3. THE TYCHO INPUT CATALOGUE

A specific Tycho Input Catalogue was constructed, before the launch, as an essential preparatory task for the Tycho data reduction. This catalogue of three million stars brighter than V = 12.1 mag resulted from the cross-matching of a subset of the Hubble Space Telescope Guide Star Catalog with the Hipparcos INCA Data Base. Estimated external errors of the Tycho Input Catalogue positions, at the epoch of the Hipparcos satellite observations, were in the range 1 to 2 arcsec. This was sufficient to allow the Hipparcos star mapper transits to be identified at the epochs when a 'Tycho star' was predicted to be transitting the star mapper slits.

3.1. Introduction

The strategy for the Tycho data analysis was based on a Tycho Input Catalogue (Egret *et al.* 1989; Egret *et al.* 1992) which was used to identify the detections of star transits with real stars, a process complicated by the fact that the photon counts of a given detection may be due to a star anywhere on the 40 arcmin long inclined or vertical star mapper slits, in either of the two fields of view. For this purpose, the Tycho Input Catalogue was thus constructed to be complete to the limit of detection of the instrument, and even beyond, in order to take into account the uncertainty on the stellar magnitudes.

The reasons for using a Tycho Input Catalogue, and not reducing the Tycho records in a pure survey mode, have been discussed by Høg (1985). The main advantages, besides the savings in data processing, are an easier identification of the detected transits with real stars, and the possibility to work to a fainter limiting magnitude.

Producing such a complete catalogue was made possible by using as a basis the Hubble Space Telescope Guide Star Catalog, a survey of about 20 million objects, complete at the fainter magnitude limit to some 13–15 mag, depending on galactic latitude. At the bright end, the catalogue was completed for the stars missing in the Guide Star Catalog (roughly those brighter than 7 mag) by merging with the Hipparcos INCA Data Base, with stars common to both data sets being identified and flagged accordingly.

The Tycho Input Catalogue contains the positions of 3 154 204 objects, to a magnitude limit of $V = 12.1$ mag or $B = 12.8$ mag.

The present chapter concentrates on a description of the production of the Tycho Input Catalogue, followed by a description of its contents and format.

3.2. The Production of the Tycho Input Catalogue

The Guide Star Catalog

The primary source for constructing the Tycho Input Catalogue was the Guide Star Catalog, compiled at the Hubble Space Telescope Science Institute for the needs of the Hubble Space Telescope. A detailed description is given in a series of three papers, by Lasker *et al.* 1990; Russell *et al.* 1990; Jenkner *et al.* 1990.

The Guide Star Catalog (the version used is GSC 1.0, published in June 1989, and distributed as a set of two CD–ROMs) contains 25 126 027 entries for 18 819 291 objects in the 7–16 mag range, of which more than 15 million are classified as stars. The star positions were obtained by scanning some 1500 Schmidt plates covering the whole sky at epochs around 1980. The expected accuracy is 1 arcsec rms for the positions (3 arcsec in the worst case, near the plate edges) and 0.7 mag for the magnitudes. Internal errors are about 0.25 arcsec and 0.15 mag, respectively, within an individual plate.

As a result of an agreement between the Space Telescope Science Institute and the Tycho project, the Centre de Données astronomiques de Strasbourg (CDS) was given early access to the first version of the Guide Star Catalog in order to be able to produce the Tycho Input Catalogue in time. This access, prior to publication, consisted of the delivery of a subset of the Guide Star Catalog, prepared at the Space Telescope Science Institute, limited to 13 mag, and containing 7 026 931 entries for 5 907 922 stars.

The INCA Data Base

The INCA Data Base (215 000 stars of interest for the Hipparcos mission; see Turon *et al.* 1989, Gómez *et al.* 1989) was used to complete the Guide Star Catalog towards the bright end, and to improve the positions and magnitudes, at least for the brightest stars. The INCA Data Base is essentially complete to between $V = 7.3$ and 9.0 mag (depending on galactic latitude, colour index and spectral type). Additional fainter stars, down to $V \simeq 12.5$ mag, were included from all programmes proposed in 1982 for Hipparcos observations.

