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# Detection and Measurement of Double Stars with HIPPARCOS: Provisional Results from NDAC

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**ABSTRACT: The HIPPARCOS satellite observes 118,000 stars from a predefined list. Some 10% of these are known doubles or multiples, and another 2—3% may ultimately be found to be non-single with separations above 0.″1 and magnitude–differences below 4–5. This paper describes briefly the special reduction methods used by NDAC (Northern Data Analysis Consortium) for treating these non-singles. A key feature is the use of the main reduction results to calibrate and collect the data for individual doubles in 'case history files'. This enables a global solution of both absolute and relative parameters for a double to be carried out in a single step. Using provisional data tapes covering small parts of a 14-month interval, tests have been made of major parts of the double star reductions. These early results are compared with independent HIPPARCOS data and with ground–based speckle interferometry.**

## 1. INTRODUCTION

ESA's space astrometry mission HIPPARCOS is so far very successful. Although stuck in an unplanned elliptical orbit, the satellite has collected high–quality data since the end of 1989, and full–scale data analysis was begun in July 1991. Most aspects of the project are described in a 3-volume book (Perryman & Hassan 1989; Perryman & Turon 1989; Perryman *et al.* 1989) published by ESA just before launch, and the May (I), 1992 issue of *Astronomy & Astrophysics* is devoted to early results. It is important to note that the extensive data reductions are made independently by two consortia called NDAC (Northern Data Analysis Consortium) and FAST (Fundamental Astronomy by Space Techniques), with the final goal of publishing a single agreed–on astrometric catalogue for the 118,000 stars listed in the *Input Catalogue* (Turon *et al.* 1992). For the double stars in particular, the methods used are rather different, and the following applies only to NDAC. For more details, see Söderhjelm *et al.* (1992).

After some general descriptions of the reduction principles, most of this paper exemplifies solution results obtained from a small subset of 'provisional' data intended for comparisons between the NDAC and FAST reductions. The data cover only about 15% of the interval 1989.8–1990.8, with a small addition from around 1991.1, but double star solutions could still be obtained for nearly 2,000 objects. By now (March 1992), the 'real' data from the first year are available, but no double star reductions have yet been made from them.

## 2. REDUCTION PRINCIPLES

The basic idea is to complete the main reductions with as little interference as possible from non-single objects, and then afterwards to collect the double–star observations in one file per object. The 'standard' HIPPARCOS reductions for single stars are described in Lindegren *et al.* (1992a, 1992b). They are split in three (sequential) subtasks, carried out at Royal Greenwich Observatory (RGO), Copenhagen University Observatory, and Lund Observatory. The main result is a catalogue with astrometric (and photometric) data for the 'single' stars in the Input Catalogue, but these reductions also give the (time-dependent) geometric and photometric calibrations of the instrument, plus its accurate ($\sim 0\farcs1$ across, $0\farcs003$ along scan) attitude throughout the mission. In NDAC, the double star reductions are postponed until these reductions are completed, and calibrated observations for each specific object are collected in 'case-history files' (CHF:s). Afterwards, the double star reductions may be done for one object at a time.

The CHF-derivation is an important (and difficult) key step in the reductions. As each object traverses the modulating grid, the photon counts are parametrized by a vector **b** of Fourier coefficients according to the model

$$N_k \sim b_1 + b_2 \cos p_k + b_3 \sin p_k + b_4 \cos 2p_k + b_5 \sin 2p_k \qquad (1)$$

Data from a few million such field-of-view crossings have to be calibrated photometrically and the phases have to be referred within a few milliarcseconds to given reference positions. The originally chronological data are then sorted object-wise, giving CHF:s with some 100–200 **b**-vectors, together with their covariances and the exact scan-geometries.

