1. INTRODUCTION

In the Tycho project astrometric and photometric data of 1 052 000 stars to a limit of V_T = 11.5 mag were derived. The brightest 99 per cent of the stars obtained magnitudes in two passbands B_T and V_T. A precision (median standard error) of 7 mas was achieved in astrometry (positions, annual proper motions and parallaxes) for stars with $V < 9$ mag, and 25 mas for all stars. The median precision in photometry is 0.012 mag for V_T of the bright stars and 0.06 mag for the whole catalogue. Double stars with separation larger than 2 arcsec have been resolved, and duplicity down to 0.4 arcsec has been detected. The results were obtained by appropriate treatment of the continuous data records generated by the Hipparcos satellite's star mapper which provides simultaneous measurements in two spectral channels. The processing was based on predicted star transits using its own 'Tycho Input Catalogue'. The data treatment was carried out by the Tycho Data Analysis Consortium (TDAC), using calibration and satellite attitude information from the Hipparcos data reduction consortium, NDAC, and photometric standard stars from the FAST Consortium. An overview of the data reductions and of the astrometric and photometric results is given. Raw observation data and their numerical treatment are described.

1.1. Overview

The astrometry satellite Hipparcos was launched by the European Space Agency on 8 August 1989 into an elliptical transfer orbit, from which observations were carried out in the period November 1989 to August 1993, instead of from the intended geostationary orbit. A major consequence of this was that some 50 per cent of the data were lost for the Tycho project due to enhanced background counts during passage through the van Allen belts resulting in the loss of accurate attitude determination. Nevertheless, the Tycho Catalogue (TYC) from the 'revised' mission of 37 months surpassed the expected number of stars by a factor of 2.5, and exceeded the precision predicted before launch.

The photon counts from the star mapper of the Hipparcos astrometry satellite were processed to detect star transits exceeding a certain signal-to-noise ratio. These detections or transits, collected throughout the mission, were identified with stars contained in a Tycho Input Catalogue of 3 million stars. Stars down to a limiting magnitude of $V = 11.5$ mag, depending on star colour, were recognized within small areas of 40 arcsec diameter centred on each Tycho Input Catalogue position, leading to the final Tycho

Catalogue of a million stars. The typical (median) astrometric and photometric precision of a mean value in the Tycho Catalogue is 0.025 arcsec and 0.06 mag, respectively. This is also the typical precision at the median magnitude $V_T = 10.5$ mag. Annual proper motions and parallaxes were obtained with the same precision. The standard errors of positions and magnitudes roughly decrease by a factor of 2 per magnitude towards brighter stars, reaching a roughly constant level of about 2 mas for stars brighter than $V_T = 6$ mag. The Tycho Catalogue content is described in Chapter 16 and in Volume 1, Section 2.2. The complete stellar content is mapped in Volumes 14–16.

Photometry for individual transits is given in the Tycho Epoch Photometry Annex A for a selection of about 34 000 stars, on average 170 epochs per selected star (see Section 2.7). Annex A is made available on a CD-ROM, while an Annex B with epoch photometry for 481 000 stars is available from the Centre de Données astronomiques de Strasbourg (CDS). Double stars with separations larger than about 2 arcsec are resolved. For separations down to 0.4 arcsec, duplicity was recognized from a correlation between the position angle of the slit and the estimated magnitude.

1.2. Pre-Launch Preparations

When the Hipparcos project was approved by ESA early in 1980, it had not been realized that the star mapper could be used as a powerful astrometric and photometric device. Soon afterwards, in 1981, the idea was explored by E. Høg in notes to ESA. It was shown that the star mapper could give very important scientific results (Høg, Jaschek & Lindegren 1982). Indeed, the results would by far outweigh all ground-based observations of all meridian circles already made during the present century, meridian circles being the principal source of fundamental astrometric observations. It would, furthermore, represent the largest and most homogeneous photometric catalogue ever produced.

The primary purpose of the Hipparcos star mapper was to observe the transit time of bright reference stars of known position when they crossed the slits. By means of known positions and transit times, the attitude of the satellite was determined. The satellite attitude had to be known with an accuracy of about 1 arcsec during the mission in order to point the light-sensitive area of the main detector at the individual programme stars as they crossed the main field of view. A good attitude knowledge is also required at a later stage to achieve the best astrometric accuracy in the data analysis for the programme stars, and here the attitude must be known with an accuracy of 0.1 arcsec; in fact 0.03 arcsec was achieved on average perpendicular to the scan direction, and 0.002 arcsec along the scan direction.

Since stars used for the satellite real-time attitude determination are a small subset of all stars brighter than the star mapper detection limit, it is evident that observations of transit times for many stars, other than those required for attitude determinations, can be exploited to derive the positions of these stars. The photometric results are obtained from the analysis of the stellar photon flux at the slit transits.

