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LETTER

Letter to the Editor

The Tycho Catalogue*

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Abstract. The principal observational characteristics of the Tycho Catalogue, and a summary of its main astrometric and photometric properties, are presented. Median astrometric standard errors (in position, parallax, and annual proper motion) are typically around 7 mas for stars brighter than $V_T \sim 9$ mag, and approximately 25 mas for $V_T \sim 10.5$ mag, at the catalogue epoch (J1991.25). The Tycho Catalogue was adjusted so that the six global rotation and spin components of the catalogue reference frame coincide with those of the Hipparcos Catalogue. It therefore materialises the ICRS reference system, coinciding with its principal axes at the level of ± 0.6 mas, and with proper motions consistent with an inertial system at the level of ± 0.25 mas/yr. The 1 058 332 constituent stars provide a mean sky density of ~ 25 stars deg^{-2}. The catalogue and associated epoch photometry annex data are available in machine-readable form as part of the final Hipparcos mission products.

Key words: Tycho – Hipparcos – astrometry – photometry – catalogues

1. Introduction

The goal of the Tycho experiment on board the ESA Hipparcos space astrometry satellite was to provide astrometric and two-colour photometric measurements of the brightest stars on the sky. The measurements were obtained with the Hipparcos star mapper, a system of aperiodic slits in the focal plane of the Hipparcos telescope designed primarily for determining the satellite attitude by observation of stars with known positions. The light passing the slits was split by a dichroic mirror into two distinct colour channels (designated B_T and V_T) and recorded as photon counts by means of two corresponding photomultiplier tubes. The encoded photon counts were transmitted to the ground, and the subsequent reduction was undertaken by members of the Tycho Consortium, within the framework of the entire mission analysis.

The first stages of the data analysis were based upon a starting catalogue compiled on the basis of the Guide Star Catalog (GSC), although subsequent steps of the Tycho analysis searched for stars, above the completeness threshold, missing from the GSC for various reasons. The final result is an astrometric and photometric reference catalogue of slightly more than one million stars, the Tycho Catalogue, completed in August 1996, simultaneously with the Hipparcos Catalogue (Perryman et al. 1997) and now published together (ESA 1997). This paper summarises the key attributes of the Tycho Catalogue, complete details of which are provided in the documentation accompanying the catalogue (in Volume 4).

2. Observational Principles

The observational capabilities and operational principles of the Hipparcos satellite have been presented in the literature on numerous occasions. The Tycho experiment has been described previously (e.g. Høg et al. 1995). The key features of the Tycho observations (see also Table 1) were very similar to those of the Hipparcos main field observations and may be summarised as follows:

(a) through observations from space, the effects of atmospheric seeing, instrumental gravitational flexure and thermal distortions could be obviated;

(b) all-sky visibility permitted a direct linking of the stars observed all over the celestial sphere;

(c) the continuous ecliptic-based scanning of the satellite, resulted in an optimum use of the available observing time,

* Based on observations made with the ESA Hipparcos astrometry satellite

Table 1. Principal observational characteristics of the Tycho Catalogue. ICRS is the International Celestial Reference System.

Measurement period	1989.85–1993.21
Catalogue epoch	J1991.25
Reference system	ICRS
coincidence with ICRS[1]	±0.6 mas
deviation from inertial[1]	±0.25 mas/yr
Number of entries	1 058 332
based on Tycho data	1 052 031
with only Hipparcos data	6301
Sky density[2]	~ 25 deg^{-2}
Limiting magnitude	$V \sim 11.5$
Completeness to ~ 90 per cent	$V \sim 10.5$
Completeness to ~ 99.9 per cent	$V \sim 10.0$
Total number of observations	$\sim 130 \times 10^6$

[1] about all 3 axes
[2] depending on galactic latitude

with a resulting catalogue of reasonably homogeneous limiting magnitude and astrometric accuracy;

(d) the various geometrical scan configurations for each star, at multiple epochs throughout the 3-year observation programme and simultaneously with the Hipparcos observations, resulted in a close connection to the Hipparcos astrometric reference frame represented by about 100 000 stars. The barycentric coordinate direction (α, δ), the parallax (π), and the object's proper motion ($\mu_\alpha \cos\delta$, μ_δ) could be solved for in least-squares reductions of the observations. The astrometric parameters as well as their standard errors and correlation coefficients were derived in the process;

(e) the large number of observations per object, of order 130, provided accurate and homogeneous photometric information for each star, from which mean magnitudes in two passbands, B_T and V_T were derived. Studies of variability and duplicity were undertaken.

