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LETTER

*Letter to the Editor*

# Double star data in the Hipparcos Catalogue*

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**Abstract.** The Hipparcos Catalogue contains astrometric results for 117 955 catalogue entries, many of which are in reality double or multiple stars. For 17 917 entries special solutions were made in order to cope with the various manifestations of multiplicity, and 6763 other entries were flagged as suspected binaries but solved as single stars. Details of the special solutions are contained in the Hipparcos Catalogue Double and Multiple Systems Annex, divided in five parts according to the type of solution: resolved systems (13 211 entries with a total of 24 588 components), astrometric binaries with curved proper motion (2622 entries) or orbital solutions (235 entries), 'variability-induced movers' (288 entries) and 'stochastic' solutions (1561 entries). Trigonometric parallaxes and the positions and proper motions in the extragalactic reference system ICRS are provided for all entries.

**Key words:** Hipparcos – astrometry – double stars – catalogues

## 1. Introduction

The Hipparcos Catalogue (ESA 1997) provides the positions, proper motions and trigonometric parallaxes for over 100 000 stars observed between 1989 and 1993 with the European Space Agency's astrometry satellite Hipparcos. The published catalogue contains detailed documentation of the data, the satellite and its operation, and of the data reductions. Some key attributes of the Hipparcos Catalogue have been presented by Perryman et al. (1997). The present paper summarises the information content of the catalogue with respect to double and multiple stars, as given in the Hipparcos Catalogue Double and Multiple Systems Annex (subsequently referred to as 'the Annex').

The presence of double and multiple systems severely complicated the construction of the Hipparcos Catalogue. A global reference frame had to be established through a simultaneous solution of the astrometric parameters of a dense network of stars covering the entire sky. This process had to be restricted to observationally single stars, i.e. either real single stars or unresolved objects whose proper motions could be considered constant over the few years of data gathering. It was thus necessary to identify the subset of stars satisfying this criterion, build the global reference frame from their observations, and afterwards attach the remaining objects to this frame using the appropriate object models. This process was further complicated by the necessity to reconcile the results of several groups treating the satellite data by different methods.

A major difficulty was that no unique alternative model could be applied to all the objects for which deviations from the 'single-star model' were detected: these had to be classified according to observational criteria which do not necessarily correspond to well-defined regions of the physical characteristics of the systems. Thus, while the astrometric processing of the 'single' stars can be characterised as quite stringent, various *ad hoc* procedures had to be adopted for the objects in the Annex. The classification of these objects as well as their published solutions should consequently be regarded with appropriate caution.

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* Based on observations made with the ESA Hipparcos astrometry satellite

## 2. Observational effects of duplicity

The basic observational entity of the Hipparcos Catalogue is an 'entry', identified by a HIP number. This concept was derived from instrumental limitations and refers to whatever fell inside the $\sim$ 35 arcsec diameter (FWHM) instantaneous field of view of the Hipparcos main detector system. An entry may consist of a single star, a (resolved or unresolved) double or multiple system, or one or more components of a wide system. Unresolved objects were observed by their photocentres in the *Hp* wavelength passband of the Hipparcos main detector. The components or the photocentre may exhibit significant orbital motion about the system's centre of mass. Even if only double systems are considered, several observationally different types are distinguished depending mainly on the separation ($\varrho$), magnitude difference ($\Delta Hp$), and orbital period ($P$):

1. Very close binaries ($\varrho \lesssim 2$ milliarcsec [mas]): the photocentre practically coincides with the centre of mass, making such systems astrometrically equivalent to single stars.
2. Unresolved systems ($2 \lesssim \varrho \lesssim 100$ mas or $\Delta Hp \gtrsim 4$):
   (a) short-period binaries ($P \lesssim 0.1$ year) where the observations provided a quasi-random sampling of the orbit of the photocentre producing mean results usually representing the centre of mass;
   (b) for intermediate periods ($0.1 \lesssim P \lesssim 10$ years) the full Keplerian orbit of the photocentre could sometimes be determined, possibly with the help of ground-based elements;
   (c) for somewhat longer periods ($5 \lesssim P \lesssim 30$ years) the motion of the photocentre may have been significantly non-linear, although no periodic solution was possible;
   (d) for moderately long periods ($10 \lesssim P \lesssim 100$ years) the motion of the photocentre may have appeared linear over the mission, although it differed significantly from the motion of the centre of mass;
   (e) long-period binaries ($P \gtrsim 100$ years) have no significant bias in the proper motion, although the photocentre may be offset from the centre of mass.
3. Resolved systems ($0.1 \lesssim \varrho \lesssim 10$ arcsec and $\Delta Hp \lesssim 4$ mag): the detector signal could be decomposed into the contributions of the different stellar components.
4. Known systems with $10 < \varrho < 30$ arcsec were sometimes observed as 'two-pointing doubles' by including the components as separate entries. To properly take into account their mutual influence the components had to be treated together in the data analysis.
5. Wide systems ($\varrho \gtrsim 30$ arcsec): only one component at a time was included in the instantaneous field of view.

