to be submitted to dedicated double-star treatment during the reprocessing, as described in the next two sections.

14.4. Astrometric Reduction of Close Double Stars in Reprocessing

Solving Astrometric Observation Equations for Selected Double Stars

This section describes the dedicated treatment for known or suspected close doubles that was performed in the course of the astrometry processing at Copenhagen.

All detections assigned to a star flagged for double-star treatment in the Tycho Input Catalogue Update (see Sections 14.2 and 14.3) were collected in an *ad hoc* 'Catalogue of Observation Equations of Close Doubles' (OECD), containing all necessary information for the analysis. During generation of the OECD, there was no rejection of detections due to the usual astrometric criteria (see Chapter 7). In particular, detections with large residuals or large normalized residuals were not rejected, for obvious reasons. Thus, detections as far as 5 arcsec (the limit set up by transit identification) from the specified position in the input catalogue were available. Parasite recording (see Section 7.2, Figure 7.1) was also ignored, otherwise a lot of useful observations would have been lost as disturbed by parasites when both components of a double star had been detected in the recognition process and had obtained separate entries in the Tycho Input Catalogue Revision.

The OECD contained all parameters of the original observation equations (see Equation 7.7), plus the B_T and V_T amplitudes and the background values in the B_T and V_T passbands. These photometric quantities were needed to compute median B_T and V_T magnitudes of resolved components, corrected for the photometric bias at faint magnitudes due to the detectability threshold. The resulting B_T and V_T magnitudes were included in the Tycho Catalogue, along with the astrometric parameters. The photometric treatment was somewhat simplified and less precise compared to the routine photometry for the Tycho Catalogue, however.

Detections assigned to a selected double star were processed with an algorithm divided into a few steps. First, an astrometric solution for a 'central' component was attempted. To start an iterative process, all detections with residuals (observed minus predicted) smaller than 1.1 arcsec in absolute value were chosen, and a starting estimate of the position was calculated by the least-squares method. This solution was used later on as a first approximation. The median magnitude $T_{\rm m}$ of the central component was also estimated from the set of detections used in the adjustment. This quantity was used at subsequent iterations for the selection of detections in the following way. All detections with magnitudes more than 1 mag from $T_{\rm m}$ were excluded from the analysis, whatever their astrometric residual. This allowed the diminution to some extent of the influence of disturbing parasitic transits, and the improvement of the assignment of detections, provided the two components were of considerably different magnitudes.