These **b**-vectors are the 'observations' that have to be fitted by some model double (or multiple) star. For any $n$-tuple star (with component intensities $I_i$), a theoretical photon count model may be written

$$N_k \sim I_b + \sum_{i=1}^{n} I_i[1 + M_1 \cos(p_k + \Delta p_i) + M_2 \cos 2(p_k + \Delta p_i)] \qquad (2)$$

where the background $I_b$ and the 'modulation coefficients' $M_1(\sim 0.7)$ and $M_2(\sim 0.2)$ are assumed to be known. Equivalencing Eqs. (1) and (2) gives basic expressions for the **b** in terms of $I_i$ and $\Delta p_i$, which may then be differentiated further with respect to any convenient set of astrometric and orbital parameters. (The $\Delta p_i$:s are of course different for each grid-crossing, depending on the scanning directions). The general result is one (linearized) observation equation for each component of **b** and each field-of-view crossing, typically some 500–1000 equations. A 12-parameter model valid for most doubles has two position coordinates, two proper motions, a parallax and an intensity for each component, and it is natural to use a non-linear, iterative least-squares fitting. The main difficulty lies in choosing the start values for the positions. For proper convergence, these have to be accurate to some $0\farcs3$ (because the $1\farcs2$ grid-period sometimes allows spurious solutions at about that spacing).

For known doubles of long period, linear relative motion between the components is assumed, and the above 12-parameter model is used in the STDDBL program. The same model is used in the program SEEKDBL for suspected non-single objects. A double-star solution is started with different assumed secondaries, and in some cases a good convergence shows that the star is indeed double. These two programs suffice to treat the large majority of objects. For more complicated cases, several other programs are required, but these are not yet fully specified.

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## 3. PROVISIONAL RESULTS FOR KNOWN DOUBLES

The provisional 'case history files' for about 2,500 known doubles were run through the STDDBL–program, and seemingly valid solutions were obtained for more than half of them. There is a general lack of good independent data to test these solutions, but one interesting comparison is with the 'star–mapper' data used for the satellite attitude determination. These data have been used at RGO to derive also position corrections to the original Input Catalogue (van Leeuwen *et al.* 1992). For doubles with both components brighter than about magnitude 10 and with separations above 2″, positions are obtained with typically 0″.05 precision. (Because of systematic errors in the Input Catalogue, the external errors are of the order of 0″.1). Figure 1 shows the differences between the STDDBL and star–mapper positions for the primary components. While most of the differences fall near the origin, there are also several 'outliers'. Some of these may be real errors, but several are seen to fall at roughly 1″.2+ or 2″.4+ from the origin. This is due to the 'grid–step' uncertainty in the STDDBL solutions, which will however disappear when two or three years of data are available.

For the relative positions, a similar plot is obtained, but a more stringent test is provided by ground–based speckle interferometery. Using the *Second CHARA Catalogue* by McAlister & Hartkopf (1988), almost 100 stars were found with both STDDBL solutions and speckle data. Because several of the systems are 'moving', and with the speckle data at earlier epochs than the HIPPARCOS observations, no strict comparison has been made. Typically, however (after correcting a few 180° quadrant errors in the speckle data), the differences are at the 0″.01 level. Some examples are shown in Figure 2.

For about 170 systems with separations above 10″ , one may compare also with the main reduction ('single star') HIPPARCOS positions. Figure 3 shows position differences between the STDDBL and the 'single–star' solutions, plotted against the 'total' magnitude difference between the components. (This $\Delta m_T$ is equal to the sum of the real $\Delta m$ and the attenuation in the wings of the ~33″ diameter 'sensitive spot' used for the observations). As expected, there is good agreement for large $\Delta m_T$ (little disturbance from the other component). At smaller $\Delta m_T$, the STDDBL solution should still be reliable, while the 'single star' solution becomes biased due to the unmodelled companion.

## 4. DETECTION OF NON-SINGLES

For a single star, the light curve observed when it passes over the focal–plane grid has a shape determined only by the instrument. For a double, the sum of two such curves is obtained as shown by Equation 2. During the mission, the observed second–harmonic modulation for any object passing the grid is compared with the single–star calibration. The deviation is given as a normalized $\Delta\chi^2$, which is accumulated in an 8-bin histogram for each object. These histogram data are then transformed into detection statistics $T_h$ and $T_t$, both increasing with an increased fraction of large $\Delta\chi^2$:s. (For exact definitions, see Söderhjelm *et al.* 1992).

