Contribution to *Encyclopedia of Astronomy and Astrophysics*, Macmillan Publishers Ltd., by Erik Høg, April 1999

The Tycho Star Catalogues

The 2.5 Million Brightest Stars

The knowledge of positions, motions in the sky, brightnesses and colours of the brightest stars is the basis for investigations in nearly all branches of astronomy and astrophysics. The Hipparcos space astronomy mission launched in August 1989 and operating until mid-1993 was dedicated to obtain such information. The measurements by the Tycho experiment onboard the satellite have increased the previous knowledge of this kind by orders of magnitude. The first Tycho Catalogue (Tycho-1) published in 1997 gives positions and magnitudes in two colour bands for one million stars.

The motion in the sky (proper motion) could not be accurately derived from the change of star position during the short time interval of 3 years of the Hipparcos mission. The positions in the one hundred year old Astrographic Catalogue have therefore been combined with the Tycho-1 positions to produce accurate proper motions for all stars, as published in 1998.

A second reduction of the Tycho observations has been carried out with more powerful modern computers, resulting in the Tycho-2 Catalogue to be published in 1999. It will contain accurate information for 2.5 million stars, including proper motions based on the Astrographic Catalogue positions.

Catalogues of Star Positions

Catalogues of star positions and brightnesses (magnitudes) in the optical range are prerequisites for the study of almost all celestial objects. Given the position on the sky the stars are identified as individual objects, and can then in principle be observed by any kind of telescope for electromagnetic radiation, from radio waves over infrared and optical to X-ray and gamma-ray, in order to assess the physical nature of the object. The brightest stars in the optical range encompass a wide range of astronomical objects from the compact white dwarfs to red giants and variable stars. The positions of other fainter objects as galaxies and quasars are derived from special observations, relative to the positions of brighter reference stars.

The first prominent catalogue in modern time was observed by Tycho Brahe in the late 16th century and contained about 1000 stars with an unprecedented accuracy of positions. The accuracy of measurement was gradually improved as the technology became available, and the number of stars could be increased. The primary most accurate instrument (before Hipparcos) for astrometry, or positional astronomy, was the meridian circle, a telescope mounted on an east-west axis and observing the stars as they cross the meridian, one star at a time. This resulted in catalogues of fairly bright reference stars.

A large number of fainter stars could then be tied to these reference stars by means of exposures on photographic plates covering the whole sky. The first photographic survey of the sky was one of the largest international cooperations in astronomy carried out mainly from 1891 to 1920. It resulted in the Astrographic Catalogue containing 8.6 million positions of about 4.5 million stars. But this catalogue made very little scientific impact for nearly a century for two reasons. Firstly, the Astrographic Catalogue positions were only available in 254 printed volumes, until a few years ago when they were painstakingly key-punched and thus put on machine-readable form. Secondly, an accurate net of reference stars only became available through the Hipparcos Catalogue.

During the 20th century great efforts were expended by astrometrists in the production of hundreds of position catalogues by meridian circles and photographically in order to satisfy the needs of astronomy. In the 1990-s the scene changed with the completion of the Hipparcos satellite mission. A larger and more accurate reference system became available, and the Tycho Catalogue contained positions of one million stars at a second observation epoch nearly 100 years after the Astrographic Catalogue so that accurate proper motions could be derived from a combination of these two catalogues.

Tycho Observations

The European Space Agency (ESA) satellite Hipparcos carried out astrometric and photometric observations from 1989 to 1993 resulting in the Hipparcos and Tycho Catalogues. The satellite obtained very high accuracy astrometry for 120 000 stars, the Hipparcos Catalogue. These stars plus an additional 935 000 stars were detected and measured with a more modest accuracy by the satellite's star mapper slits resulting in the Tycho Catalogue, hereafter abbreviated to Tycho-1. This catalogue contains astrometry and two-colour photometry (B_T, V_T) for all stars. The two colour bands in the blue and visual parts of the spectrum are close to the so-called Johnson B and V frequently used in astronomy.

The star mapper slits were placed in the focal plane of the Hipparcos telescope, besides of the Hipparcos main field. The light passing the slits was measured by simultaneous photon counting with two photomultipliers, one in each of the colour bands. The origi-

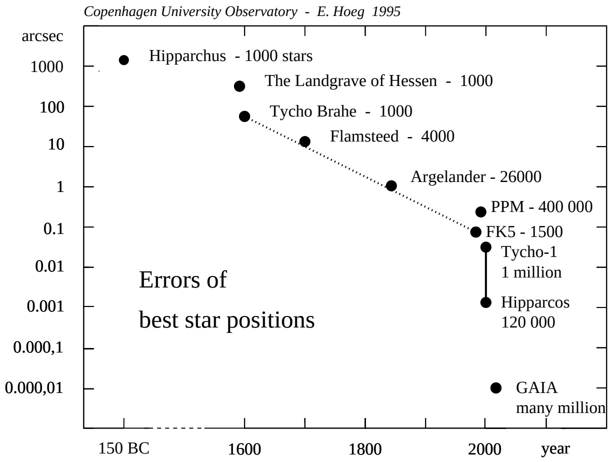

Figure 1: Errors of star positions in the most accurate catalogues. Tycho Brahe achieved a jump in accuracy. After four centuries with more gradual improvements another leap was obtained with the ESA satellite giving the Hipparcos and Tycho Catalogues containing a total of one million stars. Further improvement is expected with the planned ESA satellite GAIA for many more stars; about 40 million stars with 10 microarcsecond and 1 billion with better than 150 microarcsecond accuracy.

nal Tycho reduction was done by detecting a significant signal whenever the stars of an input catalogue crossed the slit system. The improvement in the new reduction is achieved by superposing the photons that were counted during all the about 130 observations per star obtained during the mission.