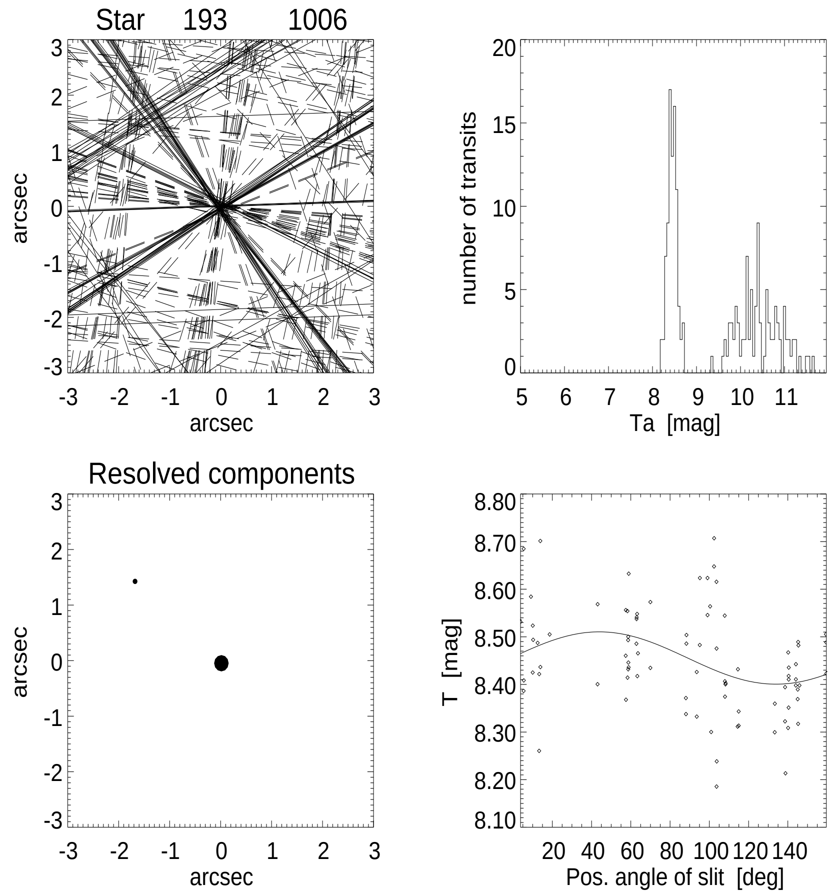

Figure 14.2. *Double star analysis in astrometry. Top left: detection line map, solid lines belong to transits of the vertical slit; top right: distribution of magnitudes T_a, derived directly from the amplitudes of each detection; lower left: resolved components, size of circles correspond to estimated T_m magnitude; lower right: T_a as function of position angle of the detection line. The first harmonic fitting curve is shown as a solid line.*

The astrometric residuals were used as additional selection criterion in the course of subsequent iterations. A detection was accepted if its residual was smaller than $3\sigma_u$, where σ_u is the expected standard deviation for this detection, as calculated in the routine processing and written into the Catalogue of Observation Equations of Close Doubles. In order to compute the residuals, the position obtained at the previous iteration was used. Hence, the iterated position could drift from one iteration to the next, and the selection of observations was repeated among the whole set of detections. The T_m value was updated every time. There were six such iterations, excluding the startup described in the previous paragraph.

Corrections to the tangential coordinates of the central component were calculated in this way. All observations assigned to the central component in the last iteration were left out of the analysis, in order to facilitate the subsequent detection of secondaries, typically fainter components. In this respect, the method resembled a cleaning algorithm of image processing.

In general, Tycho astrometry was unable to determine proper motions and parallaxes for resolved components of close double systems individually. Thus the on-ground proper motions had to be used in the calculation of the mean positions at the Tycho Catalogue standard epoch J1991.25.

Solving Secondary Components

The search for and solution of secondary components proceeded in two steps. In the first step the detections assigned to the central component were subjected to a special photometric analysis. It was aimed at finding the position angle of a secondary component in the vicinity of the first one. It exploited the simple fact that the amplitude of a detection depended on the difference between the position angle of the star mapper slits and the axis of the double star. If the slit crossed both stars at the same time, the amplitude was larger, and, vice versa; the minimum amplitude was expected when the slit was perpendicular to the axis of the double. The minimum of the function $T_a(p)$, where p is the position angle of the slit, indicated the direction towards the secondary component, modulo π. In order to determine this minimum safely, a harmonic analysis of the magnitudes:

$$T_i = a_0 + a_1 \cos(2p_i) + b_1 \sin(2p_i) \qquad [14.2]$$

was performed, where p_i is the position angle of the slit at the moment of the i-th observation, T_i is the magnitude of the i-th observation, and $i = 1, 2, ..., M$. Equations 14.2 were solved for the coefficients a_0, a_1 and b_1 by the least-squares method. Then the full amplitude of the modulation curve was $A_\mathrm{T} = 2\sqrt{a_1^2 + b_1^2}$, and the phase $\phi = \arctan(a_1, b_1)/2$ determined the possible direction p_s to the secondary component.

The larger the amplitude A_T, the more confidence existed in the presence of that secondary. The formal criterion was the signal-to-noise ratio for the amplitude:

$$F_\mathrm{T} = A_\mathrm{T} / \sigma(A_\mathrm{T}) \qquad [14.3]$$

This number was important for the flagging of suspected unresolved double stars described in Section 14.6, but in the context of the present section, the search for secondary components was undertaken no matter what the F_T value was.

Having determined the possible position angle p_s of the suspected double star, two starting points were placed in the two opposite directions p_s and $p_\mathrm{s} + \pi$ at distances of 1.9 arcsec from the central component, and an astrometric solution was attempted for both of them, in the same way as described above for the central component. The only difference was that for the iterations the threshold value of residuals was set to $4\sigma_\mathrm{u}$ instead of $3\sigma_\mathrm{u}$, in order to take into account the possible disturbing influence of the central component. Other directions were not examined, which avoided a lot of false detections of faint stars caused by the data noise. In fact, a secondary component could not be found in the rare cases when the analysis of $T_a(p)$ had given a position angle p_s wrong by more than about 30 degrees. This could happen basically for two reasons: (i) unrecorded parasitic transits survived the filtering on T_a and were accepted for the central component, and (ii) the central component was a variable star and the time-variations of its magnitude were correlated with the position angle of the slits by chance.