The INCA Data Base was originally derived from the SIMBAD astronomical data base (Egret *et al.* 1991), but has evolved independently, including new ground-based measurements, new compilations, and many corrections introduced by the Hipparcos Input Catalogue Consortium (Turon *et al.* 1991). The INCA Data Base contains all the bright stars supposed to be absent from the Guide Star Catalog, and a large number of stars of astrometric or astrophysical interest for the Tycho project, such as large proper motion and variable stars (Turon *et al.* 1992).

Early access to the INCA Data Base, in March 1989, prior to publication, was made possible through an agreement with the Hipparcos Input Catalogue Consortium.

Selection of the Tycho Input Catalogue Stars

The first step of the Tycho Input Catalogue production was the selection of the subset of stars observable by Tycho from the catalogue received from the Space Telescope Science Institute. The original plans were to include the 2 million brightest stars of the sky, of which 400 000 to 1 million were expected to be actually detected. It was thus possible to take into account the uncertainty on the magnitude.

In a first approach, the corresponding adopted magnitude limit was $V = 11.7$ mag or $J = 12.4$ mag, according to the magnitudes available in the Guide Star Catalog which are V in the northern hemisphere (Palomar Quick V survey, north of $\delta = +3°$) and J in the southern hemisphere (the letter J refers to the J plates of the ESO/SERC Schmidt survey, giving a photographic passband close to the B filter). The limits in V and J were optimized for a mean colour $B - V = 0.7$ mag.

Later on, an analysis of the first results of the Hipparcos-Tycho mission showed that the actual magnitude limit was fainter than anticipated. It was then decided to extend the Tycho Input Catalogue by adding one million stars up to the new limit of $V \leq 12.1$ mag or $J \leq 12.8$ mag. For this extension no further cross-matching was attempted with the INCA Data Base (there are, in any case, only a small number of stars from the INCA Data Base in this magnitude range).

Although all Guide Star Catalog entries with magnitudes brighter than the limit given above were included, the resulting catalogue is not fully complete to this limit, because of possible misclassifications (see below), and because the new list is getting close to the effective limit of the Guide Star Catalog in some areas, especially for objects with large magnitude uncertainties or extreme colour indices.

Average Positions in the Overlap Regions of the Guide Star Catalog Plates

The Guide Star Catalog was originally produced by merging the scans from individual Schmidt plates, for which there is a small overlap: nominally $0°.4$ in the north and $1°.4$ in the south, for $6°.4 \times 6°.4$ plates. In principle (with exceptions, including some high proper motion stars), each redundant entry in the overlap zones is identified by the same key GSC number.

In the Tycho Input Catalogue, the individual plate positions stored in the Guide Star Catalog were used for computing a mean position. This led to an intermediary catalogue (hereafter called the GSC/Tycho file) of 2 022 607 stars brighter than $J = 12.4$ mag to which the cross-matching described in the following section was applied.

3.3. Cross-Matching the Guide Star Catalog with the INCA Data Base

The cross-matching of Guide Star Catalog stars with an astronomical data base was necessary because the original Guide Star Catalog did not include the brightest stars (which cannot be properly measured on the Schmidt plates) and because for the stars brighter than about $V = 9$ mag, better positional and photometric parameters could be expected from the existing astrometric catalogues than from the Guide Star Catalog

itself, due to the saturated images on the Schmidt plates. Another result of this cross-referencing was the flagging of variable stars and high proper motion stars for which the parameters given in the Guide Star Catalog may have changed at the time of the mission. Other lists or catalogues of astrophysical interest (for example, photometric and astrometric standards, and the Hipparcos Input Catalogue) were also cross-identified.

The use of the INCA Data Base, constructed for the Hipparcos Input Catalogue preparation (some 220 000 stars), rather than the SIMBAD Data Base, was the result of a compromise which made it possible to perform the cross-matching in a limited amount of time. The whole SIMBAD Data Base, containing 600 000 stars at that time, was not used because that task appeared too ambitious within the tight schedule left after the completion of the Guide Star Catalog (Didelon & Egret 1987; Egret, Didelon & McLean 1988).