In 1981, ESA formally approved the Tycho project which then aimed at determining magnitudes and positions for at least 400 000 stars. The hardware changes required were the introduction of dichroic beam splitters and a pair of redundant photomultiplier tubes into the science payload, and the provision to transmit all photon counts from

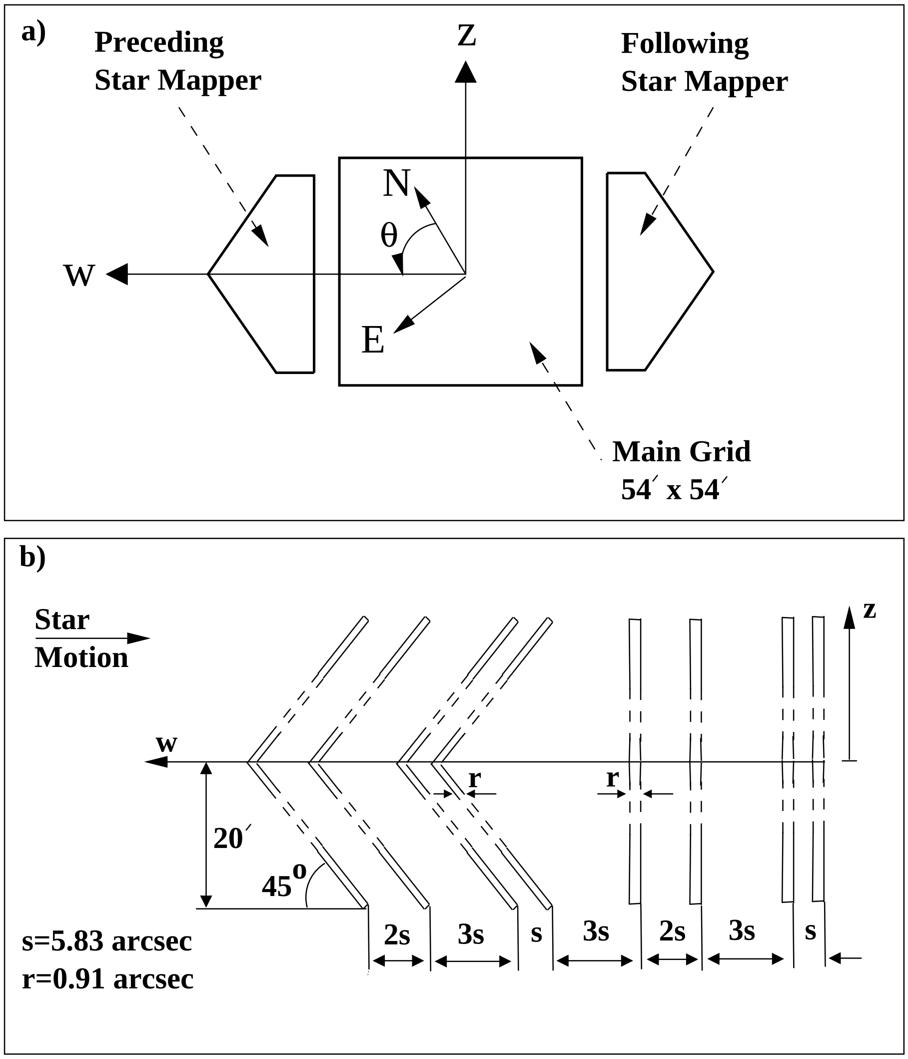

Figure 1.1. *The slit systems at the focal plane. (a) Arrangement of the star mappers and the main grid; definition of the w, z coordinate system and the position angle θ relative to celestial north and east ('N' and 'E' in the figure). (b) The preceding star mapper; the following star mapper is redundant and was in fact never used. The 'vertical' slits of the star mapper are perpendicular to the motion of the stars, while the 'chevron' slits are inclined by 45°. The light from the whole star mapper area is divided by a dichroic beam splitter onto two photomultiplier tubes which count the photoelectrons simultaneously in two bands: B_T and V_T.*

these tubes to the ground—not only during the time intervals when a reference star required for the attitude reconstruction was crossing the star mapper slits (Figure 1.1).

1.3. Organisation of the TDAC Consortium

In 1982, ESA called for commitments to perform the Tycho scientific data analysis which resulted in the formation of the Tycho Data Analysis Consortium (TDAC) with participation from most ESA countries and the USA. The participation in TDAC before launch appears in Appendix C in Perryman *et al.* (1989, Vol. III). The title pages of Volume 1 specify in detail the participation during the mission and catalogue production.

The following contains an overview of the data analysis, illustrated in Figure 1.2, as it was actually carried out. It is, however, worth recalling briefly how the concepts of the data analysis changed considerably from the first ideas in 1981 through the studies before launch and the practical experience with real observations.

The first idea was already based on detection of a stellar transit over a group of four slits, and this feature was maintained throughout. The usefulness of an input catalogue for the Tycho data reduction was briefly discussed by Høg, Jaschek & Lindegren (1982), but no uniform catalogue with more than 400 000 stars existed at that time. In the summer of 1982 an unexpected possibility appeared when the plan for the Guide Star Catalog (GSC) of 20 million stars for the Hubble Space Telescope became known. Enormous savings in computational efforts would be made if the mapping of the detections could be limited to very small areas centred on the positions of the brightest 1 or 2 million GSC stars. This idea implied that the Tycho Catalogue would then not be truly unbiased in terms of the stellar content, but this was not considered too serious a handicap. The idea of a Tycho Input Catalogue based on the Guide Star Catalog was quickly accepted.

