10. REPROCESSING OF THE SATELLITE DATA

The reprocessing of the Tycho data remedied some defects of the Tycho Input Catalogue and some defects of the main processing. For this purpose it repeated most processing steps, but for a much smaller number of objects. The use of improved software and of an update of (a part of) the input catalogue were the essential ingredients for the improvement over the main processing. All the raw data from the Tycho instrument were treated a second time, but no prediction updating and no star recognition processes were needed, because good on-ground attitude and a sufficiently precise star catalogue were used from the very start. The photometric and astrometric analysis for the reprocessing was performed independently from that for the main processing. The two separate data sets were then merged into the Tycho Catalogue, as described in Chapter 11.

10.1. Introduction

The main processing of the Tycho raw data was a compromise between the wish to complete an output catalogue within a given (short) time and with the given resources of computing power and man power, while at the same time aiming for an optimum scientific exploitation of the data. Some of the drawbacks on data quality stemming from this compromise were eliminated for some groups of celestial objects by the reprocessing, as described in this chapter. Only after the start of the main mass processing did it become apparent that such a reprocessing for the most badly treated objects would be possible within the time frame and resources of the Tycho data analysis. Also, some of the defects needing improvement were discovered only at that stage. Thus, the reprocessing served a collection of different purposes. A special input catalogue, called Tycho Input Catalogue Update (TICU) was prepared. Its composition, reflecting the various specific purposes of the reprocessing, is described in Section 10.2. It had a total size of 306 766 entries, i.e. less than 10 per cent of the size of the Tycho Input Catalogue.

Special versions of the prediction, detection and transit identification software had to be written for the reprocessing, in order to avoid the prediction updating steps and to speed up and improve detection and transit identification. In contrast, the procedures used in the photometric and astrometric calibrations and reductions for the reprocessing