Another way that the light curve of a double object differs from that of

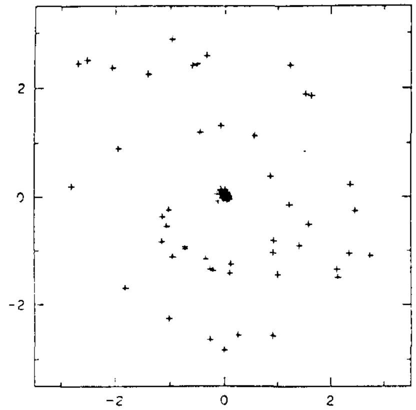


**FIGURE 1.** Differences (″) between the STDDBL and star–mapper data for primary positions.

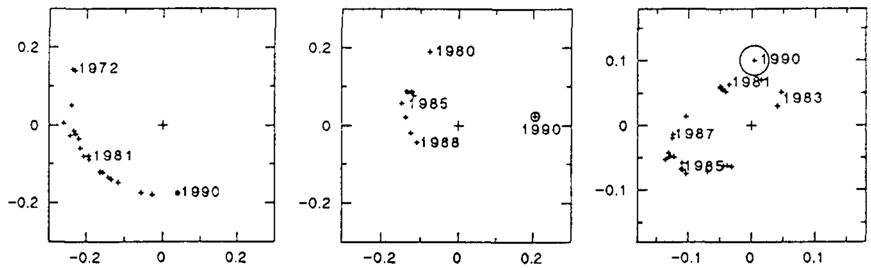


**FIGURE 2.** Ground–based speckle positions and HIPPARCOS data for three close, moving binaries. (Scales in arcsec).

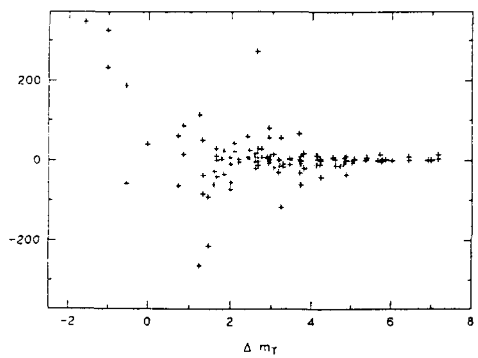


**FIGURE 3.** Position differences (milli-arcsec) between STDDBL and (biased) single–star reductions for some wide doubles.

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a single is with respect to the first harmonic amplitude. As seen again from Equation 2, the total mean intensity (after correcting for the background) is simply the sum of the component intensities. The total first harmonic, however, is less than such a sum unless the relative phase $\Delta p_i$ happens to be an exact multiple of $2\pi$. For single stars, the (mean) magnitudes determined from the total intensity ($H_{p_1}$) and from the first harmonic ($H_{p_2}$) should be equal, but for a double, the latter will be fainter. A third discovery statistic for non-singles is thus the magnitude difference $T_m (\equiv H_{p_2}\text{-}H_{p_1})$, determined in the photometric analysis performed at RGO.

The 'reference' distributions of $T_h$, $T_t$ and $T_m$ have to be derived empirically from samples of single stars of different magnitudes, and what matters is the *difference* between the distributions for non-singles vs. singles. A problem with this approach is the lack of a sample of true single stars. By simulation experiments, one may show that the 'effective amplitude' of the double–star effects in the HIPPARCOS data can be described by the single parameter $\Delta m_{\rm eff}$ defined by

$$\Delta m_{\rm eff} = \begin{cases} \Delta m & \rho \geq 0''.32 \\ \Delta m - 5.5\ \lg(\rho/0.32) & 0.10 < \rho < 0''.32 \\ \Delta m - 20\ \lg(\rho/0.14) & \rho \leq 0''.10 \end{cases} \qquad (3)$$

where $\rho$ is the separation and $\Delta m$ the magnitude difference between the components. Values of $\Delta m_{\rm eff}$ may be calculated for the known doubles, but as shown in Söderhjelm *et al.* (1992), the available $\Delta m$'s are generally of poor quality. Originally, it was thought that the known doubles with $\Delta m_{\rm eff} > 5$ or 6 would constitute a good sample of 'effective singles'. In reality, the proportion of high $T$ values is as high among these stars as among the *a priori* singles.