The most recent description of the data reduction processes have been given by Høg et al. (1995) and Großmann et al. (1995). Complete details of the data, the reductions, and the properties of the final catalogue, are given in the published Tycho Catalogue (ESA 1997).

3. Presentation of Results

3.1. Astrometric parameters

The standard astrometric model adopted for all stars in the Tycho reductions assumes uniform rectilinear space motion relative to the solar system barycentre. At some reference epoch, T_0, the stellar motion on the celestial sphere is then described by the following five 'astrometric' parameters: the barycentric coordinate direction (α, δ); the annual parallax, π, from which the coordinate distance is $(\sin\pi)^{-1}$ AU or, with sufficient approximation, π^{-1} pc if π is expressed in arcsec; and the rate of change of the barycentric coordinate direction expressed as proper motion components $\mu_{\alpha*} = \mu_\alpha \cos\delta$ and μ_δ, in angular measure per unit time.

Table 2. Astrometric characteristics of the Tycho Catalogue.

Standard errors for $V_T < 9$[1]	7 mas
Standard errors for $V_T \sim 10.5$[1]	25 mas
Smallest errors[1]	3 mas
External errors/standard errors[2]	$\sim 1.0 - 1.5$
Systematic errors in astrometry[2]	~ 1 mas (/yr)

[1] on each of the five astrometric parameters
[2] estimated in Volume 4, Chapter 18 (ESA 1997)

The five astrometric parameters, determined from an analysis of the Tycho observations, are given for almost all stars in the catalogue. The catalogue includes astrometric quality flags, and indicators of variability and/or duplicity – nearly 900 000 of the catalogue entries are classified as 'recommended' reference stars, having good Tycho astrometric quality, and not recognised as double.

The principal characteristics of the astrometric results are given in Table 2. As in the case of the Hipparcos Catalogue, corresponding standard errors, also at the catalogue epoch (J1991.25), are given in the final catalogue, along with the associated correlation coefficients. Positions and proper motions are referred to ICRS. The astrometric positions and their errors can be propagated to the standard epoch J2000.0, or to any other epoch, within the ICRS frame, by methods described in the published catalogue.

Since for many Tycho Catalogue entries the proper motion has a standard error larger than the expected proper motion itself ($\mu \simeq 20$ mas/yr for a star of spectral type F5 and $V = 11$ mag), the accuracy of the Tycho proper motions is generally too low to calculate positions at other epochs with sufficient accuracy for reference purposes. More precise proper motions may be taken from the PPM Catalogue (Röser & Bastian 1991; Bastian et al. 1993; Röser et al. 1994) for approximately one half of the Tycho stars, although zonal errors present in the PPM should be accounted for in such applications – the Tycho Catalogue includes the PPM identifier where available. A plan for deriving proper motions for all Tycho stars by means of positions from the Astrographic Catalogue has been described by Röser & Høg (1993). The accuracy of Tycho parallaxes is such that their astrophysical interest is restricted principally to the brighter stars.

Double stars were subject to dedicated data reductions, resulting in the resolution of pairs with separation down to about 1.5 arcsec. Detection of the effects of duplicity was effective down to separations of about 0.5 arcsec. The Tycho Catalogue contains various flags indicating such entries.

3.2. Photometric parameters

The Tycho Catalogue includes accurate and homogeneous photometric information for each star: two-colour (B_T and V_T) magnitudes derived from the Tycho (star mapper) observations; Johnson V magnitude and $B - V$ colour index, derived from the observed $B_T - V_T$ by simplified transformations reflecting the fact that the spectral type, luminosity class, reddening,

