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1

The Hipparcos and Tycho Catalogues

1.1 Overview

This chapter describes various aspects of the Hipparcos and Tycho Catalogues useful for understanding the scientific exploitation considered in subsequent chapters. It describes some of the satellite measurement principles relevant for an understanding of the catalogue contents; the published intermediate astrometry data; details of the adopted reference frame; basic transformations relevant to catalogue users; details of the Tycho 2 Catalogue construction; error assessment; and details of associated data such as radial velocities and cross-identifications.

The Hipparcos Catalogue contains 118 218 entries, corresponding to an average of some three stars per square degree over the entire sky. Median precision of the five astrometric parameters ($Hp < 9$ mag) exceeded the original mission goals, and are between 0.6–1.0 mas. Some 20 000 distances were determined to better than 10%, and 50 000 to better than 20%. The inferred ratio of external to standard errors is ~ 1.0–1.2, and estimated systematic errors are below 0.1 mas. The number of solved or suspected double or multiple stars is 23 882. Photometric observations yielded multi-epoch photometry with a mean number of 110 observations per star, a median photometric precision ($Hp < 9$ mag) of 0.0015 mag, and 11 597 entries were identified as variable or possibly variable.

The Tycho Catalogue of just over 1 million stars was superseded in 2000 by the Tycho 2 Catalogue of some 2.5 million stars; both included two-colour photometry.

1.2 Observation principles

Key features Some key features of the observations were as follows: (a) through observations from space, the effects of atmospheric seeing, instrumental gravitational flexure and thermal distortions could be obviated or minimised; (b) all-sky visibility permitted a direct linking of the stars observed all over the celestial sphere; (c) the two viewing directions of the satellite, separated by a large and suitable angle, resulted in a 'rigid' connection between quasi-instantaneous one-dimensional observations in different parts of the sky. In turn, this led to parallax determinations which are absolute (rather than relative, with respect to some unknown zero-point); (d) the continuous ecliptic-based scanning of the satellite resulted in an optimum use of the available observing time, with a resulting catalogue providing reasonably homogeneous sky density and uniform astrometric accuracy; (e) the various geometrical scan configurations for each star, at multiple epochs throughout the three-year observation programme, resulted in a dense network of one-dimensional positions from which the barycentric coordinate direction (α, δ), the parallax (π), and the object's proper motion $(\mu_\alpha \cos\delta, \mu_\delta)$ could be solved for in what was effectively a global least-squares reduction of the totality of observations. The astrometric parameters as well as their standard errors and correlation coefficients were derived in the process; (f) since the number of independent geometrical observations per object was large (typically of order 30) compared with the number of unknowns for the standard model (five astrometric unknowns per star) astrometric solutions not complying with this simple 'five-parameter' model, could be expanded to take into account the effects of double or multiple stars, or nonlinear photocentric motions ascribed to unresolved 'astrometric binaries'; (g) a somewhat larger number of actual observations per object, of order 110, provided accurate and homogeneous photometric information for each star, from which mean magnitudes, variability amplitudes, and in many cases period and variability type classification could be undertaken. Further details can be found in the published catalogue (ESA, 1997, Volume 2).

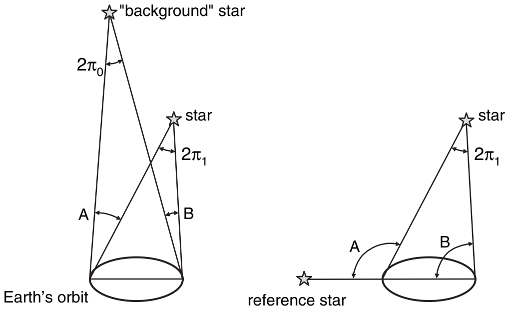

Figure 1.1 The principle of absolute parallax determination. Left: the measurement of the (small) angles A, B only allows determination of the relative parallax $\pi_1 - \pi_0 = (A - B)/2$. Right: in contrast, measurement of the large angles allows determination of the absolute parallax $\pi_1 = (A - B)/2$, independent of the distance to the reference star. From Lindegren *(2005, Figure 4).*

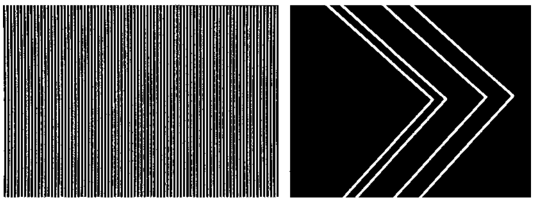

Figure 1.2 Optical micrograph of part of the main modulating grid used for the main mission (Hipparcos Catalogue) observations (left), and part of the inclined slits of the star mapper grid used for the Tycho Catalogue observations (right). From ESA *(1997, Volume 2, Figure 2.14).*

Understanding Hipparcos and space astrometry The basic measurement principles of Hipparcos were reasonably simple, and indeed rather elegant. A purely qualitative description of the principles are given here, to guide the understanding of the detailed operational and mathematical formulation that has been presented in detail in the published catalogue (Volume 2: the Hipparcos Satellite Operations; Volume 3: Construction of the Hipparcos Catalogue; Volume 4: Construction of the Tycho Catalogue). The space platform did not access any part of the spectral region not visible from the ground, but rather exploited the absence of the perturbing atmosphere and the essential absence of gravitational and thermal flexure, at the same time permitting all-sky visibility which is central to the concept of two simultaneous viewing directions separated by a large, fixed, angle. This, in turn, is essential for the derivation of absolute trigonometric parallaxes, independent of the assumption of distances of reference stars (Figure 1.1). Descriptions can be found in early Hipparcos studies (Høyer *et al.*, 1981), and more recently in the context of Gaia, e.g. Lindegren & Perryman (1996, Section 3.1) and Lindegren (2005, Section 3.2).