In order to define a simple detection–criterion, one may compare first the $T$ distributions for the *a priori* singles with those for the roughly 1000 doubles with STDDBL solutions giving reliable $\Delta m_{\rm eff}$'s. Such studies show that the $T_m$ criterion is generally the most sensitive, with small improvements from $T_h$ and $T_t$. A typical 'combined' criteron used below is $T_c = T_m + 0.01 T_h + 0.002 T_t$ (the ranges of the different $T$'s are *not* equal!), but different coefficients should be used for different magnitude intervals. Figure 4 shows the variation of $T_c$ with $\Delta m_{\rm eff}$ for the STDDBL doubles ($\Delta m_{\rm eff} < 4$) and for some *a priori* doubles with large $\Delta m_{\rm eff}$. (Before calculating $T_c$, both $T_h$ and $T_t$ are also corrected for a magnitude equation).

The flagging of 'suspected non-singles' is now effected by simply defining a maximal $T_c$ value. A low value will catch many non-singles, *plus* a large proportion of the true singles, while a less 'expensive' flagging risks missing some true doubles. Different $T_c$ limits have been tested on the STDDBL doubles in different ranges of magnitude and $\Delta m_{\rm eff}$ as exemplified in Table 1, and in practice, a 5–10% flagging of singles may be adopted. (Beyond $\Delta m_{\rm eff} = 4.5$, very few non-singles are likely to be detected).

A rough estimate of the proportion of undetected doubles in the 'single'–data is obtained from the high-$T_c$ tail in Table 1. Assuming that all $T_c$'s above 0.10 are due to doubles, one may solve (for $H_p = 7 - 10$) to get upper limits approximately 0.5% for doubles with $\Delta m_{\rm eff} < 2$ or 2.5% for $\Delta m_{\rm eff}$=2–3. These limits will be compared below with the 'real' discoveries.

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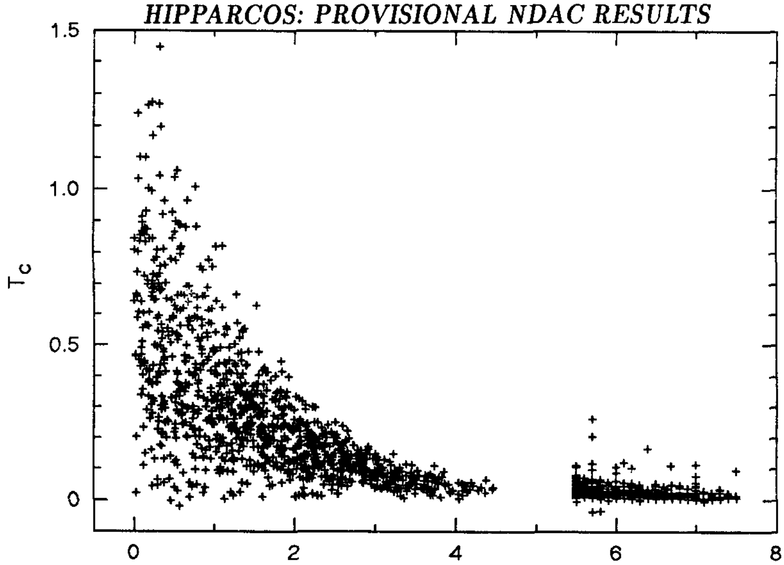


**FIGURE 4.** The detection criterion $T_c$ as function of $\Delta m_{eff}$.

**TABLE 1.** Flagged fraction(%) of a priori singles (S) and doubles (DA, DB, DC with $\Delta m_{eff} < 2$, 2–3, 3–4.5) for different $T_c$-limits and different ($H_p$) magnitude intervals.