The following time was busy with the design of the data analysis for the main Hipparcos mission, but in 1984 the detection of star transits on the star mapper was studied by Høg (1985) and the quality of various estimators for the detection was discussed by Yoshizawa *et al.* (1985). In 1985 the concept of mapping in a small area was presented by Grewing & Høg (1986). Numerous meetings of the Tycho participants helped develop the concepts. Simulations of the processes were made and described in internal technical reports. Internal Tycho reports reached the total number of 265 in 1995, not including a thousand short messages by electronic mail. The development of ideas up to the time of launch is also recorded in Høg (1985), and in Perryman *et al.* (1989, Vol. III, Sections 10 and 11).

The first real photon counts from the satellite revealed that three problems had not obtained an optimal solution before launch: (1) determination of the background level; (2) suppression of side lobes generated by the four slits; and (3) suppression of narrow spikes caused by cosmic events. The solutions were found and implemented by A. Wicenec in early 1990. This was reported in Høg & Wicenec (1991) with the other good news that the stellar count rates were 20 per cent higher than predicted, the typical background was slightly lower than expected, and the effect of the background noise was decreased by the new determination method. This implied that a million stars could perhaps be detected, in spite of the 50 per cent loss of effective observing time due to passage through the van Allen belts and at perigee. This is indeed the number of stars finally included in the Tycho Catalogue. The astrometric accuracy of 0.03 arcsec predicted in 1982 for stars of $B = 10$ mag, or $V = 9.3$ mag, is obtained for stars one magnitude fainter.

The apparent complexity of the Tycho data processing results from three main features: (i) the large number of faint stars with poor *a priori* positions to ± 1 arcsec (source confusion in the photon counts); (ii) the possibility of the transit arising from either field of view and from different slit systems; (iii) the relatively poor early knowledge of the satellite attitude of ± 1 arcsec.

These conditions lead to an iterative data processing approach, and as a result the raw photon counts from the star mapper underwent a sequence of processing steps. Firstly, the ‘detection’ process was used to detect slit transits above a certain signal-to-noise threshold, and to estimate the epoch, amplitude and background associated with each such transit. Each transit was identified or associated with a star by means of a series of processes explained below: prediction, recognition and identification. The ‘Identified Transits’ (IT in Figure 1.2) were finally analyzed to yield the astrometric results. The photometric results were produced by means of the identified transits and a data set of ‘All Transits’ (AT in Figure 1.2) containing the information on how close each transit is to the star defined by the astrometric processing.

The astrometric and photometric results were merged into the main Tycho Catalogue, containing mean values for each star and some external data, e.g. the identification numbers of stars in the Hipparcos Catalogue.

1.4. Relevant Properties of the Mission and the Star Mapper

The Hipparcos satellite observed from an elliptical orbit with the apogee at the geostationary distance as a result of the apogee boost motor failure. The spin axis pointed at an angle of 43° from the Sun, and moved with nearly constant angular velocity around the Sun 6 times per year in the so-called revolving scanning mode. The spin rate was 11.25 revolutions per day or 168.75 arcsec per second, with variations up to 1 per cent. With a sampling frequency of 600 Hz for the star mapper the stars moved about 0.281 arcsec/sample. Payload characteristics are given in Table 1.1. Chapters 2, 3, 5, 7, 9, 10 and 14 of Volume 2 contain further information on the star mapper.

Calibration of the star mapper properties was obtained from a combination of laboratory measurements and in-flight calibrations based on the routine star observations; no special observations were performed for the purpose of calibration alone. The slits of the modulating grid have been manufactured by electron beam scanning thus ensuring utmost accuracy, (see the grid specifications in Volume 2, Table 2.6), so that star observations were sufficient to provide the final high accuracy. Some of the calibration parameters varied with time during the mission, e.g. due to changes of the telescope focal length and the orientation of the grid in the telescope.

The single-slit response functions, giving the light curve as a star crosses a slit, were obtained from star observations and are given in Section 1.5. Such functions were used in every signal amplitude estimation of the transit of a star over a group of four slits (see Section 4.4).

The spectral transmission curves are discussed in Section 1.5. The slits did not have ideally constant width along their length and the optics were not ideally transparent. The photometric sensitivity therefore had to be calibrated by means of star observations as described in Chapter 8.

The positions of the slits in the focal plane were known beforehand so that the time of transit for stars with known positions could be predicted by means of the satellite attitude. For highest precision the positions of the slits in the focal plane and their deviation from being ideally straight had to be calibrated by the astrometric star observations. This so-called geometric calibration is described in Section 7.3.