An 'INCA/Tycho master file' was produced in April 1990 by extracting the required information from the INCA Data Base. At that time the number of entries in the data base was 214 754. For 10 915 multiple systems within the INCA Data Base, the entries of close components (closer than 10 arcsec) had been merged into one single entry. For all systems with distances between two components larger than 3 arcsec (according to the data base), the individual components were restored. As a result, the total number of entries in the master file increased to 220 352.

It should be noted that the positions included in the INCA Data Base for all multiple systems at that time were still on the FK4 system, not on the J2000 FK5 system of the other catalogue positions (they were transformed to the FK5 before the publication of the Hipparcos Input Catalogue, but too late for inclusion into the Tycho Input Catalogue).

A total of 4547 complementary entries from the Catalogue des Données Astrométriques (CDA, produced at Astronomisches Rechen-Institut, Heidelberg for the Input Catalogue consortium, Jahreiß 1989) were also added to the master file: these comprised all known stars with proper motion larger than 0.15 arcsec/year and not already included in the INCA Data Base.

The Cross-Matching Procedure

The cross-matching between the Guide Star Catalog file and the INCA master file was made through a comparison of celestial positions and magnitudes. When the positions of objects from both files matched within an error box corresponding to the internal standard errors, the cross-identification was considered acceptable. In case a better match with another INCA entry was found later on, an iterative procedure deleted the previous cross-identification. Due to the characteristics of the Tycho data reduction, whenever some doubt arose about an entry, it was preferable to keep a spurious entry (not related to a real star) rather than risk missing a star. False entries were eliminated in the course of the Tycho data reductions.

The cross-identification was always assigned to the closest object, unless there was a better choice for that (the closest) object. An estimated error box was derived from the standard errors given in the Guide Star Catalog and the INCA Data Base (hereafter

abbreviated as G and I) for positions and magnitudes, with a minimum value of 1 arcsec and 1 mag, respectively:

$$E_{\text{pos}} = \max (1 \text{ arcsec}, \sigma_{\text{pos}_G}, \sigma_{\text{pos}_I}) \qquad [3.1a]$$

$$E_{\text{mag}} = \max (1 \text{ mag}, \sigma_{\text{mag}_G}, \sigma_{\text{mag}_I}) \qquad [3.1b]$$

When the distances were smaller than three times the estimated errors:

$$|\text{pos}_G - \text{pos}_I| < 3E_{\text{pos}} \; ; \; |\text{mag}_G - \text{mag}_I| < 3E_{\text{mag}} \qquad [3.2]$$

the cross-identification was considered acceptable. When the distance was between three and four times the error, the cross-identification was still accepted, but the entries were flagged accordingly.

For stars with large proper motion the comparison procedure included the computation of the position to a common epoch: the mean epoch of the Guide Star Catalog plates (i.e. 1983 for stars with $\delta > -17.0°$ and 1975 for stars with $\delta < -17.0°$). For the identified stars, the position recorded in the Tycho Input Catalogue is the position at epoch 1990 (and equinox J2000).

The non-cross-matched INCA or CDA entries (generally bright stars absent from the Guide Star Catalog, or components of multiple systems, see below) were added to the Tycho Input Catalogue, when their magnitude was brighter than the adopted limit of $B = 12.4$ mag. In the operational version of the Tycho Input Catalogue the positions recorded for the non-cross-matched stars with proper motions larger than 0.15 arcsec/year were inadvertantly given at the Guide Star Catalog plate mean epoch instead of at epoch 1990. This error was corrected as part of the reprocessing procedure described in Chapter 10, and in the published version of the Tycho Input Catalogue (Egret *et al.* 1992).

The Cross-Matching Results

A satisfactory cross-matching was found for 198 360 out of the original 224 899 entries in the INCA master file (88 per cent). After omission of the stars actually fainter than the adopted $B = 12.4$ mag limit, the remaining 19 264 entries constituted the additional INCA/CDA stars to be added to the Guide Star Catalog stars.