| | $H_p < 7$ | | | | $H_p = 7-10$ | | | | $H_p > 10$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_c$ | S | DA | DB | DC | S | DA | DB | DC | S | DA | DB | DC |
| 0.03 | 10.1 | 98 | 94 | 81 | 8.5 | 98 | 94 | 86 | 12.8 | 93 | 82 | 0 |
| 0.05 | 5.6 | 96 | 94 | 56 | 4.0 | 97 | 92 | 52 | 7.9 | 93 | 64 | 0 |
| 0.07 | 3.6 | 96 | 91 | 39 | 2.6 | 95 | 84 | 32 | 5.8 | 92 | 64 | 0 |
| 0.10 | 1.6 | 94 | 84 | 11 | 1.6 | 92 | 68 | 8 | 4.0 | 88 | 54 | 0 |
| 0.15 | 0.4 | 86 | 44 | 0 | 0.9 | 85 | 36 | 0 | 2.4 | 86 | 18 | 0 |
| 0.20 | 0.2 | 74 | 19 | 0 | 0.4 | 78 | 17 | 0 | 1.8 | 74 | 9 | 0 |

## 5. PROVISIONAL NEW DISCOVERIES

The SEEKDBL–program was run for some 2,400 'suspected' CHF's. Several hundred 'new' doubles (not in the preliminary 'IC8' version of the Input Catalogue) were found, but not all of these solutions can be trusted. Mainly, the $1.2n$ arcsec 'slit errors' may give spurious separations, and this problem is aggravated because solutions are only attempted out to a 'cut–off' radius $r_{lim}$. With a small $r_{lim}$, doubles with larger separations will be placed at smaller values or will get no solution, but because of the quadratically increasing computing times, too high $r_{lim}$-values should be avoided. In practice, very few new systems should have separations larger than $2''$ , and $r_{lim} = 2.4$ may be taken as a 'safe' compromise.

Figure 5 shows all 'new' systems brighter than $H_p = 10$ in a $\lg \rho/\Delta m$-diagram, for two different values of $r_{lim}$. In an attempt to estimate the reliability of the solutions, SEEKDBL was also run on a sample of stars with good

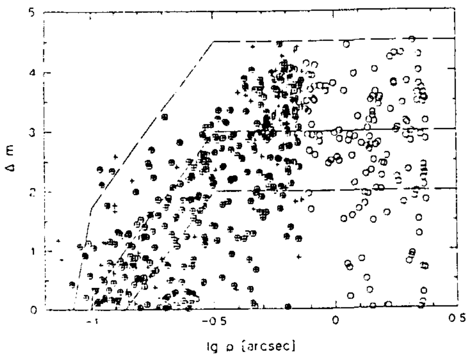


**FIGURE 5.** The distribution of the new discoveries from SEEKDBL in a lg $\rho/\Delta m$-plane. Crosses are for $r_{\rm lim}$=0″.8, open circles for $r_{\rm lim}$=2″.4. The limits 2.0, 3.0 and 4.5 for $\Delta m_{\rm eff}$ are indicated.

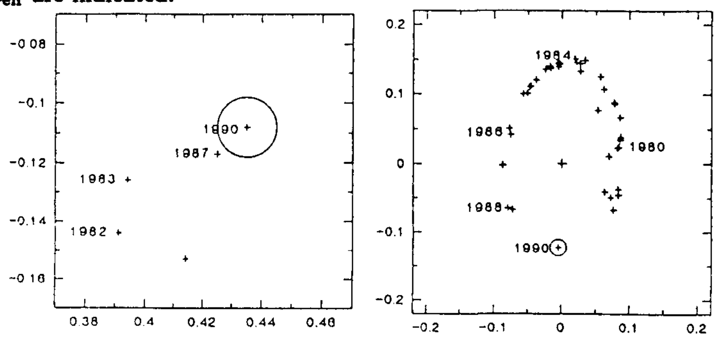


**FIGURE 6.** Speckle-interferometric and HIPPARCOS data for two 'new' short-period systems. (Scales in arcsec.)

STDDBL solutions. The SEEKDBL solutions were considered as 'good' if they agreed reasonably with STDDBL, as 'useful' if the separation differed (by more than 0″.1) but the magnitude difference was correct, and otherwise as 'bad'. In this way, the relative distributions in these categories were studied for different intervals of magnitude, $\Delta m_{\rm eff}$ and $r_{\rm lim}$. Using these figures, the solutions in Figure 5 were categorized as shown in Table 2. Although these numbers have large uncertainties, the sum of the 'good' and 'useful' categories should be reasonably correct. More solid evidence for the reality of some of these solutions comes again from comparison with the 2nd CHARA catalogue (McAlister & Hartkopf 1988). Four of the 'new' doubles are found already in this catalogue, with closely agreeing relative positions. Two examples are given in Figure 6.