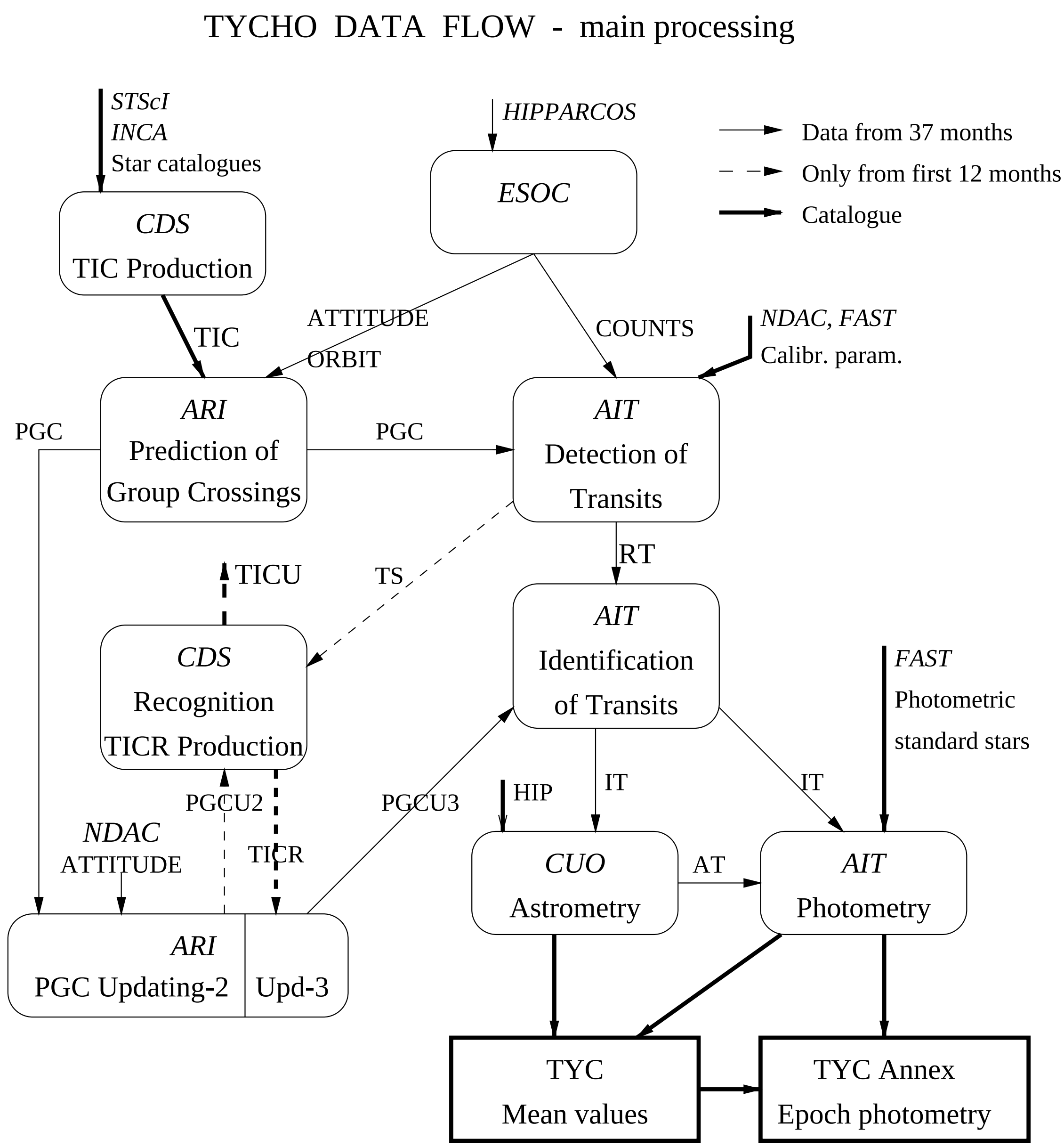

Figure 1.2. *The data flow of Tycho main mass processing. Further explanation is given throughout these chapters on Tycho. A more complete representation of the data flow and processes and their distribution on the participating institutes is given in Figure 12.1. The main institutes, in italics, are situated in: Darmstadt (ESOC), Strasbourg (CDS), Heidelberg (ARI), Tübingen (AIT) and Copenhagen (CUO). Abbreviations for data are: TIC = Tycho Input Catalogue, TICR = TIC Revision; the output catalogues are HIP = Hipparcos Catalogue and TYC = Tycho Catalogue; PGC = Predicted Group Crossing, PGCU = PGC Updating, RT = Raw Transit, IT = Identified Transit, TS = Transit Summary, AT = All Transits.*

Table 1.1. Hipparcos and Tycho payload characteristics from Volume 2, Table 2.1.