The measuring instrument consisted of two superimposed fields of view, each $0\overset{\circ}{.}9 \times 0\overset{\circ}{.}9$ in size (thus ensuring a sufficient number of stars in each field), and separated by a 'basic angle' of about 58°. Rotation about a spin axis perpendicular to the two viewing directions, and at a reasonably uniform rate, yielded modulated light signals due to a regular opaque/transparent grid at the focal surface (Figure 1.2). The signal amplitude provided the photometric intensity, while the relative signal phases yielded the instantaneous measurement of the along-scan (angular) separation between stars in the two fields of view (modulo the period of the grid, of approximately 1.208 arcsec). A slow precession of the spin axis resulted in slowly precessing great circle scans across the celestial sphere, and hence a network of one-dimensional angular measurements progressively and repeatedly covering the sky at different orientations. One great circle was scanned every 2.1 hours, resulting in approximately 14 000 great circle scans, or some 2500 'reference great circles' each of about 12-hour duration over the 3.3-year measurement period.

The measurement principle can be understood in three steps. In the first step, Figure 1.3, left illustrates a distribution of (single) stars in space with no space motions, with an observer at rest amongst them. The position of each star is fully described by just two angular coordinates α and δ. From the 100 or so repeated measurements at different orientations over the satellite's three-year lifetime, estimates of these two parameters can be extracted from the system of measurement equations, along with a formal estimate of their standard errors. As long as the instrument stability, and its associated geometrical calibration terms, varied only slowly with time, and could therefore be described by a small number of terms within the very large number of individual measurements, the system is self-calibrating, and the estimation of stellar parameters largely unaffected. The scanning 'law' was optimised, with its symmetry axis in the ecliptic plane, with a fixed angle between the spin axis and the Sun line, in order to maximise the thermal stability of the payload during its sky scanning. Small and large Sun aspect angles would have yielded poor uniformity in sky coverage or weak determinations of one or other stellar coordinate. An angle of 43° was finally adopted as compromise, still inevitably leading to asymmetries in coverage and parameter determination as a function of ecliptic latitude; details of the scanning law are given in ESA (1997, Volume 2, Chapter 8). The choice of basic angle between the two viewing directions can also be understood qualitatively, and was optimised rigorously:

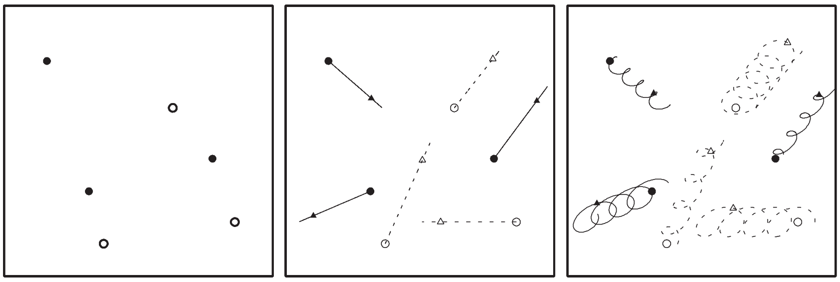

Figure 1.3 Principles of the astrometric measurements. Filled circles and solid lines show three objects from one field of view (about 1° in size), and open circles and dashed lines show three objects from a distinct sky region superimposed by virtue of the large basic angle. Left: object positions at one reference epoch. Middle: their space motions over about four years, with arbitrary proper motion vectors and scale factors; triangles show their positions at a fixed epoch near the end of the interval. Right: the total positional changes including the additional apparent motions due to annual parallax, the four 'loops' corresponding to four Earth orbits around the Sun. Again, parallaxes are of arbitrary amplitude. The parallax-induced motions are in phase for all stars in the same region of sky, so that relative measurements within one field can only provide relative parallaxes. Although the relative separations between the stars change continuously over the measurement period, they are described by just five parameters per star.

a large angle of order $\pi/2$ radians provides good interconnectivity and hence rigidity of the reference system between different parts of the sky. Yet angles near to 90°, or 60°, or indeed $(m/n)2\pi$ radians, where m and n are (small) integers, lead to weakened rigidity due to the smaller number of independent links between different parts of the sky. A basic angle of 58° was adopted, and in practice calibrated over intervals of a few hours with an accuracy of a few tens of microarcseconds (ESA, 1997, Volume 3, Figures 10.2 and 10.8).

In the second step, including a space motion of each star in the plane of the sky, orthogonal to the line-of-sight, the star's linear velocity is transformed (through its unknown distance) into an angular motion in the two angular coordinates – the star's 'proper motion' (Figure 1.3, middle). Only two additional unknowns are thereby introduced for each star, leading to a total of four unknowns for each star, compared with the 100 or so independent observations over three years. So, again, the proper motion is well determined, as are its standard errors.

In the third step, the motion of the Earth (or more strictly the orbiting satellite) around the Sun provides the periodic shift in measurement baseline necessary for the star's distance to be determined as a consequence of the apparent shift in the star's position as a function of the Earth's location (Figure 1.3, right). This apparent angular shift, the trigonometric parallax, provides a direct measurement of the star's distance through knowledge of the Earth's orbital geometry. Its inclusion adds just one unknown to the parameters describing the star's instantaneous position as a function of time. The total of five unknown parameters per star (two position components, two proper motion components, and the parallax) are the basic astrometric results provided by the measurement programme. The associated (5) standard errors and (10) covariances were determined and published, along with goodness-of-fit parameters.