The non-cross-matched stars can be roughly divided into three subsets. Approximately 8000 stars are the bright stars actually missing in the Guide Star Catalog because they generated large images on the Schmidt plates. This includes all the stars brighter than $V = 6.0$ mag and an additional fraction of stars between 6–8 mag. Another large subset (about 6250) comprises the components of multiple systems not recorded in the Guide Star Catalog, in general because a faint component was masked by a bright primary star. The third part (about 5000 objects) contains stars missed on the Guide Star Catalog plates (for instance stars close to an extended object) and also possible errors or uncertainties in the INCA master file (this is especially true for the stars not selected for the Hipparcos Input Catalogue, for which positional data possibly remained inaccurate).

Flagging of Specific Objects

The cross-identification was also useful for flagging 'peculiar objects', namely:
- known proper-motion stars;
- known high-proper-motion stars (larger than 0.2 arcsec/year);

- stars with known parallax;

- known variable stars;

- known multiple systems as described below;

- non-stellar images in the Guide Star Catalog (this flag indicates a doubtful classification); misclassification is estimated to be about 1 per cent in uncrowded fields and about 3 per cent in crowded ones (Lasker *et al.* 1990).

Of course, these flags could only be provided when the 'peculiarity' was known to INCA; this was generally not the case for the faintest stars. Some specific lists were also flagged within the Tycho Input Catalogue, namely:

- reference stars for astrometry (FK5, IRS);

- standard stars for photometry (from multicolour photometric systems);

- monitor stars (to be used during the data reduction for monitoring the processing);

- stars from the Hipparcos Input Catalogue (about 120 000 stars);

- INCA stars (when additional information is available for these objects from INCA).

Additional flags concern discrepancies found while cross-matching the Guide Star Catalog and the INCA Data Base:

- position discrepancy (larger than 3σ);

- magnitude discrepancy (larger than 3σ);

- position and magnitude discrepancy.

As a result of the cross-identification with the INCA Data Base, the following actions were taken:

- bright objects from the INCA Data Base not included in the Guide Star Catalog were added to the Tycho Input Catalogue; this list of additional stars was provided to the Space Telescope Science Institute for operational use (the stars brighter than 7.5 mag have been included in GSC 1.1 and later versions);

- bright objects from the Guide Star Catalog not found in the INCA Data Base were checked and kept when no error was detected.

Finally, an attempt was made to flag double stars according to separation and data origin. The resulting flags were the following:

- close pair with separation less than 3 arcsec in the INCA Data Base;

- component of pair in the INCA Data Base with separation less than 10 arcsec;

- double or multiple system from the Catalogue of Components of Double and Multiple Stars (CCDM), with any separation (see Dommanget 1989b);

- component of Tycho Input Catalogue pair whose separation is less than 20 arcsec.

It should be understood that this task remained an 'automatic' flagging (through computer software) and was certainly not an extensive study of multiple systems which, in any case, was not necessary as far as the Tycho Input Catalogue was concerned. This was made from existing information in the INCA Data Base and CCDM Catalogue concerning double stars, and for the last flag, through an analysis of the neighbourhood of the Tycho Input Catalogue stars.

3.4. The Contents of the Tycho Input Catalogue

The Tycho Input Catalogue contains the items listed in Tables 3.1 and 3.2: identification; J2000 coordinates, mean errors; magnitudes, mean errors; flags.

The Tycho Input Catalogue Identification

This identification is the common key of all data streams in the Tycho data reduction. It is also used in the auxiliary files. The original Guide Star Catalog is organised into regions so that the Guide Star Catalog identification for an object consists of the region number and a sequential number within the region. To determine the region limits, the sky is divided into approximately square areas of 50 square degrees which are subdivided, depending on the star density, into 4, 9, 16 or 25 regions. The total number of regions is 9537.

The identification system adopted for the Tycho Input Catalogue keeps the Guide Star Catalog identification described above. There are gaps in the running numbers because objects fainter than the magnitude limit adopted for Tycho are omitted.

In the operational version, additional stars (e.g. bright stars absent from the Guide Star Catalog) were numbered with a region number corresponding to the Guide Star Catalog region in which the star appears and a running number starting from 10001. This was later replaced by a running number provided by the GSC team, and consistent with their scheme. Only this improved numbering scheme is used in the final Tycho Catalogue.