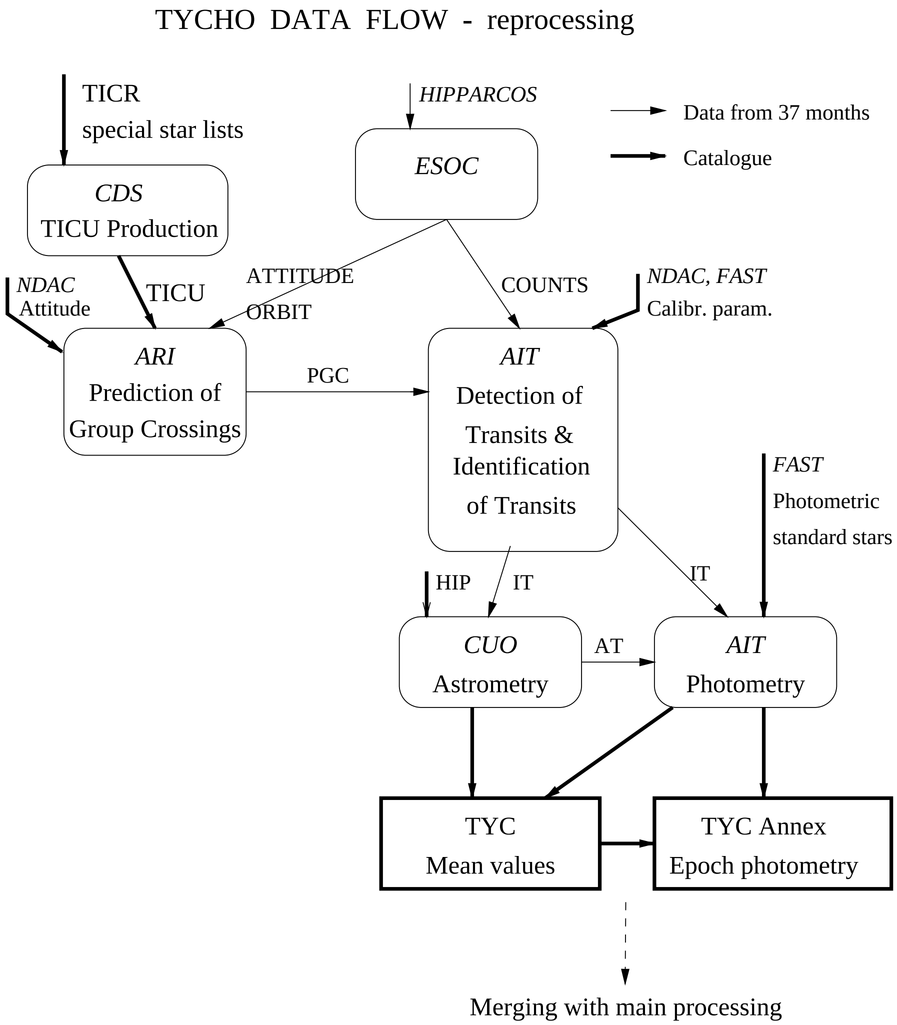

Figure 10.1. *The data flow of the Tycho reprocessing. Explanation is given throughout Chapter 10. The abbreviations for the main institutes and data streams are the same as in Figure 1.2. TICU is the Tycho Input Catalogue Update, described in Section 10.2.*

were the same as in the main processing. A special data stream was created for the solar system objects, which is described in Chapter 15.

The data flow in the Tycho reprocessing is sketched in Figure 10.1. It is simpler than that of the main processing. The individual steps and data streams are described in the following sections.

Originally, it was expected that the reprocessing results would be preferred over those from the main processing for a large fraction of the Tycho Input Catalogue Update objects. But later it was found that the reprocessing had some weaknesses, too. In the end, astrometric results from the reprocessing were included in the Tycho Catalogue for about 9000 stars, and photometric results for about 55 000 stars. This choice, and the reasons for it, are described in Chapter 11.

10.2. The Tycho Input Catalogue Update

The Tycho Input Catalogue Update served the same purpose for the reprocessing as the Tycho Input Catalogue did for the main processing. It contained eight different groups of stars, reflecting the different purposes of the reprocessing. They are described in this subsection. The eight groups of stars partly overlap, so that the sum of their sizes is larger than the total size of the Tycho Input Catalogue Update quoted previously.

Companion Stars

The search for companion stars (Section 5.4) yielded slightly more than 100 000 non-redundant objects which were between 3 and 20 arcsec from their 'parent' Tycho Input Catalogue position. They were all included in the Tycho Input Catalogue Update, because some transits for them might have been lost in the main processing. The reason for this is that transits with signal-to-noise ratios below 1.8 were not searched for beyond 6 arcsec from the Tycho Input Catalogue position (see Section 2.4). Almost all transits with offsets between 6 and 20 arcsec were outside the original Predicted Group Crossing interval, and were lost when the signal-to-noise ratio was below 1.8. In other words, the inclusion of the distant companion stars into the reprocessing improved their detection threshold.

Serendipity Stars

All the 57 933 serendipity stars (see Section 5.5) were included in the Tycho Input Catalogue Update, for the same reason as the distant companion stars. The improvement of the signal-to-noise limit for the accepted transits, from 3.5 to 1.8 in this case, was even more important for these stars than for the companions.

There was a second reason to include the serendipity stars. Prediction is strictly valid at the Tycho Input Catalogue position only. Using the predicted group crossings for the interpretation of transits at other positions meant an implicit extrapolation of the attitude. The limited precision of the scan speed led to a loss of precision with increasing distance from the Tycho Input Catalogue position. Furthermore, no attitude extrapolation at all was possible across attitude control jet firings. This subject, and its consequences for the serendipity search, were already discussed in Section 5.5.

Stars with Duplicate Tycho Input Catalogue Identifications

Due to a trivial error, the Tycho Input Catalogue contained 61 pairs of stars with identical TICID1 and TICID2 (see Table 3.1) identification numbers. These 122 stars could not be treated in the main processing, since their predictions and detections were inseparably mixed in the various Tycho data streams. They were included in the Tycho Input Catalogue Update with new, unambiguous identification numbers.

Stars with High Proper Motions

Another trivial error in the production of the Tycho Input Catalogue led to incorrect input positions for about 2000 stars with high proper motions. Most of them were found by the recognition process in spite of this. But for some of them, a significant improvement could nevertheless be expected from the reprocessing. Thus, a selection of about 350 stars was included into the Tycho Input Catalogue Update, either because the correct position lay far from the Tycho Input Catalogue position, or else because the Tycho Input Catalogue Revision did not contain a good solution at all.