Whilst of enormous astronomical importance, double and multiple stars provided considerable complications to the observations (due to the finite size and profile of the detector's sensitive field of view) and to the data analysis. Details are covered in Chapter 2. Yet the principles of analysis are easily incorporated into the qualitative framework described. If a binary star has a long orbital period such that nonlinear motions of the photocentre were insignificant over the short (three-year) measurement duration, the binary nature of the star would pass unrecognised by Hipparcos, but could show as a Hipparcos proper motion discrepant compared to those established from long temporal baseline proper motion programmes on ground. Higher-order photocentric motions could be represented by a seven-parameter, or even nine-parameter model fit (compared to the standard five-parameter model), and typically such models could be enhanced in complexity until suitable fits were obtained. A complete orbit, requiring seven elements, was determined for 45 systems. Orbital periods close to one year can become degenerate with the parallax, resulting in unreliable solutions for both. Triple or higher-order systems provided further challenges to the data processing. No valid astrometric solution could be obtained for 263 entries, of which 218 were flagged as suspected double; they are interesting cases for further ground-based and long-term astrometric monitoring.

Classical astrometry concerns only motions in the plane of the sky and ignores the star's radial velocity, its space motion along the line-of-sight. Whilst critical for an understanding of stellar kinematics, and hence population dynamics, its effect is generally imperceptible 'astrometrically', and therefore it is generally ignored in large-scale astrometric surveys. In practice, it can be measured as a Doppler shift of the spectral lines. Strictly, the radial velocity does enter a rigorous astrometric formulation (see Sections 1.4.5 and 1.13.2). Specifically, a space velocity along the line-of-sight means that the transformation from tangential linear velocity to (angular) proper motion is a function of time. The resulting effect of 'secular' or 'perspective' acceleration is the interpretation of a transverse acceleration actually arising from a purely linear space velocity with a significant radial component, with the positional effect proportional to $\pi \times \mu \times V_R$. At the accuracy levels of Hipparcos it is of (marginal) importance only for the nearest stars with the largest radial velocities and proper motions, but was accounted for in the 21 cases for which the accumulated positional effect over two years exceeds 0.1 mas (ESA, 1997, Volume 1, Section 1.2.8).

A few further complications should be mentioned. A detailed optical calibration model was included to map the transformation from sky to instrumental coordinates. Its adequacy could be verified by the detailed measurement residuals. The Earth's orbit, and the satellite's orbit with respect to the Earth, were essential for describing the location of the observer at each epoch of observation, and were supplied by an appropriate Earth ephemeris combined with accurate satellite ranging. Corrections due to special relativity (stellar aberration) made use of the corresponding satellite velocity. Modifications due to General Relativistic light bending were significant (4 mas at 90° to the ecliptic) and corrected for deterministically assuming $\gamma = 1$ in the PPN formalism. Residuals were examined to establish limits on any deviations from this General Relativistic value, as described further in Section 1.15.

1.3 Hipparcos Input Catalogue

The satellite observations relied on a pre-defined list of target stars. Stars were observed as the satellite rotated, by a sensitive region of the image dissector tube detector. This pre-defined star list formed the Hipparcos Input Catalogue: each star in the final Hipparcos Catalogue was contained in the Input Catalogue (Turon *et al.*, 1995). The Input Catalogue was compiled by the INCA Consortium (led by Catherine Turon) over the period 1982–89, finalised pre-launch, and published both in printed form (Turon *et al.*, 1992) and digitally (Turon *et al.*, 1996). Although fully superseded by the satellite results, it nevertheless includes supplemental information on multiple system components as well as compilations of radial velocities and spectral types which, not observed by the satellite, were not included in the published Hipparcos Catalogue. Its construction and properties are described in detail in Perryman *et al.* (1989, Volume II).

Figure 1.4 The third Scientific Proposal Selection Committee meeting in Paris, 6–7 April 1987. From left to right, where parentheses indicate meeting participants who were not committee members: (Jean Delhaye), Roland Wielen, Christian de Vegt, (Walter Fricke), Wilhelm Gliese, (Jean Kovalevsky). Members not in the picture: Adriaan Blaauw (chair), Jean Dommanget, Margarita Hack, Ed van den Heuvel, Carlos Jaschek, James Lequeux, Per Olof Lindblad, André Maeder, Poul Erik Nissen, Bernard Pagel, Alvio Renzini, Patrick Wayman.

Constraints on total observing time, and on the uniformity of stars across the celestial sphere for satellite operations and data analysis, led to an Input Catalogue of some 118 000 stars. It merged two components: first, a 'survey' of around 58 000 objects as complete as possible to the following limiting magnitudes

$$V \leq 7.9 + 1.1 \sin|b| \quad \text{spectral type} \leq \text{G5} \qquad (1.1a)$$

$$V \leq 7.3 + 1.1 \sin|b| \quad \text{spectral type} > \text{G5} \qquad (1.1b)$$

where b is the Galactic latitude. If no spectral type was available, the break was taken at $B - V = 0.8$ mag. Stars constituting this survey are flagged in the Hipparcos Catalogue itself (Field H68).

The second component comprised additional stars selected according to their scientific interest, with none fainter than about $V = 13$ mag. These were selected from around 200 scientific proposals submitted on the basis of an Invitation for Proposals issued by ESA in 1982, and prioritised by the Scientific Proposal Selection Committee in consultation with the Input Catalogue Consortium (Figure 1.4). Again, this selection had to balance *a priori* scientific interest, and the observing programme's limiting magnitude, total observing time, and sky uniformity constraints. The relevant scientific proposals are listed in Perryman *et al.* (1989, Volume II, Appendix C) and in Turon *et al.* (1992, Volume 1). The

Table 1.1 Principal observational characteristics of the Hipparcos and Tycho Catalogues. ICRS is the International Celestial Reference System.

