TYCHO ASTROMETRY AND PHOTOMETRY

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ABSTRACT

The HIPPARCOS Star Mappers were designed to determine the satellite attitude by observation of stars with known positions. ESA has now enhanced them so that the continuous photon counts from two photo multipliers with B and V response will be recorded. The records will be used to derive an astrometric and photometric catalogue, the TYCHO Catalogue, complete to about B=11 mag and thus containing about 500 000 stars. The positions, annual proper motions and parallaxes will have an accuracy of about 0.03 arcsec and the magnitudes one of 0.03 mag.

The instrument is described and some aspects of the data reduction are discussed, namely the evaluation of a photon record by means of numerical filters, and the use of a TYCHO Input Catalogue.

1. INTRODUCTION

The HIPPARCOS satellite is designed to scan the sky systematically with its main field of view obtaining astrometric parameters for 100 000 stars with a accuracy of 0".002 from a 2.5 years mission, Kovalevsky (1986). A Star Mapper (SM) in front of the main field of view (Fig. 1) will produce photon records of all stars in a band of 40' width and will thus permit a determination of the satellite attitude within 1" rms in real time and 0".1 rms later in an On-Ground Attitude Reconstitution by means of stars with known positions. It was, however, realized after ESA's approval of the main mission that these photon records would contain valuable photometric and astrometric information for half a million stars. Consequently, ESA approved the enhancement of the mission under the name TYCHO experiment, see Høg, Jaschek, and Lindegren (1982).

This experiment has subsequently been optimized during ESA's Phase B study of the project through efforts by Dr. L. Lindegren and MATRA as presented in a dozen or more technical reports. This meant especially introduction of a non-periodic slit system of increased

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length, redundant photo multipliers, colour filters, and continuous telemetry of the SM counts, as described in Sections 2 and 3.

The evaluation of a photon record is discussed in Section 3 and the expected performance from a single SM crossing is given in Table 2.

The data reduction will be carried out by TDAC (TYCHO Data Analysis Consortium), a group of scientists from 15 institutes in Europe and USA who have taken responsibility for the different tasks, see Høg and Mauder (1982) and Section 4.

2. STAR MAPPER SYSTEM

The configuration of the non-periodic vertical and inclined Star Mapper slits is given in Fig. 1 and by Table 1.

Only one SM is used at any time, the other one being redundant. The separation of the TYCHO colours B_T and V_T is obtained by a dichroic mirror behind the Star Mapper slits. It has been possible, therefore, to synchronize the sampling in the two colours so that they may be added in the later data reduction in order to detect fainter stars. The sampling interval for photon counting is 1/600 s in each colour. All samples are telemetered to the ground and recorded on magnetic tape. Since bialkali multipliers were selected the optimized system has obtained a spectral response quite close to Johnson B and V, which was also based on bialkali multipliers, cf. Table 1. An S20

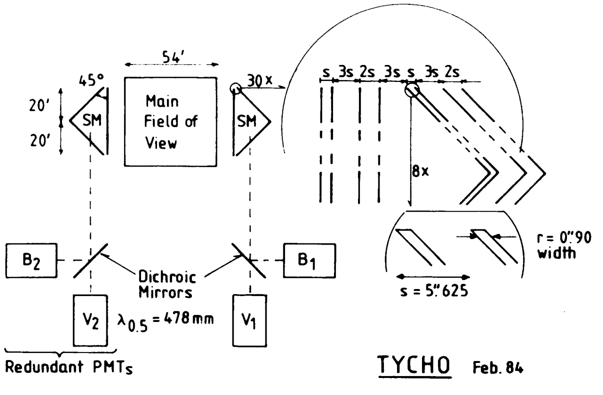

Fig. 1. Configuration of Star Mapper slits and photo multiplier tubes (PMTs). - The 4 "vertical" slits are perpendicular to the "horizontal" motion of the stars. A dichroic mirror with separation wavelength λ = 478 nm defines the photometric system (relay lenses and blocking filters are omitted in this figure)

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Table 1. TYCHO Parameters

Optical configuration and Figs. 1,2,3:

- Slit width along scan $r = 0''.90 (= 6.11\,\mu m)$
- Separations along scan 1 s, 3s, 2 s; $s = 5''.625$
- 4 vertical and 4 inclined slits
- Slit height 40'
- Width (FWHM) of the recorded image
  0''.9 at vertical slit, 1''.2 at inclined slit
- Bialkali photo multipliers and dichroic filter
- Effective wavelength, TYCHO: B_T 426 nm V_T 532 nm
  Johnson: B 440 V 548
- Passband, FWHM, TYCHO: B_T 92 V_T 96
  Johnson: B 96 V 90
- Count rates (Hz)
  I_o for star (for clear plate), b for background
  for B_T: $I_o = 1101 \cdot 10^{-0.4(B-11)}$, $b = 2453$ Hz
  for V_T: $I_o = 830 \cdot 10^{-0.4(V-10.3)}$, $b = 1935$ Hz

Observation:

- Scan velocity, nominal 168.75"/s
- Sampling interval in each colour 1/600 s ≃ 0.28125"
- 1 byte = 8 bits per sample
- Records for 2.5 years mission on 2500 tapes of 1600 bpi

Data reduction:

- 1 SM crossing = vertical + inclined slits, 2 colours
- 100 SM crossings per average star in 2.5 years
- TYCHO input catalogue of > 400 000 stars = $40 \cdot 10^6$ SM crossings
- Average distance between main lobes of these stars
  is 170" = 600 samples

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cathode was considered for the V channel in order to increase the separation between the two bands, but it was finally abandoned for reasons of economy and reliability.

The slits are somewhat wider than the telescope resolution limit, but they are much longer. The ensuing disturbance from background stars starts to be significant at stellar magnitude B = 11. Table 1 gives the expected count rates I_o for a star if the slit plate were replaced by a clear plate. The dark counts from the PMT is 350 Hz, small compared to the total background b (≃ 2000 Hz) including the (average) sky.

The recorded intensity profile for a star moving across a vertical slit is symmetric but, at an inclined slit it is slightly asymmetric, because the half aperture of the telescope is asymmetric in direction perpendicular to the scan, and because the telescope has a spherical aberration in that direction. Care must be taken in the data reduction to avoid systematic errors from this asymmetry.

3. EVALUATION OF A PHOTON RECORD

The four slits have non-periodic spacings giving advantages in the presence of noise and/or other star(s) crossing the slits about the same time. Figs. 2a and 2b illustrate the data reduction for a periodic and a non-periodic grid, respectively.

The intensity record I(t) as function of time is folded with a numerical filter F(t) giving the output Y(t). The central intensity I_c of I(t) has, arbitrarily, been normalized to unity, and so has I'_c of Y(t) corresponding to a single slit. It appears, of course, that the main lobe of Y(t) is 4 times higher above the background than if the grid had contained only one slit. It is also noted that the background b in I(t) is 4 times and, therefore, 4b' in Y(t) is 16 times higher than if there were only one slit, since the background is dominated by the sky and not by the dark count of the PMT.

This means that the limiting magnitude determined by the sky background is hardly changed by going from 1 to 4 (or even to 8) slits, as has been confirmed in the studies. For brighter stars, however, the rms errors in astrometry and photometry are, of course, reduced by 50 percent.

Comparing the periodic with the non-periodic grid it appears that the central lobe is the same, and that, therefore, the same accuracy should be obtained. But the non-periodic grid has a larger number of smaller side lobes in the filter output Y(t) than the periodic grid. This means that the central peak is more prominent and clearly distinguishable in the presence of noise. This advantage of the

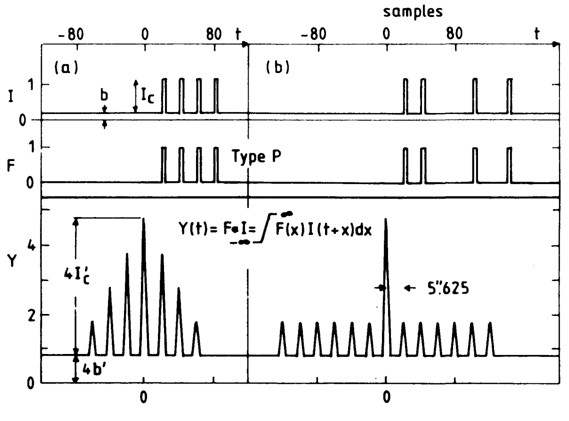

Fig. 2. Periodic and non-periodic grids. The result of folding the intensity record I(t) with a digital filter F(t) is Y(t). Profiles have been simplified for ease of drawing. Unit of t = 1 sample = 1/600 s

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non-periodic grid is important if the a priori knowledge of the star position may be in error by more than 3", i.e. 1" rms. This is the case for the TYCHO Input Catalogue where up to 2" rms is expected. Another advantage is that a neighbouring star cannot disturb as much if its side-lobe touches the main lobe of the first star, but, obviously, the total area under the side lobes is the same in both cases. Since the average distance between detectable stars, see Table 1, is several hundred samples the overlap problem is a managable one.