Double Stars

Two groups of stars were included into the Tycho Input Catalogue Update in order to subject them to the special double star treatment described in Chapter 14. The first, containing about 14 000 objects, was selected by cross-identifying the Tycho Input Catalogue Revision with the Catalogue of the Components of Double and Multiple Stars (CCDM, Dommanget 1989a), the Washington Catalogue of Visual Double Stars (WDS, Worley & Douglass 1984) and the catalogue of Couteau (1990). The second, containing roughly 8 000 objects, was a list of stars without previously known duplicity, but which had been discovered (or at least suspected) to be double in the course of the Tycho main processing. Entries for this list arose in the detection of transits, as well as in the astrometry processing. More details are given in Chapter 14.

Standard Stars

The astrometric and photometric standard stars used in the main processing had to be included into the Tycho Input Catalogue Update in order to do the instrument calibrations for the reprocessing in the same way as for the main processing. A separate calibration was necessary because the modifications in the detection of transits (see Section 10.5) necessarily led to differing calibration parameters. In addition, an independent calibration should give confidence in the correctness of the results. The list of standards thus included into the Tycho Input Catalogue Update had about 60 000 entries. Whenever possible, the astrometric data from the Tycho Input Catalogue Revision (but only for close companions) were used instead of the Tycho Input Catalogue data for the standard stars.

Bright Stars

Finally, all Tycho Input Catalogue objects brighter than magnitude 9, but having no counterpart in the previously discussed stellar groups were added to the Tycho Input Catalogue Update. There were two reasons for doing so. First, all bright stars should receive the photometric improvement due to the refined detection and estimation of transits in the reprocessing (see Section 10.5). Second, the bright stars were needed to perform the parasite recording, i.e. the flagging of (potentially) disturbed transits. This set increased the size of the Tycho Input Catalogue Update by about 70 000 objects. All bright Tycho Input Catalogue entries having a close companion counterpart in the Tycho Input Catalogue Revision within 3 arcsec were entered into the Tycho Input Catalogue Update with the improved data from the Tycho Input Catalogue Revision, all others with their original Tycho Input Catalogue data.

Cross-Identification Files

Some of the Tycho Input Catalogue Update entries had to be renumbered, in order to avoid confusion, and in order to accommodate the several companions that occasionally had arisen under the same Tycho Input Catalogue identification number. Cross-identification files between the Tycho Input Catalogue Revision and the Tycho Input Catalogue Update, and between the Tycho Input Catalogue and the Tycho Input Catalogue Update were produced to keep track of the identities and correspondences.

10.3. Prediction of Group Crossings

Special prediction software was set up for the reprocessing. The basic algorithm of the prediction process was the same as in the main processing (Chapter 4). In particular, reprocessing prediction used the Tycho Input Catalogue Update in the same way as the prediction process of the main processing had used the Tycho Input Catalogue. The big difference was the usage of on-ground attitude instead of on-board attitude. This, in combination with the much more precise stellar input data provided by the Tycho Input Catalogue Update (as compared to the Tycho Input Catalogue), made the prediction updating steps unnecessary.

Despite the basic similarity, the reprocessing prediction software differed from the original prediction software in many respects. The on-ground attitude files did not provide all the information contained in the telemetry tapes. Therefore the data interfaces between the various Tycho processing steps had to be slightly modified for the reprocessing. Furthermore, some information which was added to the data flow in the prediction updating steps of the main processing, had to be inserted at the (first) prediction step of reprocessing. In addition, the prediction of group crossings for solar system objects was included in the reprocessing (see Section 10.4).

Prediction for the main processing was fairly slow, for two reasons. First, it was a heavy computation process. The computing time was reduced by a factor of 10 in the reprocessing, because it is almost exactly proportional to the number of objects in the input catalogue. Second, the handling of 1400 telemetry tapes was very time-consuming at the Heidelberg computing centre. This was avoided in the reprocessing by eliminating the telemetry tapes altogether. For this purpose, the European Space Operations Centre on request provided cumulated Data Catalogue and Orbit files, covering the whole Hipparcos mission in a very compact form.

All this made reprocessing prediction very quick. After some trial runs, the final processing commenced in September 1994. Within five weeks, 80 per cent of the mission had been processed. The reprocessing prediction was completed in November 1994.

The reprocessing prediction software was also used for prediction redoing (see last paragraphs of Section 4.1), however it used the Tycho Input Catalogue as input instead of the Tycho Input Catalogue Update.