Optics:	Telescope configuration	All-reflective Schmidt
	Field of view	$0\overset{\circ}{.}9 \times 0\overset{\circ}{.}9$
	Separation between fields	58°
	Diameter of primary mirror	290 mm
	Focal length	1400 mm
	Scale at focal surface	6.8μm per arcsec
	Mirror surface accuracy	$\lambda/60$ rms (at $\lambda = 550$ nm)
Primary Detection System:	Modulating grid	2688 slits
	Slit period	1.208 arcsec (8.2μm)
	Detector	Image dissector tube
	Photocathode	S20
	Scale at photocathode	3.0μm per arcsec
	Sensitive field of view	38 arcsec diameter
	Spectral range	375–750 nm
	Sampling frequency	1200 Hz
Star Mapper (Tycho) System:	Modulating grid	4 slits perpendicular to scan
		4 slits at ±45° inclination
	Detectors	Photomultiplier tubes
	Photocathode	Bi-alkali
	Spectral range (B_T)	$\lambda_{\rm eff} = 430$ nm, $\Delta\lambda = 90$ nm
	Spectral range (V_T)	$\lambda_{\rm eff} = 530$ nm, $\Delta\lambda = 100$ nm
	Sampling frequency	600 Hz

1.5. Calibration Inputs

Single-Slit Response Functions

Figures 1.3(a) and 1.3(b) show response functions for the inclined slits and illustrate the significant difference between the preceding field of view and the following field for these slits. Such a difference does not exist for the vertical slits as appears from Figure 1.3(c).

The inclined slits, but not the vertical, show a considerable asymmetry for the preceding field: For $z < 0$ shown in Figure 1.3(a) the trailing side, i.e. the side with larger sample number, is higher than the leading side. This is reversed for $z > 0$. This phenomenon would be observed if the stellar image in the preceding field is accompanied by a fainter 'ghost' image at about 1 arcsec smaller z-value. It is noted that the direction of the z-axis is defined in Figure 1.1, in accordance with Equations 1.15 and 1.16 in Volume III of Perryman *et al.*(1989) and Figures 2.7.4 and 2.7.6 of Volume 1 (Perryman *et al.* 1989).

All functions in the figures are for the B_T channel and $z < 0$. The functions for V_T are essentially identical. In practice 16 combinations of vertical/inclined, preceding/following, B_T/V_T, and $z < 0$ / > 0 were determined and used in the photometric signal estimation.