Property	Value	
Common:		
Measurement period	1989.8–1993.2	
Catalogue epoch	J1991.25	
Reference system	ICRS	
coincidence with ICRS (3 axes)	± 0.6	mas
deviation from inertial (3 axes)	± 0.25	mas yr^{-1}
Hipparcos Catalogue:		
Number of entries	118 218	
with associated astrometry	117 955	
with associated photometry	118 204	
Mean sky density	~ 3	deg^{-2}
Limiting magnitude	$V \sim 12.4$	mag
Completeness	$V = 7.3 - 9.0$	mag
Tycho Catalogue:		
Number of entries	1 058 332	
based on Tycho data	1 052 031	
with only Hipparcos data	6301	
Mean sky density	~ 25	deg^{-2}
Limiting magnitude	$V \sim 11.5$	mag
Completeness to 90 per cent	$V \sim 10.5$	mag
Completeness to 99.9 per cent	$V \sim 10.0$	mag
Tycho 2 Catalogue:		
Number of entries	2 539 913	
Mean sky density:		
$b = 0°$	~ 150	deg^{-2}
$b = \pm 30°$	~ 50	deg^{-2}
$b = \pm 90°$	~ 25	deg^{-2}
Completeness to 90 per cent	$V \sim 11.5$	mag
Completeness to 99 per cent	$V \sim 11.0$	mag

indication of which catalogue stars are associated with any particular proposal was maintained in the Consortium's database, but is not publicly available and is unlikely to be preserved indefinitely.

1.4 Hipparcos Catalogue and Annexes

The data reductions were carried out in parallel by two data analysis consortia, known by their acronyms FAST (led by Jean Kovalevsky) and NDAC (led initially by Erik Høg and later by Lennart Lindegren). Early descriptions of the data reduction processes were given by Kovalevsky *et al.* (1995), with details of the properties of the preliminary catalogue in comparison with ground-based stellar positions and proper motions given by Lindegren *et al.* (1995). The analyses, proceeding from nearly 1000 Gbit of satellite data, incorporated a comprehensive system of cross-checking and validation of the entire data reduction and catalogue construction process. Final results of the two independent analyses were rigorously combined into the single final Hipparcos Catalogue and associated annexes. The main features of the Hipparcos Catalogue were presented at its publication by Perryman *et al.* (1997), and the main characteristics are given in Table 1.1.

Details of the data, their reductions, the merging of the two independent astrometric solutions, and the properties of the final catalogue, are given in the published Hipparcos and Tycho Catalogues (ESA, 1997, Volume 2–4). A summary of the data fields of the Hipparcos Catalogue is given in Table 1.2.

The following basic definitions and concepts relevant to discussions of accuracy and errors were adopted throughout the project: (a) standard error: defined as the standard deviation of an estimator, providing an estimation of the random part of the total estimation error involved in estimating a population parameter from a sample (*ISO Standards Handbook 3: Statistical Methods*); (b) accuracy: defined as the uncertainty of a measured quantity, including accidental and systematic errors, often used synonymously with 'external standard error'; (c) precision: defined as the uncertainty of a measured quantity due to accidental errors, often used synonymously with 'internal (or formal) standard error' as derived, e.g. from a least-squares solution.

The notation milliarcsec, or mas, is used to denote 10^{-3} arcsec, and the notation microarcsec, or µas, is used to denote 10^{-6} arcsec.

1.4.1 Hipparcos astrometry

The standard astrometric model adopted for single stars assumes uniform rectilinear space motion relative to the Solar System barycentre. Individual positions obtained over the three-year observation period were then combined through the five-parameter model fit. The stellar motion is then described by the following five astrometric parameters (the third component of the space velocity, the radial velocity, being undetermined from the Hipparcos observations): the barycentric coordinate direction at some reference epoch, T_0, (α, δ); 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, expressed in milliarcsec per Julian year; and 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. These five astrometric parameters (see Table 1.4 below) are given for almost all stars in the catalogue. The $\cos\delta$ factor, signified by the asterisk in $\mu_{\alpha *}$, relates the rate of change of position in right ascension to great-circle measure. The notation was introduced in

Table 1.2 Data fields of the Hipparcos Catalogue, taken from ESA (1997). † indicates data may have been derived from satellite and/or ground-based data. Fields H71–77 appear only in the machine-readable version.