The astrometric information of a SM transit may be obtained by determining the location τ of the main lobe of Y(t) in Fig. 2b.

The photometric information is obtained from the amplitude of the lobe with due subtraction of the background, and this can be done in different ways.

3.1 Subtraction of background

The numerical filter in Fig. 2, called Type P has only positive elements, while Type I and II filters defined below contain additional negative elements such that they are balanced, i.e. $\int F\,dt = 0$.

The background may e.g. be taken close to the main lobe in the output from a Type P filter. But as yet only the balanced filters were considered, both for astrometry and photometry. It appears, however, that the astrometric information should be extracted with the unbalanced Type P filter, since the negative elements in a balanced filter will add noise from the background onto the main lobe and thus make its location less accurate.

The amplitude of the central peak above zero in the output from Type I and II filters will be free from background, since the filters are balanced.

The Type I filter, Fig. 3a, gives especially small side lobes thanks to the clever positions of the 9 negative elements. Even smaller side lobes may be obtained by an even wider filter with a larger number of negative elements, but this would be impractical to use.

A Type II filter, Fig. 3b, with a width of 320 samples, has been used in Phase B and gives a few percent better astrometric accuracy than Type I and this is only about 10 percent above the Cramer Rao bound. It is noted that the output close to the central lobe from a Type II filter may be obtained with less computation from a Type P filter output combined with the average value of I(t) over a length equal to that of the negative elements in the Type II.

Table 2 gives the TYCHO performance using the Type II filter.

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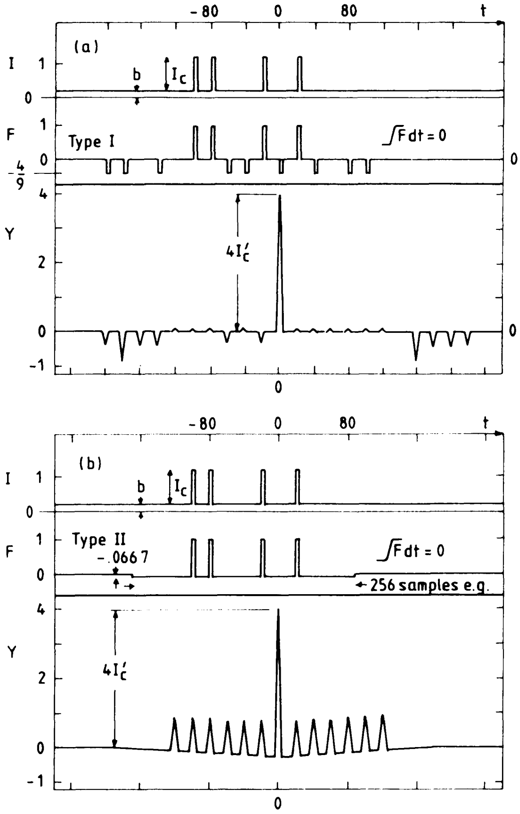

Fig. 3. Use of balanced numerical filters to reduce a photon record

Table 2. TYCHO performance from one combined SM crossing for star with B - V = 0.7. The astrometric precision σ_t corresponds to a one-dimensional information

B	V	σ_t	σ_B	σ_V
9	8.3	0.″02	$0^m.08$	$0^m.11$
10	9.3	0.07	0.16	0.21
11	10.3	0.16	0.31	0.44

The real evaluation should be done according to the Maximum-Likelihood principle with optimum filters. This optimum depends somewhat on the expected profiles at vertical or inclined slits and on stellar magnitude and background.