A number of separate components (maximum 3) could indeed be detected as a result of this treatment. Their equatorial coordinates α and δ were derived from the known tangential coordinates and the input catalogue position. B_a and V_a magnitudes were calculated for all detected components with a simplified photometric calibration procedure. These magnitudes were forwarded for inclusion in the Tycho Catalogue. The final decision on whether a newly-found component was to be used as an additional star in the Tycho Catalogue was made after a redundancy analysis of all astrometric results.

Performance of the Method

The reprocessing list of 22 083 known or suspected close double stars contained more than 2000 stars having a preliminary double-star solution by NDAC derived from measurements of the Hipparcos main instrument. These were used to assess the success of the above-described double star processing. The preliminary NDAC solutions for double stars provided separations and position angles rather than coordinates of components. Consequently only relative positions of the components could be compared. Generally, the accuracy of the NDAC solution was better than that of Tycho by almost one order of magnitude. It could therefore be assumed that any difference in relative positions of the components was due to the inaccuracy of the Tycho solution.

It happened quite often that the algorithm described above gave two resolved companions located in approximately opposite directions relative to the central one. Since triple stars are fairly improbable with this limiting magnitude, one of the companions was almost surely false. Such false stars were due to a side effect of the filtering of the raw data in the detection process. Any fairly bright star generated a 'blind area' around itself of about 1.4 arcsec radius, where detections were extremely scarce, while the probability of a detection was enhanced by the filtering at distances from 1.4 to 2.8 arcsec. On a detection line map (e.g. Figure 14.2) the star is surrounded by a cloud of transits, mostly false by nature. Occasionally, dense concentrations of false detections are interpreted as a faint companion star.

The problem was therefore to distinguish between real and false resolved companions (the latter are called 'ghosts' in the following discussion). From the sample of NDAC double stars it was concluded that a resolved companion is most probably true if the difference of separations $\rho_{\rm TYC}-\rho_{\rm HIP}$ fell into the interval $[-0.34, 0.26]$ arcsec and position angle $\mathrm{PA}_{\rm TYC} - \mathrm{PA}_{\rm HIP}$ was in the interval $[-23, +23]$ degrees. The real distribution of the true companions is much narrower, as shown in Figure 14.3. The full width at half maximum of the distribution is 0.07 arcsec for separations and 3° for position angles. Figure 14.3 (centre left) represents the separations of all 817 pairs resolved by Tycho versus the NDAC separations. The cloud of ghosts (diamonds) is concentrated around $\rho_{\rm TYC} \simeq 2.5$ arcsec, as expected. It was found that the magnitudes of the ghosts were typically fainter than 10.7 mag, but a fair number of true companions as faint as that were also detected.

The signal–to–noise ratio $F_{\rm s}$, defined in Section 7.4, proved to be highly efficient in separating false and real stars. Figure 14.3 (centre right) shows the $F_{\rm s}$ distributions of the 152 ghosts and 665 true companions. Choosing a limit of 4.4 on $F_{\rm s}$ would provide a clear distinction between true and false stars. With this limit, only 2 of the 152 ghosts in the figure remain, which were in fact badly solved real stars, and 638 of the 665 true companions survived.

The 0.1, 0.5 and 0.9 quantiles of the $\rho_{\rm TYC} - \rho_{\rm HIP}$ distribution as a function of the true separation are shown in Figure 14.3 (lower left). There is a strong bias of Tycho separations, appearing also in Figure 14.3 (top left). It was caused by the adopted detection filtering, devised for single symmetric star images in the raw photon counts. When a star image was highly asymmetric due to the presence of a nearby companion, the symmetric detection filter gave a transit time shifted towards the companion, i.e.