Solar system objects were given a dummy region number equal to zero.

The Coordinates

Equatorial coordinates are given at equinox J2000 (both in the Guide Star Catalog and the Tycho Input Catalogue). Positions coming from the INCA Data Base are corrected to the epoch 1990 by means of proper motions. The epoch of a position from the Guide Star Catalog is generally (by definition) that of the Schmidt plates used for the Catalog, i.e. around 1980. The epoch difference is significant for the high-proper-motion stars (for which a 10- or 15-year motion is larger than the confidence interval of 2 or 3 arcsec) and was handled by adding to the Guide Star Catalog position the proper motion, when known. The estimated error on position given in the Guide Star Catalog (Russell *et al.* 1990) was kept, but sometimes updated from the INCA Data Base.

B and *V* Magnitudes

The *V* magnitude, and its estimated error, are from the Guide Star Catalog (or INCA) in the northern hemisphere, or from INCA or (most frequently) unknown in the south. The *B* magnitude, and its estimated error, are from the Guide Star Catalog (or INCA) in the southern hemisphere, or from INCA or (most frequently) unknown in the north. The source (Guide Star Catalog or INCA) is given by a flag.

Table 3.1. The Tycho Input Catalogue format (binary). The record length is 28 bytes.

Name	Offset	Length	Unit	Range	Short Description
TICID1	0	2	–	0–9537	Guide Star Catalog region number
TICID2	2	2	–	1–32767	Running number in region
TICRA	4	4	0.01 arcsec	0–$1296{\times}10^5$	Right ascension J2000, epoch 1990
TICSPD	8	4	0.01 arcsec	0–$648{\times}10^5$	South polar distance ($\delta + 90°$)
TICPOSE	12	2	0.01 arcsec	0–32767	Error on position
COMPI	14	1	–	–	Reserved for catalogue revision
–	15	1	–	–	Spare
TICBE	16	1	0.01 mag	0–255	Error on B mag (0 if absent)
TICB	17	1	0.05 mag	0–255	B magnitude (0 if absent)
TICVE	18	1	0.01 mag	0–255	Error on V mag (0 if absent)
TICV	19	1	0.05 mag	0–255	V magnitude (0 if absent)
TICFL	20	4	–	–	31 one-bit flags (see Table 3.3)
TICDRA	24	2	–	–	Reserved for catalogue revision
TICDDEC	26	2	–	–	Reserved for catalogue revision

Table 3.2. The Tycho Input Catalogue format (ASCII). The record length is 80 bytes.

Name	Bytes	Format	Unit	Range	Short Description
TICID1	1-4	I4	–	0–9537	Guide Star Catalog region number
TICID2	6-10	I5	–	1–32767	Running number in region
TICRA	11-20	I10	0.01 arcsec	0–$1296{\times}10^5$	Right ascension J2000, epoch 1990
TICSPD	21-29	I9	0.01 arcsec	0–$648{\times}10^5$	South polar distance ($\delta + 90°$)
TICPOSE	31-34	I4	0.01 arcsec	0–32767	Error on position
TICBE	36-38	I3	0.01 mag	0–255	Error on B mag (0 if absent)
TICB	39-43	I5	0.01 mag	0–255	B magnitude (0 if absent)
TICVE	45-47	I3	0.01 mag	0–255	Error on V mag (0 if absent)
TICV	48-52	I5	0.01 mag	0–255	V magnitude (0 if absent)
TICFL	54-80	27I1	–	–	Flags 1 to 27 (see Table 3.3)

Table 3.3. Tycho Input Catalogue flags. For each flag, the number of entries for which the flag value is set to 1 is given within parentheses.