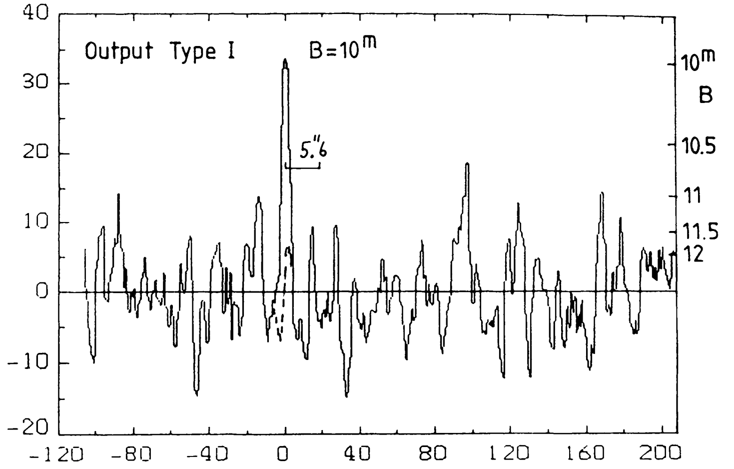

Fig. 4. Output from Type I filter in channel B, simulated with realistic count rates for background and for a star of $B = 10^m$

A simulated output from a Type I filter is shown in Fig. 4. It appears, using the B-scale on the right side that stars of B = 10, and perhaps 10.5, may be detected without a priori knowledge of positions and without getting too many false detections from noise. If an interval of short enough length, say 20" = 71 samples, may be pointed out from an a priori position it appears that stars of B = 11 and slightly fainter may be recognized correctly.

4. DATA REDUCTION

The photon count records in the two colours from the star mapper will be transmitted to the ground where the data will be put on magnetic tape together with information on timing, satellite attitude, satellite orbit etc. before it is sent to the Consortium (TDAC).

The continuous photon records (600 samples per second per colour) will be available so that a sky survey independent of all previous surveys of stars could be made, and it would perhaps be worth-while to do at some time. TDAC will, however, base its work on an a priori catalogue of stars, a TYCHO Input Catalogue (TIC) obtained by a merging of the catalogues at the Strasbourg Data Center and part of the Space Telescope Guide Star Catalogue, Russell (1986). This TIC shall contain between 400 000 and one million stars. It will be almost complete to the magnitude B = 11 and contain many fainter stars.

There are two reasons for using an input catalogue. It decreases the required computing time by an order of magnitude, since an independent identification of detections found as main lobes in Fig. 3b with real stars is a very heavy task due to the length of the slits (40'). A second reason is that a fainter detection limit can be applied without obtaining too many false detections due to noise, when an a priori star position is available.

The first processing of the raw SM records is the "Pick and Fold". A piece of the record is picked out like I(t) in Fig. 2b around an expected crossing of a star in the TIC. Then it is folded with a filter F(t) of Type P as in Fig. 2b but having only one sample point at each slit. Nearly all relevant information about star and background will now be contained in a short piece of the filter output Y(t). It needs only be long enough to contain the central peak, i.e. about 20" (= 71 samples) since the rms error of positions in TIC is expected to be $< 2''$ rms.

The folded records can be contained on about 200 tapes, an order of magnitude less than the raw data. These tapes shall also contain information on star number, epoch, grid coordinate, satellite attitude, and the average background, and they will be used exclusively by TDAC for all further processing instead of the raw photon records.

In this planned data compression the assumption has been made that a short unbalanced filter combined with the average background will be adequate and that the long balanced filter in Fig. 3a will not be needed.

The satellite attitude will be determined with an accuracy better than 0."005 along the scan and 0."1, or perhaps 0."05, perpendicular to the scan. This error source will not affect the photometry, and the astrometric effect will be insignificant for stars fainter than B = 10, cf. Table 2.

The photometry based on the folded records will require calibration of cathode sensitivity drift and dependence on position in the field of view. This calibration will be performed partly on ground and partly during the mission by means of available photometric standard stars having multicolour photometry. Due to the moderate photometric accuracy of TYCHO, cf. Table 2, the standard stars need not be of first class accuracy, and 10 000 to 20 000 are already available in present day catalogues.

The astrometry will require calibration of grid geometry and optical modelling of the image formation. A combination of on-ground and on-orbit calibration will be used, including the final reference system provided by the 100 000 HIPPARCOS program stars. Each crossing of four slits gives a one-dimensional coordinate perpendicular to the slits, and the 2 x 80 such crossings must be combined to give position, annual proper motion, and parallax for a star. The accuracy of these five astrometric parameters will be about equal, i.e. 0."03 for B = 10. This figure for the final astrometric accuracy contains some margin and is unaltered from the original value predicted in 1981.

The final TYCHO catalogue is expected to appear in 1994.