Field	Description
H1	Hipparcos Catalogue (HIP) identifier ('*' = entry is of sequence in right ascension)
H2	Proximity flag indicating objects within 10 arcsec: H = HIP, T = TYC
H3–4	Positional identifier: truncated right ascension (h m s) and declination ($\pm^{\circ}\ '\ ''$); epoch J1991.25, ICRS
H5†	V (Johnson) magnitude
H6	Coarse variability flag: variable or possibly variable in Hp at (mag): 1: < 0.06; 2: 0.06–0.6; 3: > 0.6
H7	Source of V magnitude in Field H5: G = ground-based, H = HIP, T = TYC, $\sqcup$ = not available
H8–9	Right ascension, α, and declination, δ (degrees); epoch J1991.25, ICRS
H10	Reference flag for the astrometric parameters (Fields H3–4 and H8–30) of double and multiple systems: A, B, ... = specified component; * = photocentre; + = solution with respect to centre of mass
H11	Trigonometric parallax, π (mas)
H12–13	Proper motion in right ascension, $\mu_{\alpha*}$, and declination, μ_δ (mas yr^{-1}); epoch J1991.25, ICRS
H14–15	Standard error of position in right ascension, $\sigma_{\alpha*}$, and declination, σ_δ (mas); epoch J1991.25
H16	Standard error of the trigonometric parallax, σ_π (mas)
H17–18	Standard error of proper motion in right ascension, $\sigma_{\mu_{\alpha*}}$, and declination, σ_{μ_δ} (mas yr^{-1})
H19–28	Correlation coefficients: $\rho^{\delta}_{\alpha*}$, $\rho^{\pi}_{\alpha*}$, ρ^{π}_{δ}, $\rho^{\mu_{\alpha*}}_{\alpha*}$, $\rho^{\mu_{\alpha*}}_{\delta}$, $\rho^{\mu_{\alpha*}}_{\pi}$, $\rho^{\mu_\delta}_{\alpha*}$, $\rho^{\mu_\delta}_{\delta}$, $\rho^{\mu_\delta}_{\pi}$, $\rho^{\mu_\delta}_{\mu_{\alpha*}}$
H29	Percentage of rejected data, F1
H30	Goodness-of-fit statistic, F2
H31	Hipparcos Catalogue (HIP) identifier (as Field H1)
H32–33	Mean magnitude in the Tycho (star mapper) photometric system, B_T (mag), and standard error, σ_{B_T}
H34–35	Mean magnitude in the Tycho (star mapper) photometric system, V_T (mag), and standard error, σ_{V_T}
H36	Reference flag for B_T and V_T (Fields H32–35): A, B, ... = component, * = combined, – = multiple
H37–38†	Colour index in the Johnson photometric system, $B-V$ (mag), and standard error, σ_{B-V}
H39	Source of $B-V$: G = ground-based, T = Tycho, $\sqcup$ = not available
H40–41†	Colour index in the Cousins' photometric system, $V-I$ (mag), and standard error, σ_{V-I}
H42	Source of $V-I$: A, B, C, ..., T
H43	Reference flag for colour indices (Fields H37–42) and Field H5: * = combined
H44–45	Median magnitude in the Hipparcos photometric system, Hp (mag), and standard error σ_{Hp}
H46	Scatter of the Hp observations, s (mag)
H47	Number of photometric observations for the Hp photometry, N
H48	Reference flag for Fields H44–54: A, B, ... = component, * = combined, – = multiple
H49–50	Observed magnitude at maximum/minimum luminosity (from 5th/95th distribution percentiles)
H51	Variability period from Hipparcos, P (days)
H52	Variability type: C = 'constant'; D = duplicity possibly causing variability; M = micro-variable; P = periodic; R = revised photometry; U = unsolved; $\sqcup$ = constant or variable
H53	Variability annex flag: further data in Volume 11: 1 = periodic, 2 = 'unsolved'
H54	Variability annex flag: light-curves in Volume 12: A = folded; B = AAVSO; C = unfolded
H55	CCDM identifier
H56	Historical status of the CCDM identifier: H = Hipparcos; I = Input Catalogue; M = miscellaneous
H57	Number of separate Hipparcos Catalogue entries with the same CCDM identifier
H58	Number of components into which this entry is resolved: 1, 2, 3, 4
H59	Flag indicating details provided in the Double and Multiple Systems Annex: C, G, O, V, X
H60	Flag indicating source of absolute astrometry: F, I, L, P, S
H61	Flag indicating solution: A = good, B = fair, C = poor, D = uncertain, S = suspected non-single
H62	Component designation, brighter/fainter (in Hp), for parameters in Field H63–67
H63	Position angle of the fainter component (at epoch J1991.25), θ (degrees, rounded value)
H64	Angular separation (at epoch J1991.25), ρ (arcsec, rounded value)
H65	Standard error of the angular separation, σ_ρ (arcsec)
H66–67	Magnitude difference of components, ΔHp (mag), and standard error $\sigma_{\Delta Hp}$
H68	Flag: S = 'survey' star (i.e. complete to the magnitude limits defined in Section 1.3)
H69	Flag indicating identification chart in Volume 13: D = DSS; G = GSC
H70	Flag indicating note at end of relevant volume(s): D, G, P, W = D + P, X = D + G, Y = G + P, Z = D + G + P
H71–74	Cross-identifiers to HD/HDE/HDEC; DM: BD, CoD, CPD (see also Table 1.12)
H75	$V-I$ used for the photometric processing (see Section 4.10)
H76–77	Spectral type and source of spectral type (compilation, primarily from Hipparcos Input Catalogue)

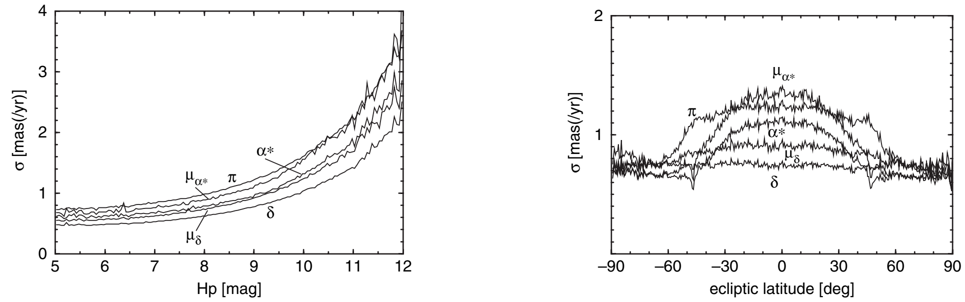

Figure 1.5 Left: median standard errors of the five astrometric parameters as a function of Hp magnitude. The unit of the standard error is milliarcsec (mas) for the positional components (α, δ) and parallax (π), and mas yr^{-1} for the proper motion components ($\mu_{\alpha*} = \mu_\alpha \cos\delta$, μ_δ). Right: median standard errors of the astrometric parameters as a function of ecliptic latitude. The dependency on ecliptic latitude is a consequence of the ecliptic-based scanning law. The errors are given at the catalogue epoch, J1991.25. From Perryman et al. *(1997, Figures. 1 and 2).*

the Hipparcos Catalogue publication to avoid possible confusion in the meaning of μ_α.

Median astrometric standard errors (in position, parallax, and annual proper motion) are in the range 0.7–0.9 mas for stars brighter than 9 mag at the catalogue epoch (J1991.25). The catalogue is a materialisation of 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^{-1} (see Section 1.4.1). The 118 218 constituent stars provide a mean sky density of $\sim$ 3 stars deg^{-2}.