For multiple stars the set of possible configurations is vastly expanded as each sub-pair could fall into any of the above categories. The not uncommon photometric variability of components may cause additional complications, such as spurious motion of the photocentre (Sect. 3.5).

Apart from the use of ground-based information, duplicity could basically be detected in two ways: from analysis of the detector signal, in particular the visibility expressed as a difference between the Hipparcos 'ac' and 'dc' magnitudes (van Leeuwen et al. 1997), and from the residuals of the fit to a standard five-parameter astrometric model for a single star. The first method was mainly sensitive to systems of type 3 and 4, the second to type 2a–c. Type 1, 2d–e and 5 were virtually indistinguishable from single stars.

**Table 1.** Number of entries in the Hipparcos Catalogue for the different categories of astrometric solutions

| Type of solution | Annex | No. of entries |
|---|---|---|
| Single-star solutions | — | 100 038 [1] |
| Component solutions | C | 13 211 [2] |
| Acceleration solutions | G | 2 622 |
| Orbital solutions | O | 235 |
| Variability-induced movers | V | 288 |
| Stochastic solutions | X | 1 561 |
| No valid astrometric solution | — | 263 [3] |
| Total number of entries | | 118 218 |
| Entries with valid astrometry | | 117 955 |

[1] of which 6763 flagged as suspected double
[2] comprising 24 588 components in 12 195 solutions
[3] of which 218 flagged as suspected double

## 3. Classification of solutions

In the limited time available for the double-star processing it was not feasible to consider all the different situations that might apply to a given object, with due regard to available ground-based information, and to select and publish in each case the most appropriate solution. What emerged was a practical scheme dividing the astrometric solutions into the seven categories summarised in Table 1. The last category contains the entries without associated astrometry, e.g. because of no detectable signal, too few observations, or where the signal could not be adequately interpreted in terms of any of the attempted models. The other categories are described hereafter.

The Hipparcos Catalogue gives primarily the five astrometric parameters (Sect. 3.1) for all entries with associated astrometry, whether the entry was treated as a single star or not. The precise meaning of the position and proper motion (e.g. component, photocentre, or centre of mass) depends on the type of solution, and the relevant flags in the catalogue must be consulted for correct interpretation of these data. Additional information for the double and multiple systems is given in the various parts of the Annex.

### 3.1. Apparently single stars

The vast majority of entries (85%) could be solved as single stars, astrometrically characterised by five parameters: the position at epoch J1991.25 ($\alpha$, $\delta$), the parallax ($\pi$) and the proper motion ($\mu_{\alpha *} = \mu_\alpha \cos\delta$, $\mu_\delta$). Many are in reality binaries, and duplicity effects may be implicit in the results of some of them.

For instance, binaries of type 2d may have proper motions which differ significantly from ground-based values determined with temporal baselines of several decades. The positions for types 2d–e may depend on the effective wavelength of the observations. 6763 of the entries are flagged as suspected non-single based on various criteria, although no significant or convincing non-single star solution was found. Some 4200 of the entries were listed as double or multiple in the Hipparcos Input Catalogue, most of them with large separations (> 30 arcsec) or magnitude differences (> 4 mag) making them effectively single for Hipparcos.

### *3.2. Component solutions (Part C of the Annex)*

These are resolved systems of type 3 and 4 for which the Annex gives the five astrometric parameters and the *Hp* magnitude of each resolved component. This allows linear (but not curved) relative motion among the components. Of the 12 195 solutions 12 005 are double, 182 triple and 8 quadruple star solutions; 10 895 were solved as fixed configurations, i.e. constrained to a common parallax and proper motion; 1186 included linear relative motion, and 202 more included linear relative motion and individual parallaxes of the components. 2996 of the double stars were not previously known as such. Figure 1 shows the distribution of separations and magnitude differences for all the pairs and for the newly detected pairs. The Annex provides a fairly complete census of binaries among the Hipparcos stars with $\Delta Hp < 3.5$ and $\varrho > 0.12$ to 0.3 arcsec (depending on $\Delta Hp$).