5. ASTROMETRY AND PHOTOMETRY

The scientific impact of the TYCHO results has been discussed by Høg et al. (1982) and only some main points shall be given here. The expected resulting accuracy from the 2.5 years mission is given in Table 3.

Positions at mean epoch (= 1989) with rms accuracy about 0"03 for the 500 000 brightest stars on the sky will be the main astrometric result. The annual proper motions and the parallaxes will be obtained with the same accuracy, but will often be better known from other sources. For mcst of these stars the position accuracy at the present epoch is about 0"7, but they have been observed at an earlier epoch so that accurate proper motions can be derived. Using the AGK2 catalogue positions at epoch 1930 for the Northern hemisphere p.m.s with an accuracy of 0"003 yr^{-1} could be derived. For the fainter TYCHO stars not contained in the AGK2 catalogue it would be valuable to remeasure the AGK2 plates. For the Southern hemisphere the situation is more complicated since no uniform old coverage like the AGK2 exists, but for most stars a p.m. better than 0"01 yr^{-1} could be obtained.

It thus appears that TYCHO positions and derived p.m.s will provide a reference system with a density of 10 stars per square degree and an accuracy about 0"1 for the rest of this century. This star density is sufficient for photographic astrometry even with the small fields of large Ritchey-Chrétien telescopes.

A magnitude in each of the colours B_T and V_T will be obtained each time a star crosses a system of 4 non-periodic slits. The values

Table 3. Astrometric and photometric accuracy for the average over the mission. - The expected accuracy of positions and proper motions for the HIPPARCOS stars is given in the first line. Line No. 2 gives the expected typical accuracy for the TYCHO stars brighter than B = 11, and Line No. 3 gives the accuracy of present catalogues for these stars.

	Position	p.m.	B,V	B-V
HIPPARCOS, 100 000 stars	0"002	0"002 yr^{-1}	-	-
TYCHO, 500 000 stars, $B \simeq 10$	0.03	0.003	$0^m.03$	$0^m.05$
Present, most of the 500 000	0.7	0.015	0.3	0.2

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obtained at the vertical and inclined slits shall be combined and be considered as one photometric observation. An average of 80 such SM-observations per star will be obtained in each colour during the mission, cf. Table 2.

These observations will be used to study known variables and in particular to detect new variable stars. A fairly homogeneous coverage of all lengths of period is facilitated by the fact that the observations of each star are far from being equidistant in time. Due to the special scanning law the following spacings will occur most frequently: 0.5 h, 2.5 h, 5h, 1 month, 2 months, 6 months.

The new sample of variable stars will constitute an unprecedentedly uniform all-sky coverage to well-defined limits of magnitude and amplitude and will, therefore, provide a good basis for statistical studies.

Acknowledgement
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6. REFERENCES

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Kovalevsky, J.: This Volume
Russell, J.: 1986, On the Guide Star Catalogue, This Volume

Discussion:

RÖSER: In order to detect and measure $m_B = 11^m$ stars in the Tycho data reduction you need the so-called Tycho input catalogue complete to this magnitude. Could you comment on the way of constructing this catalogue?

HØG: If the catalogue is not complete, then the method I described will yield data only for stars which are in the catalogue. The data will be treated in such a way that they can be used later to get better completeness. This is a task of computation to which the Tycho consortium was originally not committed, but we could achieve completeness to, say, tenth magnitude. The problems start when you are trying to achieve completeness to a level at which there are many false detections. The data will be analyzed by a consortium with wide participation, the input catalogue is essentially the Space Telescope guide star catalogue.

EICHHORN: What is the reason for restricting Hipparcos-Tycho to 25 years?

HØG: For economic reasons. This interval gives us a worthwhile mission.

de VEGT: The project is very important for galactic research on fainter stars. To get the early epoch of the Tycho stars, a remeasurement of

AGK2 plates is necessary because the AGK2/3 catalogue does not contain enough faint stars because only a fraction of the stars available on the plates have actually been measured and incorporated into the catalogue. If this were done, probably all stars mp = $12^{m}.0$ can be extracted. Furthermore for correcting systematic errors of these plates the color-index is a very important parameter.

HØG: I must stress the importance of having the AGK2 plates remeasured to a fainter magnitude. By this first epoch and Tycho positions, accurate proper motions can be derived for the Northern Hemisphere.

EICHHORN It seems that the AG plates as far as they are still available are as much worth remeasuring as the AGK2 plates.

HØG I agree completely, I am just more modest than you are.