10.4. Prediction for Solar System Objects

The prediction process had to treat 59 solar system objects (Chapter 4). Due to a software error, this had not been done satisfactorily in the main processing. Therefore the solar system objects were treated again in the Tycho reprocessing. Only data from the reprocessing were used for the published Tycho observations of solar system objects.

The Object List

The object list included the major planets Venus, Mars, Jupiter, Saturn, Uranus, Neptune, the five moons: Io, Ganymede, Callisto, Europa, Titan, and finally the 48 brightest minor planets. The list of minor planets was deliberately extended beyond the expected brightness limit of Tycho in order to be sure that no useful object would be missed (in analogy to the 3 million Tycho Input Catalogue for stars, where only 1 million Tycho stars could actually be expected).

The planets with large angular diameters, namely Venus, Mars, Jupiter and Saturn, were included in the list for technical reasons only. Tycho could not be expected to yield useful astrometric or photometric data for them. Their inclusion was necessary to give warnings that these very bright objects were crossing the star mapper slits, temporarily drowning any other object crossing at about the same time. Even Uranus, Neptune and the Galilean moons were expected to be too extended for correct photometric measurements through the 0.9 arcsec wide star mapper slits. But astrometry of interesting precision could be hoped for. All minor planets, on the other hand, were small enough to be measured without problems.

Inclusion into the Prediction Algorithm

The solar system objects could not be treated in the same way as the stars, because they cannot be assigned to one of the ‘regions’ on the sky which were used to organize the Tycho Input Catalogue access (see Section 4.1). They were treated quite separately, therefore, in the prediction software. About once per mission day, a subset of the 59 objects was selected for actual treatment. The main criterion was that the ephemeris position be within about 2 degrees from the instantaneous scanning great circle of the satellite. In addition, a minor planet was included in the prediction process only if its ephemeris predicted it to be brighter than $V = 11.8$ mag, i.e. the same magnitude limit as for the stellar Tycho Input Catalogue objects was used here. An enlarged analogue of the ‘scanning pentagon’ of Figures 4.1 and 4.2 (taking the daily motion of a planetary object into account) was used to further restrict the list. Due to these measures, the computing time needed for ephemeris access and apparent positions computations of planetary objects was only 1 to 2 per cent of the total time needed for reprocessing prediction.

Within each attitude time interval (see Section 4.1), satellitocentric apparent positions were computed for the selected objects from the respective ephemerides. Predicted group crossings were then calculated as for the stars. Different sorts of ephemerides were available for the three groups of solar system objects. The numerical representation as well as the astronomical meaning of the data given in the ephemerides were different for each group. Their usage for the prediction process is briefly described hereafter.

Ephemerides and Apparent Positions for the Major Planets

The Development Ephemeris, DE200, of the Jet Propulsion Laboratory was used for the major planets (including Earth). It gives barycentric cartesian location and velocity vectors $X_{\rm obj}$ and $V_{\rm obj}$ in the J2000 equatorial coordinate system (nominally). These vectors are represented by Chebyshev polynomials as a function of Barycentric Coordinate Time (BCT). In order to derive apparent positions for the objects from these data, one has to compute:

- the light-travel time from object to satellite $t = |X_{\rm sat} - X_{\rm obj}|/c$, where $X_{\rm sat}$ is the barycentric satellite location, and c is the velocity of light;
- the barycentric location vector of the object, corrected for the light-travel time, $Y_{\rm obj} = (X_{\rm obj} - V_{\rm obj})t$;
- the geometric position of the object with respect to the satellite, i.e. $Y_{\rm obj} - X_{\rm sat}$, normalized to unity;
- the aberration correction to this geometric position, using the barycentric velocity vector of Hipparcos.

This procedure implied two approximations which were, however, of no noticeable astrometric effect: the second step ignored the acceleration of the object in its orbit, while the transformation from geometric to apparent position (last step) ignores the relativistic light deflection by the Sun and the Earth.

Ephemerides and Apparent Positions for the Moons

Ephemerides were made available by J. Arlot of Bureau des Longitudes, especially for the purpose of Hipparcos data reductions. They give the geocentric position offsets between a moon and its parent planet as offsets in right ascension and declination (J2000), represented by Fourier coefficients as a function of Terrestrial Time (TT). In order to derive apparent positions for the objects from these data, one has to:

- compute the satellitocentric apparent position of the parent planet, as above;
- transform this to right ascension and declination;
- add the right ascension and declination offset derived from the moon's ephemeris.