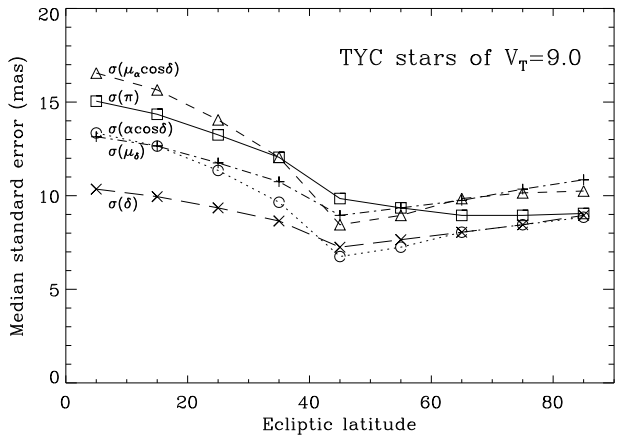


Fig. 1. Precision (formal standard errors) of the five astrometric parameters as a function of ecliptic latitude. The dependency on ecliptic latitude is a consequence of the ecliptic-based scanning law of the Hipparcos satellite. The errors are given at the catalogue epoch, J1991.25. The unit of the internal standard error is milliarcsec (mas) for the positional components (α, δ) and parallax (π), and mas/yr for the proper motion components $(\mu_\alpha\cos\delta, \mu_\delta)$.

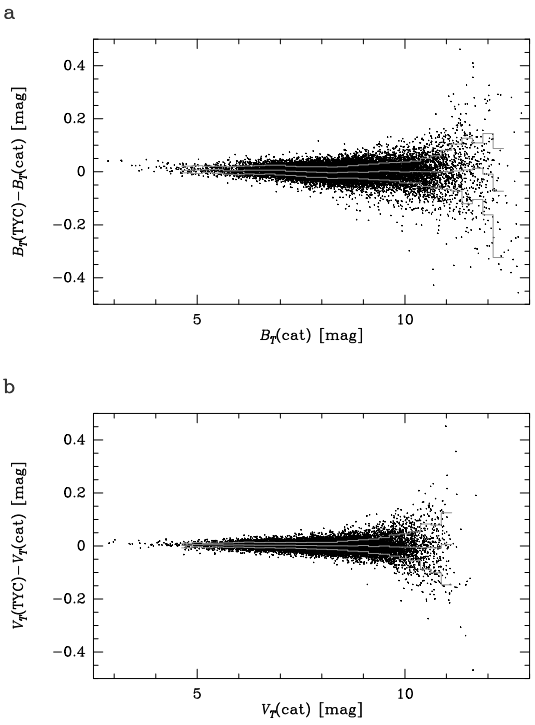


Fig. 2. Tycho mean magnitudes of 17 683 standard stars compared with ground-based magnitudes. The three lines in each plot represent the median of the difference and the 15th and 85th percentiles, indicating the systematic errors and robust estimates of the standard errors of Tycho photometry.

etc., are unknown for the majority of Tycho Catalogue objects; and various flags resulting from (preliminary) studies of variability based on an average of 130 transits per star during the 3 year observing period. The details of the Tycho B_T and V_T photometric system, and details of the corresponding transformations to V and $B - V$, are given in the published catalogue, and also described in the context of the Hipparcos main mission photometry by van Leeuwen et al. (1997).

Published mean photometric values were based on all transits for each star, including those transits where the star was not detected because the signal was too faint. These 'censored' observations were taken into account in a dedicated 'de-censoring' processing. In the basic Tycho data reductions only the detections with a signal-to-noise ratio larger than 1.5 in the combined photon counts from the B_T and V_T detectors provided astrometric and photometric estimates. The photometric results for individual transits, including the censored observations, are provided separately in a Tycho Epoch Photometry Annex for specific subsets of stars. These individual magnitude determinations, at the specified measurements epochs, will allow detection of variable stars and further studies of the variability of known variables. The principal photometric characteristics are given in Table 3.

The Tycho experiment also performed astrometric and photometric observations of solar system objects. These are described in the published Hipparcos and Tycho Catalogues (ESA 1997).

4. Final astrometric and photometric accuracies

Fig. 1 illustrates the mean precision of each of the astrometric parameters for stars of V_T = 9.0 mag as a function of ecliptic latitude. The magnitude dependence is indicated in Table 2. The external standard errors (i.e. accuracies) are only slightly larger for bright stars, increasing to a factor of 1.5 larger at the median magnitude V_T = 10.5 of the Tycho Catalogue stars.