The published component solutions were obtained by combining the results of the independent analyses performed by the reduction consortia FAST and NDAC. For nearly 90% of the solutions the agreement between the two reductions was sufficiently good to permit a straightforward averaging of the data, while the differences were used to calibrate the estimated standard errors. In 1113 cases the two reductions could not be reconciled, as they typically differed by a multiple of the fundamental period of the modulating grid ($\sim 1.2$ arcsec), and one of them had to be selected on the basis of various criteria. Such cases were flagged in the catalogue and the main parameters of the alternative solutions are given among the notes.

While other parts of the Hipparcos Catalogue are arranged according to the HIP number, Part C of the Annex uses the CCDM identifier (Catalogue of Components of Double and Multiple Stars; Dommanget & Nys 1994), sometimes corresponding to more than one HIP number. The identification of systems and components required ground-based information, often also indispensable as starting points for the highly non-linear analysis of the space results. Such data were primarily obtained from the CCDM and a special database maintained at OATO (Torino), but in some cases dedicated observations were initiated. The updating of the ground-based information benefited from the use of a pre-release version of the Washington Catalogue of Visual Double Stars (C.E. Worley and G.G. Douglass, US Naval Observatory, Washington).

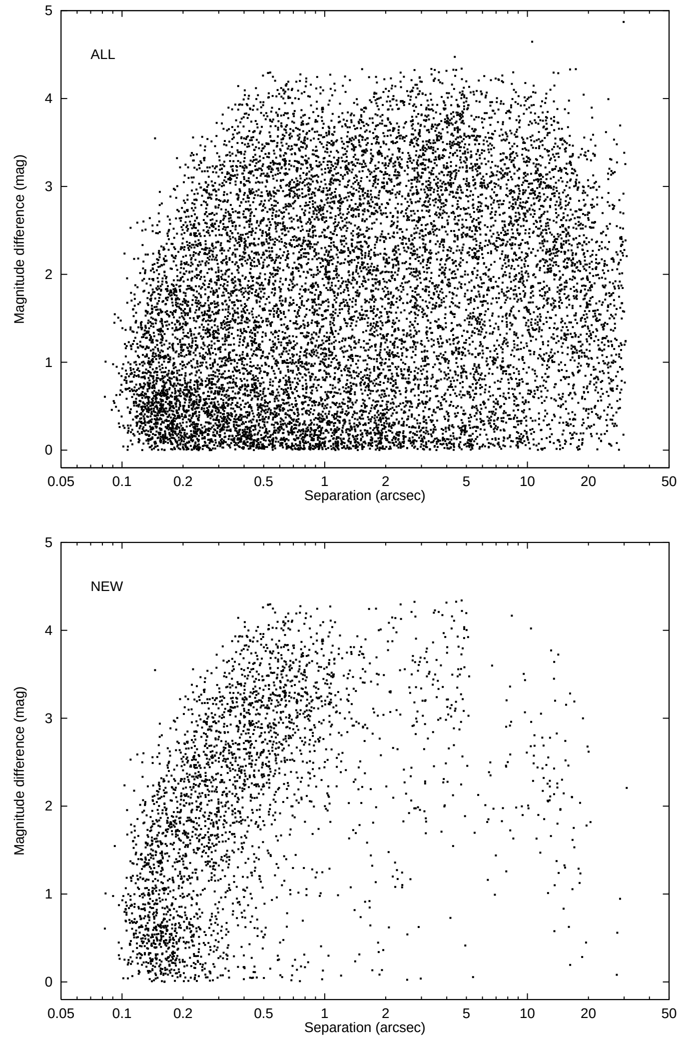


**Fig. 1.** Distribution of separation and magnitude difference for all 12 393 component pairs in Part C of the Annex (top), and for the subset of 2996 pairs discovered with Hipparcos (bottom)