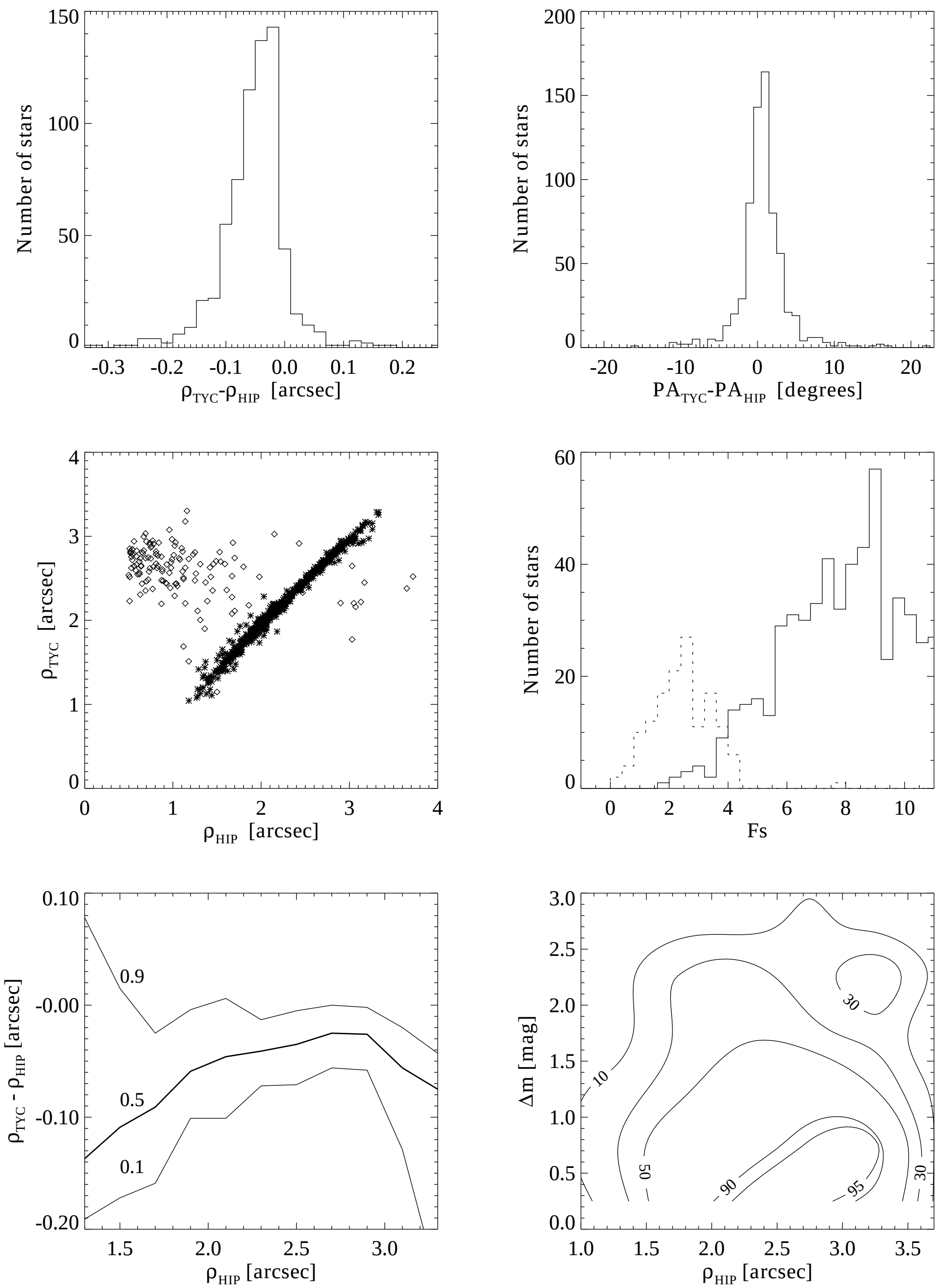

Figure 14.3. *Performance of the method to resolve close double stars: The two upper plots show distributions of successfully resolved stars versus 'Tycho – Hipparcos' differences in separations and position angles; centre left: Tycho separations versus Hipparcos separations for ghosts (diamonds) and true components of double stars (asterisks); centre right: distributions of ghosts (dashed line) and true stars (full drawn line) versus F_S value; lower left: quantiles of the distribution of resolved stars versus difference in separations, as a function of NDAC separation; lower right: percentage of successfully resolved double stars as a function of separation and difference of components in magnitude, shown as a contour map.*