In the original Tycho-1 project astrometric and photometric data for 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 internal standard error) of 7 mas was achieved in astrometry (positions, annual proper motions and parallaxes) for stars with $V_T < 9$ mag, and 25 mas for all stars. The median precision in photometry was 0.012 mag for V_T of the bright stars and 0.06 mag for the whole catalogue. Double stars with sufficient brightness and separation larger than 2 arcsec were resolved. The processing was based on predicted star transits using a dedicated 'Tycho Input Catalogue', compiled from existing star catalogues. The data treatment was carried out by the Tycho Data Analysis Consortium, using satellite attitude information, and photometric standard stars from the Hipparcos data reduction consortia.

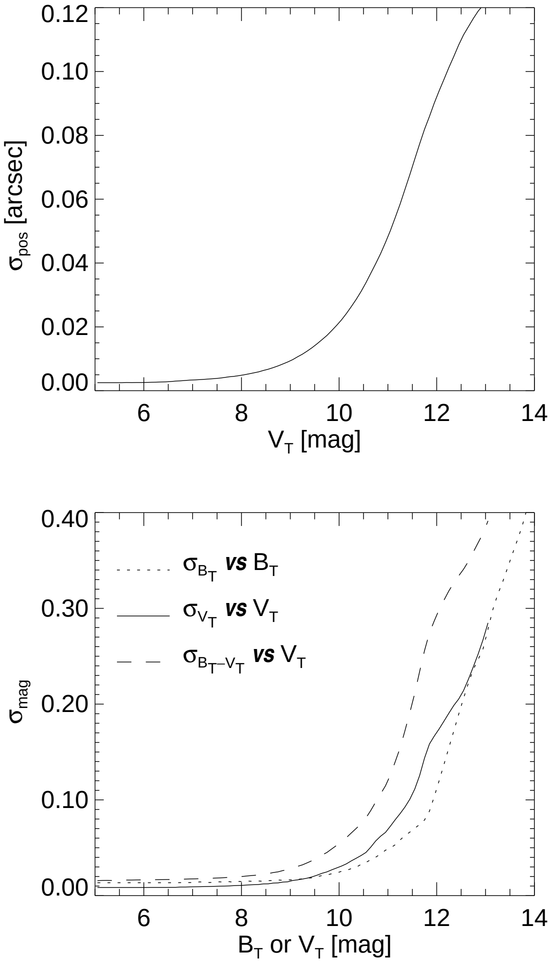

Figure 2: The Tycho-2 Catalogue : Standard errors of position components, magnitudes and colour indices.

Table 1: *Principal observational characteristics of the Tycho-2 Catalogue. ICRS is the International Celestial Reference System. By means of proper motions the observed positions are transferred to the year J2000.0, the epoch of the catalogue. The median values of standard errors are given. Unit: mas = milliarcsecond.*

Observation period of satellite	1989.85–1993.21
Mean observation epoch	~J1991.25
Epoch of Tycho-2 Catalogue	J2000.0
Reference system	ICRS
coincidence with ICRS[1]	± 0.6 mas
deviation from inertial[1]	± 0.25 mas/yr
Number of entries	2 540 000
Astrometric standard errors	
$V_T < 9$ mag, positions	9 mas
all stars, positions	60 mas
all stars, proper motions	2.5 mas/yr
Photometric std. errors on V_T	
$V_T < 9$ mag	0.012 mag
all stars	0.09 mag
Sky density[2]	~ 60 deg^{-2}
Limiting magnitude	$V \sim 12.5$ mag
Completeness to ~ 90 %	$V \sim 11.5$ mag
Completeness to ~ 99.9 %	$V \sim 11.0$ mag
Total number of observations	$\sim 300 \times 10^6$

[1] per axis for all 3 axes
[2] depending on galactic lat.

The Tycho-2 Catalogue

The processing of Tycho observations for the first Tycho Catalogue was based on detections of each transit above a certain signal-to-noise ratio (1.5 or 1.8).

For the second Tycho Catalogue a much better solution, namely *a photon superposition for the whole mission* has been realised. This idea was already suggested in 1982 when the Tycho project was proposed to ESA, but had to be abandoned at that time in favour of the more modest approach. The photon superposition gives better astrometric and photometric values for the fainter half of the original one million stars. A major reason for the improvement is that an astrometric estimation based on very few photons does not achieve the so-called Cramér-Rao limit. An estimation based on all photons from many transits comes much closer to that limit. Furthermore, many transits of the faint stars were below the limit of signal-to-noise ratio for the detection and were thus completely lost.

The Tycho-2 Catalogue (see Table 1 and Fig. 2) contains astrometry and photometry for 2.5 times as many stars as the Tycho-1.

Future Developments

In the Tycho-2 processing emphasis was placed on the optimal treatment of the bulk of stars which are single, but an effort was also made to detect and measure double stars. This resulted in about 8000 pairs with separations down to 0.8 arcsec, while the resolution limit in Tycho-1 was about 2 arcsec. The processing also gave insight in still unexploited possibilities. A special double star processing where the Tycho-2 results are used as input will give detection and measurement of closer pairs and of presently unknown fainter companions of many thousand stars. It has also become clear that a special variable star processing should be applied because thousands of new variables can be detected, many more than can be detected from the published photometric annexes to the Tycho-1 Catalogue. These surveys of double and variable stars would be complete and uniform over the sky to an extent which could only be superseded by a future astrometric satellite.

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