The 'catalogue epoch', J1991.25, corresponds to a moment in time close to the central epoch of the satellite observations. Catalogue positions are given, within the adopted reference system ICRS, at this epoch. This choice minimises the standard error of positions, but is otherwise essentially arbitrary: the provision of the correlation coefficients for each astrometric solution allows the standard errors of transformed quantities to be determined at an arbitrary epoch; including, for example, the epoch at which the standard error is minimised for each individual star, or the standard epoch J2000.0 (ESA, 1997, Volume 1, Section 1.2.7).

Figure 1.5 illustrates the median precision of each of the astrometric parameters as a function of *Hp* magnitude and ecliptic latitude, at the catalogue epoch. Detailed sky charts and histograms giving the astrometric and photometric accuracies as a function of position and magnitude are included in the Hipparcos Catalogue (ESA, 1997, Volume 1, Section 3).

The parallax determinations are trigonometric, absolute (in the sense that the parallax determination of a given star is not dependent upon either the parallaxes, or assumptions concerning the parallaxes, of other stars – including stars close by on the sky), and independent of any previous distance determinations. Analyses place a limit on the global parallax zero-point offset of less than 0.1 mas, and give confidence that the published standard errors are a reliable indication of their true external errors.

While there seems no evidence for a global zero-point shift of the Hipparcos parallaxes above an estimated 0.1 mas (ESA, 1997, Volume 3, p323), the fact that the parallax errors will likely be correlated over angular scales of 2–3° was anticipated from the measurement principle. For any astrometric parameter a, the correlation function is defined in terms of the normalised differences between the NDAC and FAST Consortium values, $\overline{\Delta a}$, as

$$R(\theta) = \frac{\langle\, \overline{\Delta a}_i \, \overline{\Delta a}_j \,\rangle}{\sqrt{\langle\, \overline{\Delta a}_i^2 \,\rangle \, \langle\, \overline{\Delta a}_j^2 \,\rangle}} \tag{1.2}$$

where averages are calculated over all star pairs (i, j) whose separations are in the range $\theta \pm \Delta\theta/2$. Figure 1.6, from ESA (1997, Volume 3, Figure 16.37) shows the sample correlation function for the parallax differences at a resolution of $0\overset{\circ}{.}1$, calculated from all $\sim 5 \times 10^9$ pairs of 100 890 stars from the Hipparcos reductions. However, the sparse mean catalogue density of about three stars deg^{-2} means that open clusters with a large local stellar concentration are probably the only regions where these small-scale systematics can be estimated, or are relevant. Van Leeuwen (2002) argued that there is no evidence for systematic or correlated errors beyond a correlation level of 0.12 and an angular scale of $1\overset{\circ}{.}2$.

For both the Hipparcos observations and the data reductions, an enormous simplicity arose from the absence of the atmosphere, and the decoupling of the observations from the rotation of the Earth. The

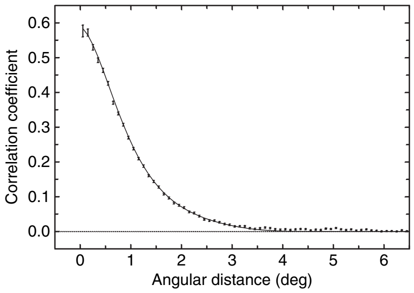

Figure 1.6 Mean sample correlation of normalised parallax difference, $R(\theta)$, as defined by Equation 1.2, out to $\theta = 6^\circ$. At angular separations less than a few degrees the correlation is strongly positive, but decreases to almost negligible values beyond about 4°. It is likely that the actual parallax errors in the published Hipparcos Catalogue exhibit a similar spatial correlation, but with some uncertain normalisation. From ESA (1997, Volume 3, Figure 16.37).

relationship between the resulting Hipparcos reference frame and the dynamical reference frame materialised by observations of Solar System objects (made from the ground and space) is considered further in Section 1.10.2 and Chapter 10.

Object directions The 'direction' to an object at each epoch of observation, as measured by a moving observer, is obtained by three successive transformations (see Murray 1983, which remains an authoritative treatment of vectorial astrometry, and ESA 1997, Volume 3, Section 12.3 for details applicable to Hipparcos): derivation of the 'coordinate direction' to the object by a translation of space-time coordinates from the adopted reference point (at the Solar System barycentre) and epoch to the observer at the time of observation; determination of the 'natural direction' to the object as measured by a hypothetical stationary observer, in a locally flat coordinate system at rest with respect to the barycentre, corresponding to the application of gravitational light deflection; and determination of the 'proper direction' taking account of the observer's motion, corresponding to the application of stellar aberration. In practice, transformations from coordinate to natural directions were carried out in space-time coordinates characterised by a spherically symmetric, heliocentric General Relativistic metric in which light-bending by the Sun (and, in NDAC only, the Earth) was taken into account. Deviations from this assumed metric were parameterised in a PPN-type formalism, from which values of $\gamma = 1.000 \pm 0.004$ (in FAST) and $\gamma = 0.992 \pm 0.005$ (in NDAC) gave further confidence in the metric formalism and global reductions (see also Section 1.15). Proper directions were computed using models of the Earth's motion with respect to the Solar System barycentre, and of the satellite motion with respect to the Earth's barycentre. The former was taken from the planetary (VSOP 82 Bretagnon, 1982) and lunar (ELP 2000 Chapront & Francou, 2003) ephemerides constructed by the Bureau des Longitudes (now the Institut de Mécanique Céleste, IMC); their use was equivalent, to within 0.01 mas, with the use of the Jet Propulsion Laboratory DE200 ephemeris. These ephemerides have since been superseded, most recently by the JPL development ephemeris solution DE414 (Konopliv *et al.*, 2006), and the numerical planetary ephemeris developed at the IMCCE–Observatoire de Paris, INPOP06 (Fienga *et al.*, 2008). The satellite position was provided by the operations centre (ESOC) with an accuracy of some 1.5 km in position and $0.2\,\mathrm{m\,s^{-1}}$ in velocity. Otherwise, the former IAU (1976) system of constants was used for the reductions (Table 1.3).