Fig. 2 shows a comparison of Tycho mean magnitudes with ground-based magnitudes for the standard stars available for the reductions. Although only relatively few standard stars are fainter than V_T = 11 mag, this figure and other studies undertaken as part of the catalogue construction and validation demonstrate that the systematic errors are relatively small at all magnitudes. Detailed sky distributions and histograms giving the astrometric and photometric accuracies as a function of position and magnitude are included in the documentation accompanying the published Hipparcos and Tycho Catalogues.

Fig. 3 shows an example of the epoch photometry results, for the Mira variable R Car (TYC 8945–1871–1). This star has an amplitude of more than 4.5 mag and a period of 302.098 days. The figure shows how the errors of a single Tycho observation depend on the magnitude itself (the error bars shown in the plots are the 1σ errors as given in the Tycho Epoch Photometry Annex A).

5. Catalogue Organisation and Products

The designation of objects within the Tycho catalogue uses the Guide Star Catalog (GSC) numbering system (a region number, designated TYC1; and a number within the region, desig-

Table 3. Photometric characteristics of the Tycho Catalogue with respect to mean values. The standard errors of individual transits in the Tycho Epoch Photometry Annex are typically 10 times larger than for the mean value of a given star.

Standard errors of V_T for $V_T < 9$[1]	0.012 mag
Standard errors of V_T for $V_T \sim 10.5$[1]	0.06 mag
Smallest errors of V_T [1]	0.003 mag
External errors/standard errors[2]	~ 1.0
Systematic errors in photometry[2]	< 0.01 mag

[1] errors on B_T are typically 10 per cent higher
[2] estimated in Volume 4, Chapter 19 (ESA 1997)

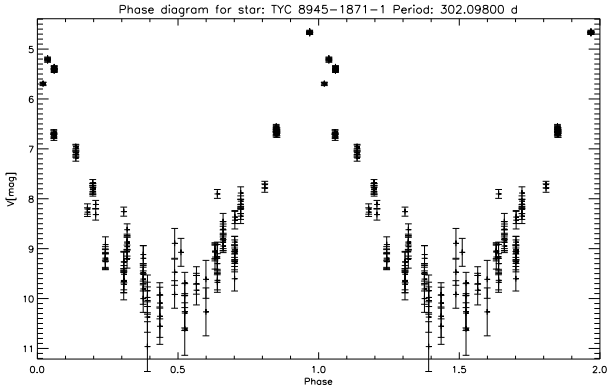


Fig. 3. Phase diagram of the Mira type star R Car showing the increase of the errors of the Tycho single observations with magnitude. The groups of clearly outlying data points are correct measurements, illustrating the typical variations of Mira light curves from cycle to cycle.

nated TYC2), followed by a Tycho Catalogue specific component number (TYC3), the latter introduced to permit the parallel classification of resolved systems. As well as giving a cross-identification to the GSC, this designation system has the advantage of giving a rough indication of position on the sky. For objects contained in the GSC, TYC1 and TYC2 are identical to the identifiers defined by the GSC numbering system. Cross-references are given to the Hipparcos Catalogue identifiers for 123 431 entries, with cross-identifications also given to the CCDM, PPM, HD and DM (BD/CoD/CPD) catalogues, and to the variable star catalogues GCVS and NSV, based on the CDS SIMBAD facility.

The Tycho Catalogue is available as part of the 17-volume publication covering the Hipparcos and Tycho Catalogues (ESA 1997). Volume 1 includes descriptions of the various data sets of the Tycho (and Hipparcos) Catalogue, and provides statistics and sky distributions of the major catalogue parameters. Volume 4 describes the construction of the Tycho Catalogue. In Volume 17, CD-ROM 1 contains the main Tycho Catalogue, comprising 57 fields covering the astrometric results, mean photometry, flags, and cross-identifications. CD-ROM 4 contains the Tycho Epoch Photometry Annex A with transit data for 34 446 objects. Epoch photometry for a significantly larger fraction of the Tycho Catalogue objects (481 553, including those in Annex A) is made available as the Tycho Epoch Photometry Annex B through the CDS, Strasbourg. The complete epoch photometry data for all Tycho Catalogue objects are kept in an archive of the Tycho Consortium.

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