This procedure implied a number of approximations: (1) the differential parallax between parent planet and moon due to the line-of-sight component of the planet-moon location vector was ignored (this vector could not be inferred from the available ephemeris data). The effect was largest for Callisto, where it could reach 40 mas at maximum; (2) the differential light-travel time was ignored for the same reason. Again, the effect was largest for Callisto, where it could be of the order of 10 mas at maximum; (3) due to the 'daily' parallax of the Hipparcos satellite (13 arcsec at the distance of Jupiter) the difference in location between planet and moon translates into different right ascension and declination offsets if viewed from the Earth or from the satellite (the effect is small); (4) the same applied for aberration. The effect again is small.

Ephemerides and Apparent Positions for the Minor Planets

Ephemerides were provided by A. Bec-Borsenberger of Bureau des Longitudes. They gave geocentric astrometric positions of the objects in the form of ecliptic longitudes and latitudes (J2000). In addition, the geocentric distance and magnitude were given. All four quantities were represented by Chebyshev polynomials as functions of Terrestrial Time (TT). In order to derive apparent positions from these data, one had to:

- compute the geocentric location vector of the minor planet from the Chebyshev representation of longitude, latitude and distance (note that this was already light-time corrected, since the input was an astrometric position);
- subtract the geocentric satellite location vector to get the geometric position of the object with respect to the satellite;
- apply the aberration correction due to the barycentric velocity of Hipparcos.

This procedure was approximate in practically every aspect, but it was computationally simple and accurate enough.

10.5. Detection of Transits

The reprocessing detection process was carried out in the same way as described in Section 4.3, except for one difference: the amplitude estimation for very bright stars was carried out using the wings of the signal, as for these stars the centre of the signal was disturbed by non-linearity in the response (saturation) of the photomultipliers. To do this, special single-slit response functions had to be constructed because those used for the main processing covered only a width of 3.8 arcsec. The new single-slit response functions were constructed at Tübingen, using individually selected transits of bright stars ($2 < m < 5$ mag). They were applied to transits with a signal-to-noise ratio above 250.

10.6. Identification of Transits

With the omission of the prediction updating steps in the reprocessing, transit identification lost two of its major tasks, namely to introduce an improved star catalogue and improved attitude into the Tycho data reduction chain. Nevertheless a sort of transit identification was necessary, for three remaining purposes: the addition of identity probabilities, the format changes necessary to transform raw transits into identified transits, and the parasite recording. This 'abridged transit identification' was performed in parallel with the reprocessing detection in a single process, and no major changes were needed in the detection and transit identification programs. A control program made calls to the detection and transit identification software in alternation. The absence of a prediction updating-3 data stream as input for transit identification was compensated by a simple intermediate program converting the reprocessing Predicted Group Crossing data to pseudo-updating data before the runs of the transit identification program. As a consequence, the raw transit files, which had been the main output of the detection and input of the transit identification process, were only temporary files in reprocessing. They were deleted immediately after treatment by transit identification and not stored on magnetic tapes. The combination of the two logical processing steps into a single program is indicated in Figure 10.1.

The parasite recording in the abridged transit identification was done with the same algorithm as for the main processing. Nevertheless the outcome was different, since the Tycho Input Catalogue Update was by definition (see Section 10.2) complete down to magnitude 9 only. In the main processing, all parasites down to Tycho Input Catalogue Revision magnitude 10.5 had been recorded.

10.7. Verification Methods

Testing and verification for the reprocessing was very similar to that of the main processing. At a very late stage, a minute but systematic astrometric defect of the reprocessing data was discovered in the calibration parameters, as described in Chapter 7. The precise cause of the defect could not be found within the available time, but it was definitely due to an error of the reprocessing prediction software.

Ironically, the error did not damage the redoing data, which had been produced with the same prediction software before the problem became known. In redoing, the defect was (unknowingly) repaired by the prediction updating step. When the defect was recognized in the reprocessing data, it was too late for an updating step there. Thus, an empirical correction was applied to the astrometric parameters, as described in Chapter 11.

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