Reference system and reference frame The terminology used in the 1991 IAU resolution on reference frames and reference systems distinguishes between the use of the term 'reference system' and 'reference frame' (Wilkins, 1990). A reference system is the complete specification of how a celestial coordinate system is formed. It defines the origin and fundamental planes (or axes) of the coordinate system. It also specifies all of the constants, models, and algorithms used to transform between observable quantities and reference data that conform to the system. A reference frame consists of a set of identifiable fiducial points on the sky along with their coordinates, which serves as the practical realisation of a reference system.

While a frame represented by the directions to distant extragalactic objects intuitively complies with the requirements of an inertial frame, there are some practical considerations. The fact that such a frame is defined kinematically, through the absence of transverse motions, rather than dynamically, is why it is sometimes referred to as a 'quasi-inertial' frame. The General Relativistic definition of an inertial frame in terms of the form of the space-time metric would require practical confirmation, for example via accurate gyroscopes, which is beyond current measurement accuracies. An inertial frame can also be defined as non-rotating with respect to the Universe, related to Mach's principle in which a body's inertia is caused by the distribution of mass throughout the Universe. Finally, the Solar System may be regarded as representing a local inertial reference frame of dynamical definition, i.e. related to Newton's laws of motion. A pragmatic definition was given by Clemence (1966): 'an inertial frame of reference is defined as a frame that is free from linear and rotational accelerations'. The consistency between the adopted extragalactic reference

Table 1.3 Physical and astronomical constants used for the Hipparcos data reductions, from ESA (1997, Table 1.2.2). The unit of time is the SI second, or the Julian Year when more appropriate. The speed of light enters mainly in the computation of stellar aberration. The astronomical unit A appears in all formulae relating linear measures to the parallax; depending on the context and the units used, it is represented by a variety of numerical values, as indicated (some older texts give slightly different numerical values for A_v, usually because they assume the now-obsolete tropical year as the time unit for the proper motions); for considerations in defining A within a General Relativistic framework, see Huang et al. *(1995). The heliocentric and geocentric gravitational constants are used to compute the gravitational light bending by the Sun and the Earth. The obliquity of the ecliptic has no direct significance for the data reductions, but is used as a conventional value to transform between the equatorial and ecliptic systems. The Earth ephemeris is relevant for the calculation of aberration and parallax. Note that some reference quantities have been (slightly) revised through subsequent work (see Appendix A).*

Symbol	Meaning/Application	Value
	Unit of time	SI second as realised on the geoid
	Time scale	Terrestrial Time (TT)
Julian Year	Proper motion unit (mas yr^{-1})	$365.25 \times 86\,400$ s (exactly)
c	Speed of light	$299\,792\,458$ m s^{-1} (exactly)
A	Astronomical unit	$(499.004\,782$ s$)\times c$ (exactly)
		$= 1.495\,978\,701 \times 10^{11}$ m (A_m)
		$= 1000$ mas pc (A_p)
		$= 4.740\,470\,446$ km yr s^{-1} (A_v)
		$= 9.777\,922\,181 \times 10^{8}$ mas km yr s^{-1} (A_z)
GS	Heliocentric gravitational constant	$1.327\,124\,38 \times 10^{20}$ m^3 s^{-2}
GE	Geocentric gravitational constant	$3.986\,005 \times 10^{14}$ m^3 s^{-2}
ϵ	Obliquity of ecliptic (J2000.0)	$23^\circ\,26'\,21.448''$ (exactly)
		$= 23^\circ\!.439\,291\,111\,1\ldots$
	Planetary/lunar ephemeris	VSOP 82/ELP 2000

The origin of right ascension and declination: The fundamental plane of astronomical reference systems has conventionally been the extension of the Earth's equatorial plane, at some date, to infinity. The declination of a celestial object is its angular distance north or south of this plane. The right ascension is its angular distance measured eastward along the equator from some agreed reference point, traditionally the equinox, i.e. the point at which the Sun crosses the equatorial plane moving from south to north. The Sun's apparent yearly motion lies in the ecliptic, the plane of the Earth's orbit. The equinox, therefore, is a direction in space along the nodal line defined by the intersection of the ecliptic and equatorial planes. Because both of these planes are moving, the coordinate systems that they define must have a date associated with them; such a reference system must therefore be specified as the equator and equinox of some specific date, previously B1950 and more recently J2000. The previous (pre-Hipparcos) astronomical reference system was based on the equator and equinox of J2000.0 determined from observations of planetary motions, together with the IAU (1976) System of Astronomical Constants and related algorithms. The reference frame that embodied this system for practical purposes was the Fifth Fundamental Catalogue (FK5).

frame and the dynamical reference frame defined by the motion of Solar System objects is considered further in Chapter 10.