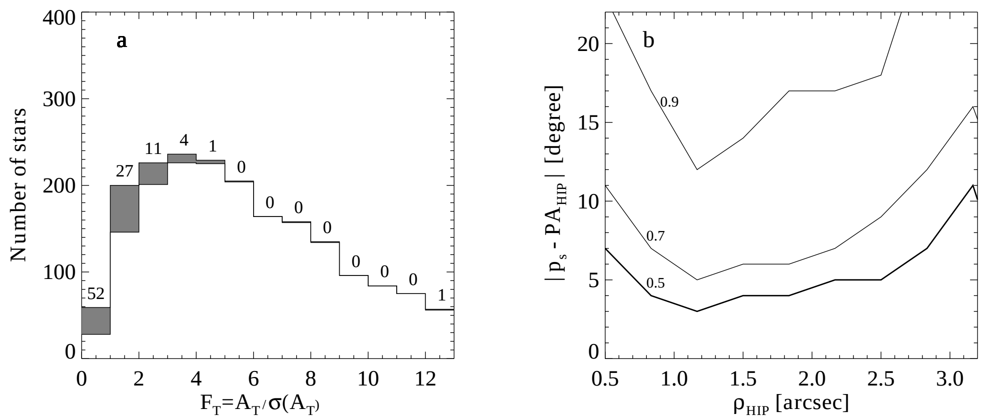

Figure 14.4. *Performance of the photometric method for determining the position angle of close double stars: (a) distribution of 2000 double stars in common with the Tycho Catalogue versus the signal-to-noise ratio F_T from Equation 14.3. The blank area under the histogram indicates the distribution of successful determinations, while the shaded area represents the number of wrong estimations. The percentage of the latter are given at the top of each bin; (b) quantiles of the distribution of $|p_s - PA_{HIP}|$ versus the separation for all the 2000 NDAC stars observed by Tycho. The slightly thicker line gives the 0.5 quantile, i.e. the median.*

too small separations were obtained. The dependence of the bias on the separation can also be qualitatively understood in this way. In principle, the Tycho separations could have been corrected by means of the available Hipparcos data, but a correction to the absolute positions of each component given in the Tycho Catalogue was not known. The bias therefore had to remain uncorrected in the Tycho Catalogue. Thus, the resolved double stars in the Tycho Catalogue are corrupted by the strong systematic error shown in Figure 14.3. They are therefore not recommended for use as astrometric reference stars.

The best performance of the method was achieved at separations from 2.3 to 2.9 arcsec. The performance depended also on the magnitude difference between the two components. Figure 14.3 (lower right) covers the whole set of 3308 NDAC double stars. The percentage of successful Tycho solutions is shown as a contour map, depending on the true separation and the difference in magnitude as found in the NDAC solution. Nearly all components of equal magnitudes with separations from 2.2 to 3.2 arcsec were correctly resolved, while double stars with $\Delta m > 3$ mag turned out to be beyond the capability of Tycho.

Altogether, some 1657 non-redundant pairs were resolved and included in the Tycho Catalogue.

The performance of the photometric method of position angle determination, described in the previous subsection, could also be determined from the NDAC double star sample. The p_s values were directly compared with the NDAC position angles. The distribution of $|p_s - \mathrm{PA_{HIP}}|$ in Figure 14.4(b) shows a good performance of the method for separations from 1.0 to 2.5 arcsec, and reasonable results were obtained for smaller separations, down to 0.5 arcsec. This high degree of success prompted the large-scale search for unknown double stars described in Section 14.6.

The distribution of the 2000 stars from the NDAC list in Figure 14.4(a) shows that the majority of doubles have signal-to-noise ratio F_T above 3. The blank part of the histogram corresponds to correctly determined position angles, i.e. when the p_s value falls within ±25 degrees of the correct angle. The shaded part represents the numbers of outliers, while the numbers at the top of each bin give the percentage of wrong determinations. It appears that the method performs well when $F_T > 3$, where less than about 4 per cent of wrong estimations can be expected. A number, though very small, of wrong estimations at high F_T values could be caused by true photometric variability of some double stars.