### *3.3. Acceleration solutions (Part G of the Annex)*

Part G lists apparently single stars with significantly non-linear motion, for which no orbital (periodic) solution could be made, i.e. systems of type 2d according to Sect. 2. A quadratic or cubic polynomial of time was fitted to the motion in each coordinate, in addition to the standard five astrometric parameters. In tangential coordinates ($\xi \sim \Delta\alpha \cos\delta$, $\eta \sim \Delta\delta$) the apparent motion—excluding parallax—was modelled as

$$\begin{aligned} \xi(t) &= \xi(0) + t\mu_{\alpha*} + \tfrac{1}{2}(t^2 - a)g_{\alpha*} + \tfrac{1}{6}(t^2 - b)t\dot{g}_{\alpha*} \\ \eta(t) &= \eta(0) + t\mu_{\delta} + \tfrac{1}{2}(t^2 - a)g_{\delta} + \tfrac{1}{6}(t^2 - b)t\dot{g}_{\delta} \end{aligned} \quad (1)$$

where $t$ is the time in years from J1991.25, $(g_{\alpha*}, g_\delta)$ are the accelerations in mas $\mathrm{yr}^{-2}$, and $(\dot{g}_{\alpha*}, \dot{g}_\delta)$ the rates of change of the accelerations in mas $\mathrm{yr}^{-3}$. The constants $a = 0.81$ $\mathrm{yr}^2$ and $b = 1.69$ $\mathrm{yr}^2$ were introduced to make the $g$ and $\dot{g}$ terms approximately orthogonal to the preceding terms in Eq. (1). Quadratic or cubic solutions were accepted depending on the statistical significance of the $g$ and $\dot{g}$ terms. The Annex includes 2163 quadratic solutions (i.e. excluding the $\dot{g}$ terms) and 459 cubic solutions. The polynomial representation of the motion has no validity outside the mission interval (1989.9–1993.2). The proper motion ($\mu_{\alpha*}, \mu_\delta$), representing the mean motion over the mission interval, is safer to extrapolate to other epochs, but the positional uncertainty may be considerably greater than indicated by the standard errors in proper motion.

### *3.4. Orbital solutions (Part O of the Annex)*

For some systems (type 2b) the orbital elements of the photocentre could be determined in addition to the normal five astrometric parameters for the centre of mass. In many cases some of the elements were adopted from ground-based observations of the astrometric or spectroscopic binaries, or taken as starting values for the solution. However, in nearly half of the cases the period was identified from periodogram analysis of the space data performed at the Astronomisches Rechen-Institut (ARI), Heidelberg, and refined elements subsequently determined by least-squares fitting to the Hipparcos intermediate astrometric data (Sect. 4). A complete orbit (requiring seven elements) was determined for 45 systems.

### *3.5. Variability-induced movers (Part V of the Annex)*

Variability-induced movers, or VIMs, are unresolved binaries in which one of the components is variable. The photocentre of a VIM shows a specific motion on the sky, coupled to the variation of the total brightness of the system (Wielen 1996). Given the total magnitude determined by the satellite for each scan across the system, a VIM solution requires two elements ($D_{\alpha*}, D_\delta$) in addition to the five astrometric parameters. From these can be derived the position angle of the constant component with respect to the variable, and a lower limit for the separation, typically in the range 10 to 90 mas. The astrometric data in the main catalogue refer to the photocentre for a specific value of the total magnitude. The VIM solutions were derived at ARI, Heidelberg, by a critical examination of variable stars, using FAST intermediate astrometry.

### *3.6. Stochastic solutions (Part X of the Annex)*

For some objects it was not possible to find an acceptable single or double star solution in reasonable agreement with the statistical uncertainties of the individual measurements. Such objects could be unresolved binaries of type 2a–b, resolved objects where the secondary could not be located or was perturbed by variability or edge effects of the instantaneous field of view. Lacking an acceptable deterministic model for these objects, a reasonable alternative is to adopt a stochastic model for the displacements relative to the centre of mass. This was achieved by quadratically increasing the standard errors of the measurements until rms normalised residual was exactly equal to 1. The added dispersion, called the 'cosmic error', typically ranges from 3 to 30 mas. Solutions with a cosmic error greater than 100 mas were rejected as this was normally an indication of grid-step errors.

## 4. Catalogue Products

The Double and Multiple Systems Annex is available in printed form as part of the 17-volume Hipparcos Catalogue (ESA 1997). The machine-readable version of the Annex, included on one of the ASCII CD-ROMs being part of that publication, includes additional information, in particular the statistical correlations of the estimated model parameters in Parts C, G, O and V. In view of the many possible alternative object models that might apply to the non-single stars, two major intermediate data sets have been included on the CD-ROMs: the 'intermediate astrometric data' for all Hipparcos entries, and the 'transit data' summarising the detector signals for almost a third of the entries, including all confirmed or suspected non-single stars. The intermediate data files contain a considerable amount of information yet to be fully explored.

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