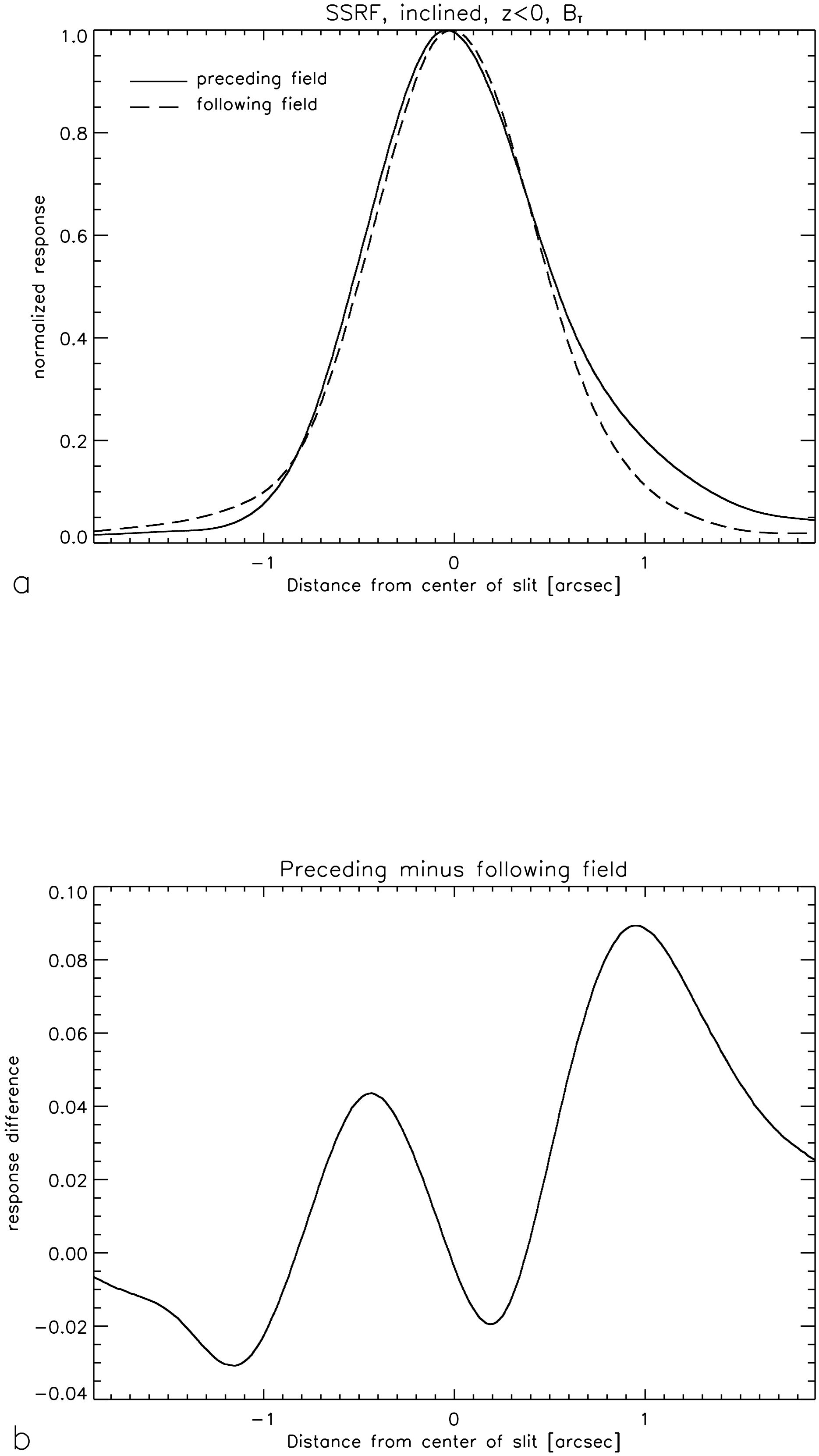

Figure 1.3(a,b). *Slit response functions for inclined slits: (a) preceding and following fields, (b) the difference. The abscissa corresponds to increasing sample number.*

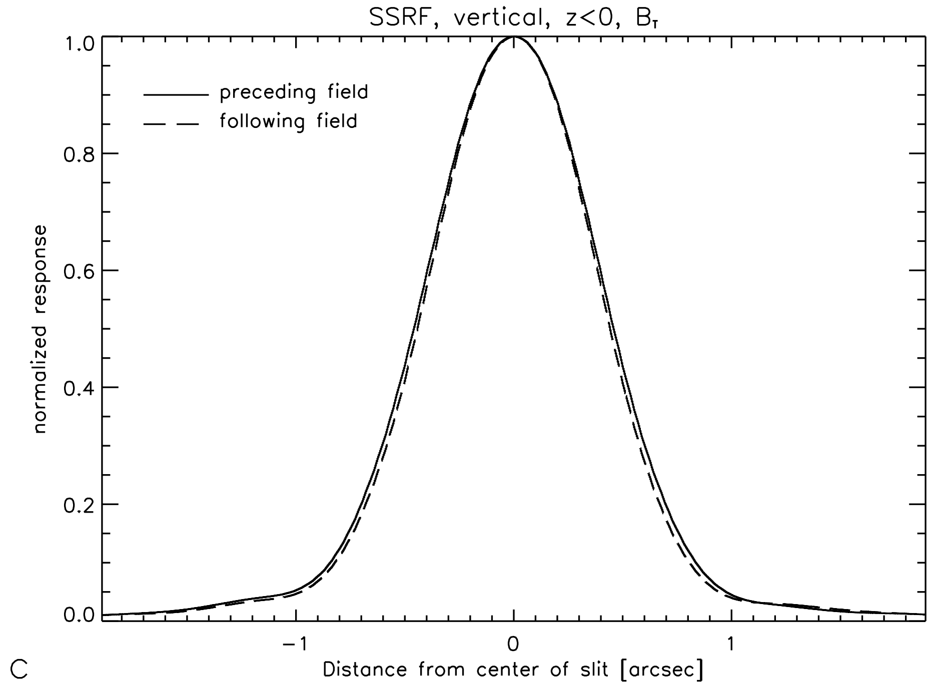

Figure 1.3(c). *Slit response functions for vertical slits.*

Preliminary Payload Geometry Calibration

Tycho reductions started using an on-ground star mapper geometry provided by ESA. It was implemented in the form of a calibration file provided by FAST. Due to the strong rotation of the grid in the focal plane, this had very soon to be replaced by an updated version, which was then used for the initial steps of Tycho data reductions throughout the mission (see Section 4.1).

For the iteration steps, however, calibration files from NDAC were used, for reasons explained in Chapter 6. The NDAC calibration files were based on the on-ground calibration of the so-called 'medium-scale irregularities' provided by ESA (Figure 1.4), complemented by 11 low-order distortion terms derived by NDAC from in-orbit data. Both the medium-scale irregularities and the distortion terms were recalibrated in the Tycho astrometry processing (Chapter 7).

The on-ground data described the actual shape of the star mapper slits quite well. The maximum value of the medium-scale irregularities in Figure 1.4 is about 180 mas; the maximum value of the Tycho corrections is only about 10 mas, see Figure 7.4.

Spectral Response and Photometric Standard Stars

Spectral transmission curves from laboratory measurements are given in Tables 2.3, 2.4 and Figure 2.19 of Volume 2. The B_T and V_T magnitudes in the Tycho passbands for available photometric standard stars were derived before launch by M. Grenon corresponding to these transmission values. It is noted that the transmissions were not otherwise used in the Tycho data reduction. More accurate spectral passbands for B_T and V_T were derived after launch from observations as given in Volume 1, Table 1.3.1