14.5. Double-Peak Detection in Reprocessing

For all transits of each known or suspected double star the raw photon count rates in a 200-sample interval, centred on the predicted transit times, were extracted into a separate file in the detection reprocessing at Tübingen (Chapter 10). This was done for the whole mission. The file was submitted to a special double-peak fitting and double star solving procedure which will be briefly described in the following.

The double-peak fit described in Section 14.3, was applied to the photon counts, but with several important differences: data from the entire mission (rather than 247 days) were used, double-peak distances up to 4.2 arcsec were accepted, and no test was carried out to check whether the secondary peak could be attributed to an unrelated ('parasitic') star.

Even for a true double star a proportion of transits yielding perfect single-star detections had to be expected, namely whenever the two stars were aligned parallel to the star mapper slits, i.e. when the position angles of the slits θ_s and that of the double star θ_d were the same. But double peaks were detectable when θ_s was sufficiently different from θ_d. The error-free double-peak distance is always given by

$$\rho_s = \rho \; |\sin(\theta_s - \theta_d)| \qquad [14.4]$$

where ρ is the true separation of the double star. Fitting this relation to the actually measured double-peak distances, the separations and position angles of the suspected doubles were calculated. The double-peak fit gave individual amplitudes which were converted to magnitudes by a rough preliminary calibration formula. Thus the position angles could be derived without the uncertainty of $\pm\pi$ mentioned in Section 14.4.

Formal fits were obtained for almost all of the 22 083 candidate double stars. But it was clear that many of these results were spurious, i.e. created by pure chance from a random combination of noise peaks. Selection criteria were developed, therefore, in order to suppress the spurious cases. They were based on the goodness-of-fit of the parameter adjustment using Equation 14.4, on the number of successful double-peak fits agreeing with Equation 14.4, and on the ratio between this number and the total number of successful double-peak fits. An additional criterion discarded all cases with high magnitude differences and small separations. The thresholds for these criteria were fixed by a comparison with the 2357 preliminary NDAC solutions already mentioned in Section 14.4. The aim was to minimize the number of 'false' solutions. A solution was assumed to be false if it had a separation difference of more than 0.2 arcsec or a position angle difference of more than 20° to the NDAC solution.

Two sets of thresholds were defined. Applying the first set led to a set of double stars with an error rate of false solutions clearly below 0.5 per cent. These stars were flagged 'D' (double) in Field T49 (Section 2.2, Volume 1) of the Tycho Catalogue. The median absolute differences between such solutions and the NDAC reference were 0.026 arcsec in separation and 1.1° in position angle.

The second set of thresholds aimed at an error rate of 5 per cent. Stars satisfying it were flagged 'S' (suspected) in Field T49, unless the photometric method of double star search (see Section 14.6) confirmed the duplicity. Applying the two sets of thresholds to all 22 083 candidate stars led to 3239 'D' and 2650 'S' stars.

The method described above was most efficient for separations between 1 and 3 arcsec. According to the NDAC comparison set, nearly all stars were correctly resolved in this range if their magnitude difference Δm was below 1.5 mag. But at least 40 per cent of the candidates were correctly resolved down to separations of 0.6 arcsec (at $\Delta m = 0$ mag) or 1.2 arcsec (at $\Delta m = 1.2$ mag).

14.6. Photometric Duplicity Search

As explained in Section 14.4, the observed magnitude for each transit of a close double star depended on the orientation of the system relative to the slits of the star mapper. A large-scale photometric search for duplicity based on this phenomenon was applied to the roughly 480 000 Tycho stars with $V_T < 10.5$ mag, i.e. roughly the brighter half of all stars observed by Tycho. The results of this investigation were used to flag stars in the Tycho Catalogue (Field T49) accordingly. Again, as for the results of the preceding section, certain and less significant cases of duplicity were distinguished in the flagging. In addition, the flags were devised to indicate whether no photometric search for duplicity was performed (about 570 000 stars) or whether no signs of duplicity were found in spite of the search (450 000 stars). The photometric search added about 5200 stars flagged 'D', i.e. fairly certain doubles, to the 3200 already found by the method of the previous section. This investigation was performed at Tübingen in the framework of the main photometric reductions.

J.-L. Halbwachs, V.V. Makarov, K. Wagner