F00	Zero (most significant bit)
F01	FK5 star (3564)
F02	IRS star (38 775)
F03	Standard star for photometry (21 559)
F04	Random set of Tycho Input Catalogue stars (15 776)
F05	Problem stars ('sick objects'), selected by flags (9340)
F06	Signature stars, individually selected (707)
F07	Stars with good quality photometry in auxiliary file (42 103)
F08	Monitor stars (logical OR of F01 to F06) (82 012)
F09	Discrepancy while attempting Guide Star Catalog/INCA cross-identification (2468)
F10	Bright stars: $V < 11.3$ mag or $B < 12.0$ mag (1 068 730)
F11	Magnitude discrepancy in Guide Star Catalog/INCA cross-identification (116)
F12	INCA or CDA star without Guide Star Catalog counterpart (19 320)
F13	Source of position (0=Guide Star Catalog, 1=INCA) (211 526)
F14	Source of B magnitude (0=Guide Star Catalog, 1=INCA) (204 122)
F15	Source of V magnitude (0=Guide Star Catalog, 1=INCA) (212 251)
F16	Non-stellar Guide Star Catalog image (classification = unknown) (480 709)
F17	Component of Tycho Input Catalogue pair (there is at least one companion with a separation smaller than 20 arcsec) (48 910)
F18	Close pair with one single entry (usually separation < 3 arcsec) from INCA (9346)
F19	One component of INCA pair (separation < 10 arcsec) (8353)
F20	INCA Data Base star (cross-identification available in auxiliary file) (217 625)
F21	Known proper motion; correction to epoch 1990 applied to the position (193 065)
F22	Known high proper motion (larger than 0.15 arcsec/year) (12 627)
F23	Known parallax (from INCA) (5548)
F24	Known variable (from INCA) (7406)
F25	Known multiple system (any separation) from INCA (30 995)
F26	Hipparcos Input Catalogue star from INCA/IC5 (117 778)
F27	CDA star (Catalogue des Données Astrométriques) (4474)
F28	zero (reserved for TICR)
F29	Additional faint Guide Star Catalog star (1 112 277)
F30	Guide Star Catalog star with a rejected cross-match (5300)
F31	Spare

Flags

The flags associated with the Tycho Input Catalogue are described in Table 3.3. Auxiliary files, described in the next section, are associated with some of these flags.

Additional faint Guide Star Catalog stars (flag 29) have all other flags set to zero, except the following: 4, 8 and 16 which may be 0 or 1. The Tycho Input Catalogue pair flag 17 has not been computed for these stars.

The Auxiliary Files

The general format of the auxiliary files is the following: the key is the Tycho Input Catalogue identification and the record contains the information related to the flag (generally extracted from the INCA Data Base). The following auxiliary files were produced:

- known proper motions (flags 21 and 22);
- photoelectric photometry: B_T and V_T in the Tycho system are computed from observations in multicolour photometric systems (flag 7, and flag 3 for standard stars);
- known double and multiple systems (flag 25);
- known parallaxes (flag 23);
- known variable stars (flag 24);
- Hipparcos Input Catalogue; more precisely 'IC5', the provisional version of the Hipparcos Input Catalogue available at the time of finalisation of the Tycho Input Catalogue (flag 26);
- cross-identification from the INCA Data Base (flag 20);
- signature stars: stellar nebulae, or stars associated with extended regions, specially selected for their expected response; this constitutes a subset of the monitor stars (flag 6).

3.5. The Tycho Input Catalogue Revision

The Tycho Input Catalogue Revision is the intermediate catalogue derived from the first twelve months of satellite observations, as described in Chapter 5. It includes a reduced number of stars (only those definitely detected), additional serendipity stars, and companion stars detected around the Tycho Input Catalogue stars. It also includes a number of false (spurious) stars which were discarded in later steps of the data processing. The revised positions have an accuracy better than 0.15 arcsec rms (Halbwachs *et al.* 1992).

3.6. Publication of the Tycho Input Catalogue

The Tycho Input Catalogue as circulated within the Tycho consortium is stored in compact binary format, convenient for a working file on disk. It was released in 1992 (Egret *et al.* 1992) and made available in electronic form at the Centre de Données astronomiques de Strasbourg and other data centres in 1993.

The additional bright stars ($V < 7.5$ mag) from the INCA Data Base were subsequently included into the Guide Star Catalog for the release GSC 1.1 in 1992. Such entries are designated by the plate identifier +056 in GSC.

When the list of stars observed by Tycho was made available (Halbwachs *et al.* 1994), the related flag for 1 049 971 stars actually observed was added to the distributed version of the Tycho Input Catalogue.

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