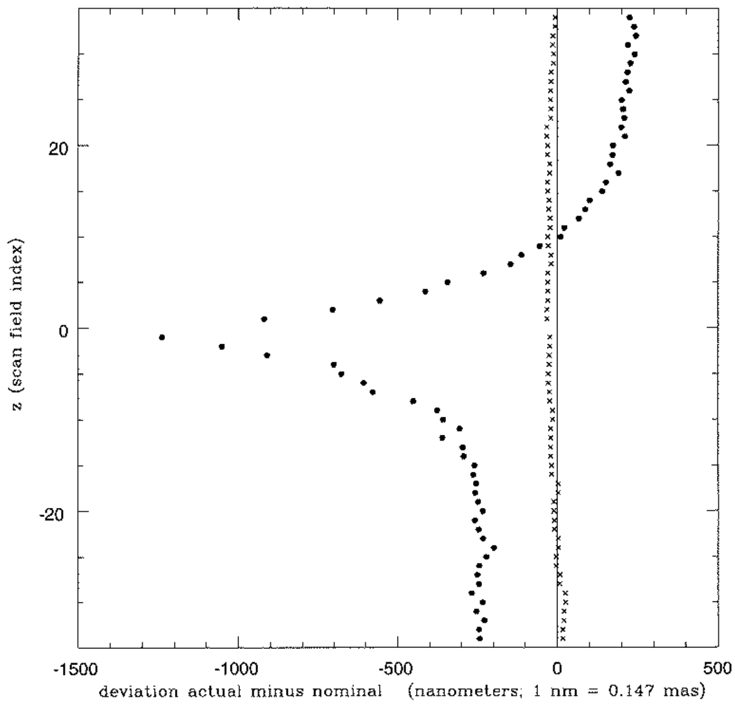

Figure 1.4. *On-ground calibration of the medium-scale irregularities of the star mapper grid. The electron beam etching of the star mapper grid was done in 68 small segments called 'scan fields', each having a size of about 0.6 arcmin perpendicular to the scanning direction. The figure shows the mean displacement of the actual slits in the direction of the scanning motion relative to their nominal location on the grid substrate, for each of the scan fields. Crosses refer to the vertical slits, filled hexagons to the inclined slits. The maximum value of –1239 nm (at the tip of the lower branch of the inclined slits) corresponds to 182 mas at the focal length of Hipparcos. The vertical scale in the figure represents the numbering of the scan fields (–34 to –1, and +1 to +34).*

and Figure 1.3.1. They were inferred by M. Grenon from Tycho observations of the photometric standard stars. The redetermination of the spectral passbands resulted in a redefinition of the standard star magnitudes, as described in Chapters 8 and 13.

1.6. Detection and De-Censoring

A part of Section 2.2 of Volume 1, related to the Tycho data reduction, is repeated here in slightly modified form. It introduces some main concepts and methods, thus complementing the more detailed description in Chapter 2 of the various work tasks.

Transits, detections, measurements: In the terminology of the Hipparcos Catalogue, a star 'transit' is defined as a crossing of the star across the main modulating grid (2688 slits covering a field of view of approximately $0\overset{\circ}{.}9 \times 0\overset{\circ}{.}9$). In the terminology of the Tycho Catalogue, a 'transit' refers to the crossing of the star across a star mapper slit system (either of a set of four vertical or inclined slits of 40 arcmin length, located at the edge of the main field of view, and used primarily for the satellite real-time attitude determination). Such a transit is defined irrespective of whether or not such a crossing yields 'useful' astrometric and/or photometric information. The transit yields useful astrometric and/or photometric information when the star is not too faint, when the background was below a certain limit, when an accurate attitude determination was available, and when the observations were not perturbed by nearby bright stars.

All relevant transits related to a given star have been combined to provide the astrometric data and the summary photometric data contained in the main Tycho Catalogue, and individual transit records (providing 'epoch photometry') are contained in the Tycho Epoch Photometry Annex. The summary photometric data provide median magnitudes for bright stars and 'de-censored mean magnitudes' for fainter stars, and a set of parameters and flags giving an overview of the variability. The Tycho Epoch Photometry Annex includes details of each transit including background, observation epoch, and related quantities and flags.

In practice, the detection process giving a signal amplitude and a transit time was carried out on a signal where the photon counts in the B_T and V_T channels had been added, forming the so-called T channel. The term 'detected transit' is used to refer to a transit containing a significant signal belonging to the relevant star, and this signal itself is called a detection. When a signal was detected above a signal-to-noise ratio of 1.5 in the T channel an estimation (or measurement) of the signal amplitude was carried out in the B_T and V_T channels separately whenever possible. If no such measurement was available, a flag (see Table 2.6.2 of Volume 1) indicates that the magnitude could not be measured in one or other of the separate channels.

Valid and invalid transits for photometry: Transits were used for Tycho (mean value) photometry irrespective of whether or not the object was actually detected in the predicted 'transit interval' of a few arcsec length for the corresponding slit group—the condition for using the transit being simply that the relevant data interval was considered to be 'valid'. Such a transit interval could contain several detections (either real detections due to the predicted star or to another star, or false detections due simply to photon noise) or it could contain no detection at all.