In 1995, the IAU Working Group on Reference Frames identified the International Celestial Reference System (ICRS) as the official IAU reference system, replacing FK5 (mean equator and equinox J2000) as the practical definition of celestial coordinates in the optical. The ICRS is a set of specifications defining a high-precision coordinate system with its origin at the Solar System barycentre and 'space fixed' (kinematically non-rotating) axes. The specifications include a metric tensor, a prescription for establishing and maintaining the axis directions, a list of benchmark objects with precise coordinates for each one, and standard models and algorithms that allow these coordinates to be transformed into observable quantities for any location and time. A review is given by Johnston & de Vegt (1999). The ICRS is itself materialised, with an accuracy of ±30 μas, by the International Celestial Reference Frame (ICRF), a catalogue of adopted positions of 608 extragalactic radio sources observed with VLBI, all strong (> 0.1 Jy) at S and X bands, i.e. at wavelengths 13 and 3.6 cm (Ma *et al.*, 1998). Most have faint optical counterparts (typically $V > 18$) and the majority are quasars. Of these objects, 212 are defining sources that establish the orientation of the ICRS axes, with origin at the Solar System barycentre. Its construction ensured that no discontinuity larger than the uncertainty of the FK5 system occurred in the transition from FK5 to ICRS. Specifically, the ICRS axes are consistent with those of the FK5 system (mean equator and equinox J2000) within the uncertainty of the latter, ±50–80 mas (Arias *et al.*, 1995), and their tie to the

Table 1.4 Astrometric characteristics of the Hipparcos and Tycho Catalogues.

Property	Value	
Hipparcos Catalogue:		
For $Hp \leq 9$ mag:		
median σ_α at J1991.25	0.77	mas
median σ_δ at J1991.25	0.64	mas
median σ_π	0.97	mas
median $\sigma_{\mu_\alpha \cos\delta}$	0.88	mas yr^{-1}
median σ_{μ_δ}	0.74	mas yr^{-1}
For each astrometric parameter:		
10 per cent better than	0.47–0.66	mas (yr^{-1})
smallest errors	0.27–0.38	mas (yr^{-1})
Fractional distance errors:		
distance < 10% ($\sigma_\pi/\pi < 0.1$)	20 853	
distance < 20% ($\sigma_\pi/\pi < 0.2$)	49 399	
Estimates of systematic errors:		
external errors/standard errors	~ 1.0–1.2	
systematic errors in astrometry	< 0.1	mas (yr^{-1})
Tycho Catalogue:		
For each astrometric parameter:		
standard errors for $V_T < 9$	7	mas (yr^{-1})
standard errors for $V_T \sim 10.5$	25	mas (yr^{-1})
smallest errors	3	mas (yr^{-1})
Estimates of systematic errors:		
external errors/standard errors	~ 1.0–1.5	
systematic errors in astrometry	~ 1	mas (yr^{-1})
Tycho 2 Catalogue (all stars):		
standard errors of positions	60	mas
standard errors of proper motions	2.5	mas yr^{-1}

best realisation of the FK5 dynamical reference system was within ±3 mas (Folkner *et al.*, 1994).

The Hipparcos reference frame The satellite observations essentially yielded highly accurate relative positions of stars with respect to each other, throughout the measurement period (1989–93). In the absence of direct observations of extragalactic sources (apart from marginal observations of 3C 273) the resulting rigid reference frame was transformed to an inertial system linked to extragalactic sources. This allows surveys at different wavelengths to be directly correlated with the Hipparcos stars, and ensures that the catalogue proper motions are, as far as possible, kinematically non-rotating. The determination of the relevant three solid-body rotation angles, and the three time-dependent rotation rates, was conducted and completed in advance of the catalogue publication by a specific working group (led by Jean Kovalevsky and Lennart Lindegren). This resulted in an accurate but indirect link to an inertial, extragalactic, reference frame.

A variety of methods to establish this reference frame link before catalogue publication were included and appropriately weighted (Lindegren & Kovalevsky, 1995; Kovalevsky *et al.*, 1997): interferometric observations of radio stars by VLBI networks, MERLIN and VLA; observations of quasars relative to Hipparcos stars using CCDs, photographic plates, and the Hubble Space Telescope; photographic programmes to determine stellar proper motions with respect to extragalactic objects (Bonn, Kiev, Lick, Potsdam, Yale/San Juan); and comparison of Earth orientation parameters obtained by VLBI and by ground-based optical observations of Hipparcos stars. Although very different in terms of instruments, observational methods and objects involved, the various techniques generally agree to within 10 mas in the orientation and 1 mas yr^{-1} in the rotation of the system. From appropriate weighting, the coordinate axes defined by the published catalogue are believed to be aligned with the extragalactic radio frame to within ± 0.6 mas at the epoch J1991.25, and non-rotating with respect to distant extragalactic objects to within ± 0.25 mas yr^{-1}. Studies by some of the groups contributing to this overall work were reported separately: the contributions by the HST Fine Guidance Sensor by Hemenway *et al.* (1997); the Bonn photographic plate observations by Geffert *et al.* (1997) and Odenkirchen *et al.* (1997); the Potsdam photographic plate observations by Hirte *et al.* (1997); and the NPM and SPM contributions by Platais *et al.* (1998).

The Hipparcos and Tycho Catalogues were constructed such that the Hipparcos Reference Frame coincides, to within observational uncertainties, with the ICRS, and representing the best estimates at the time of the catalogue completion (in 1996). The resulting Hipparcos Reference Frame is thus the materialisation of the ICRS in the optical, extending and improving the J2000(FK5) system, retaining approximately the global orientation of that system but without its regional errors.

The construction and implementation of the ICRS is supported by the International Astronomical Union (IAU). Resolution B2, passed by the 23rd General Assembly of the IAU in August 1997, states that: (a) from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS) as specified in the 1991 IAU Resolution on reference frames and as defined by the International Earth Rotation Service (IERS); (b) the corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames; (c) the Hipparcos Catalogue shall be the primary realisation of the ICRS at optical wavelengths; (d) the IERS should take appropriate measures, in conjunction with the IAU Working Group on Reference Frames, to maintain the ICRF and its ties to the reference frames at other wavelengths.

At the IAU General Assembly in 2000, Resolution B1.2 restricted the number of Hipparcos stars to be considered part of the optical realisation of the ICRS.