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**TABLE 2.** Tentative distribution (absolute numbers) of the new doubles in Figure 5 into 'good' (g), 'useful' (u) and 'bad' (b), as estimated from tests with known doubles.

| | $\Delta m_{\rm eff}$=0–2 | | | $\Delta m_{\rm eff}$=2–3 | | | $\Delta m_{\rm eff}$=3–4.5 | | |
|---|---|---|---|---|---|---|---|---|---|
| $r_{\rm lim}('')$ | (g) | (u) | (b) | (g) | (u) | (b) | (g) | (u) | (b) |
| 0.8 | 52 | 26 | 6 | 54 | 83 | 26 | 13 | 58 | 85 |
| 2.4 | 55 | 34 | 8 | 67 | 95 | 19 | 12 | 79 | 76 |

## 6. EXPECTED NUMBERS OF NEW DISCOVERIES

In Section 4, upper limits of a few percent were given for the total number of unknown doubles with observable $\Delta m_{\rm eff}$. Such figures are certainly interesting, and two additional estimates will be derived here.

From the above tests on known doubles, one obtains the total fractions of SEEKDBL runs giving a solution. This makes it possible to estimate (from the number of new solutions) roughly the true number of doubles present (in a bin of magnitude and $\Delta m_{\rm eff}$). The results are preliminary, but for the 'standard' $H_p = 7 - 10$ magnitude range, we get e.g., 0.7%, 1.3% and 1.0% for the fraction of undetected doubles (with separations below 3$''$ ) for the $\Delta m_{\rm eff}$-intervals 0–2, 2–3 and 3–4.5. More definite figures will be obtained when the whole first year of data is analyzed.

There is also a more direct third method available. One may simply look at the distribution of known doubles in the *Input Catalogue*. Theoretically and in practice, the distribution over $\lg \rho$ is nearly uniform. The distribution over $\Delta m$ is peaked around zero, but otherwise rather uniform too. One has only to assume that these distributions are independent and continue towards smaller separations and to estimate a single 'incompleteness factor' in a well–observed region (e.g., $\rho$=1–3$''$ , $\Delta m < 2.5$). The number of 'missing' objects (with $\rho < 3''$ ) may then be summed as function of $\Delta m_{\rm eff}$ and compared with the total number of 'single' IC stars. Again for $H_p = 7 - 10$, incompleteness factors in the wide range 1.0–1.5 gives undetected fractions 0.0–1.1%, 0.6–1.2% and 1.3–2.4% in the above $\Delta m_{\rm eff}$ intervals.

All three sets of figures agree that we should not expect more than some 2,000 - 3,000 new doubles from HIPPARCOS. Although this is not a major increase of the total double star population, about half the new systems will have separations below $0\overset{''}{.}3$ and/or orbital periods below 100 years. Together with the precision parallaxes also given by HIPPARCOS, several of these short–period systems may soon give interesting mass determinations.

## 7. FURTHER PLANS FOR THE REDUCTIONS

A first 'main' reduction of the first 12 months of data was finished by NDAC in February 1992, and it will be compared extensively with the corresponding one made by FAST. The double–star reductions from these data has just begun, and with a much better homogeneity and sky coverage, more and better solutions than the present ones will be obtained. Still, however, there will be many 'slit errors' that may only be removed by using a longer time–base. Further rounds of preliminary solutions will be made as more data become available, including treatment of multiples, variables and cases with rapid motion. The last round of DS reductions will only be made after the 'final' main reductions are completed, which depends on the eventual life–time of HIPPARCOS. If the observations end by the present projections ($\sim$ 1994.0), final double– and multiple–star results will not be generally available before 1996–97.

## 8. ACKNOWLEDGMENTS

NDAC's double star reductions uses data from all stages of the main reductions, and the work by Carsten Petersen at Copenhagen University Observatory is indispensable. The Lund Observatory authors are supported by the Swedish National Space Board. The HIPPARCOS team at the Royal Greenwich Observatory is supported by the UK Science and Engineering Research Council.

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