Certain transit intervals were considered as 'invalid', and subsequently excluded from use in Tycho photometry, for a variety of reasons:

(a) if the satellite attitude was poorly known, or if (attitude-control) jet firings were affecting the satellite attitude estimation at the moment of the observations;

(b) if the detector background was high, for example as a result of a passage of the satellite through the van Allen radiation belts—a higher background was acceptable for astrometry than for photometry;

(c) because the star crossed the star mapper slit system too close to the end of the slit, or to the 90° angle of the inclined slits—in such cases, attitude uncertainties may have made it infeasible to distinguish between 'uncaptured' transits, and transits where the signal was below the detectability threshold.

Non-detections and de-censored magnitudes: A valid transit interval was classified as 'non-detected' or 'censored' if it contained no detection, in the T channel, close enough to the predicted transit time for the relevant star. The criterion for rejection was that all residuals of detections in the astrometric adjustment of the transit interval were larger than given limits.

Limits used in astrometry for the rejection of detections were $|\Delta u| > 1.0$ arcsec or $|\Delta u| > 3\sigma_u$, where Δu is the difference between the observed and computed transit times (converted to an angular distance using the instantaneous satellite scan speed across the slit group), and σ_u is the standard error of Δu. A single limit was used in the de-censoring analysis, $|\Delta u| > 0.6$ arcsec. Since transit detection was based on preliminary predicted transit times, which were sometimes in error by a large amount, the real transit occasionally occurred outside the predicted transit interval. Such detected transits were not assigned to the appropriate star and were thus lost, even when the improved transit times were introduced at a later stage. As a consequence, non-detections were occasionally associated even with bright stars. This problem was accommodated within the mathematical model for the de-censoring analysis by assuming that there was a probability of 6 per cent that a predicted Tycho star transit resulted in a non-detection even for a bright star. This is referred to as the assumption of 6 per cent 'spurious non-detections', and users of the Tycho epoch photometry should be aware of this deficiency. Photometric standard star observations were used for checking the validity of the de-censoring analysis and for correcting final small biases, as described in further detail in Chapter 9.

The use of non-detected transits has two reasons. First, because detectability depends on the signal-to-noise ratio of a given transit, mean or median magnitudes have not simply been constructed from the detected transits—rather, a 'de-censored mean magnitude' in B_T and V_T was constructed, using model-based inferred magnitudes in place of transits which were either not detected in the T-channel, or detected but not measured in the B_T or V_T channels. All valid transits were thus taken into account, whether detected or not (see Chapter 9 for details). Second, non-detected transits may be relevant in variability studies, where it may be important to identify whether a photometric data point is absent because the object's magnitude fell below the threshold at that epoch, or simply because no data were acquired at that epoch. But a non-detection is not always an indication that the star was too faint to be detected due to the 6 per cent spurious non-detections described above.

For bright stars with $B_T \leq 8.5$ mag and $V_T \leq 8.0$ mag a median magnitude was derived from the measured signal in the B_T and V_T channels respectively. This median magnitude is equivalent, within 0.005 mag, to a de-censored mean magnitude because bright stars resulted in very few non-detections. The median magnitude was adopted for bright stars since the median could also be constructed for variable stars, while the de-censoring analysis was based on the assumption that the star is constant.

Parasites: Some transits have been flagged as disturbed by a 'parasite', i.e. a fairly bright star which was close in transit time to that of the star considered, according to calculations based on the stars in the Tycho Input Catalogue Revision, described in further detail in Chapter 7. Such transits were rejected in the astrometric adjustment, and (partly) in the de-censoring analysis since these analyses were sensitive to outlying observations. They are however included and properly flagged in the Tycho Epoch Photometry Annex if none of the conditions (a–c) discussed under 'Valid and Invalid Transits for Photometry' also caused a rejection in the astrometric adjustment. The flag was not used in the construction of median magnitudes since the median is only weakly affected by outliers, and since such transits in fact often do not suffer from any significant photometric disturbance.

Number of transits: The number of valid transits for a given Tycho Catalogue entry, including the non-detections, is denoted by N_{transits}. The Tycho Epoch Photometry Annex contains this number of transits for the selected stars (see Section 16.4 for details).

The final astrometric and photometric results for each star have typically been constructed from different numbers of star transits in each case—individual transits having been used, or rejected, for the final catalogue for a variety of reasons. The number of transits used in the astrometric adjustment, N_{astrom}, is given in the main Tycho Catalogue. It excludes non-detections and detections affected by parasites.

The number of transits used in Tycho mean value photometry, N_{photom}, is given in the main Tycho Catalogue. N_{astrom} and N_{photom} are about 25 per cent less than N_{transits}. The number of valid transits was slightly lower for photometry than for astrometry because a higher background was acceptable in astrometry. The process of photometric de-censoring used both detections which were unaffected by parasites, and the non-detections. Therefore, for stars brighter than $V_T \simeq 10$ mag with few non-detections the ratio $N_{\text{photom}}/N_{\text{astrom}} \simeq 0.80$, while for fainter stars with many non-detections the ratio may be as large as 1.5. For median magnitudes only detections were used, including those affected by parasites, since these were too few to have any significant effect on the median.

E. Høg