Mon. Not. R. Astron. Soc. (1992) 259, 563-568 and Microfiche MN259/1

## Double star CCD astrometry and photometry

## A. Wayman ${ }^{3}$

Accepted 1992 May 27. Received 1992 May 13; in original form 1992 March 28

ABSTRAC for 2373 binary stars, obtained with the CCD camera on the 1-m Jacobus Kapteyn
 Astrometric Satellite launched in 1989 August, and the purpose of our measurements



 $\rho$ varies between 0.01 and 0.1 arcsec, being worse for small separation $(\rho<1.95$
 narrower systems the internal consistency deteriorates to $2^{\circ}-6^{\circ}$.

Key words: techniques: image processing - astrometry - binaries: close - binaries:
visual. This means that at La Palma the limit of 0.5 arcsec is often attained. Our observations were preferentially made on systems in the range $0.5-5$ arcsec, but we also included a
reserve list (Table 7 , on microfiche) of wider separations in order to allow us to continue observing when the seeing conditions became poor. In consequence, $s_{V}$ and $s_{R}$, which
describe the point spread function (see Section 3 below),

All stars had been selected by J. Dommanget, Coordinator of the Hipparcos Input Catalogue Working Group on Double
Stars, using the following criteria: $V$ between 8 and 12 mag ; special interest or support of the satellite's observing strategy; and, lastly, a good chance of accurate observation by the satellite. This last criterion is set by a quantity called
'pressure' which is a measure of the competition for satellite observing time in the region of each candidate star. The definition has been given by Turon et al. (1992). We have
selected only those stars with pressure $<1.0$. The numbers of stars proposed by Dommanget, and the numbers actually
 only; in these cases the image in the other colour was unsatis-


The reduction of the double star measurements made by Hipparcos runs into problems in the separation range $0.5-10$
arcsec. For separations smaller than 0.5 arcsec the multiple system fits into the gaps between successive lines of the modulating grid, and the geometry of the multiple system can be interpreted by combining scans made in different directions. For separations above 10 arcsec the two components
can be treated as separate stars, and this again presents no can be treated as separate stars, and this again presents no
 these two limits that supplementary data are needed to
facilitate the reduction (Dommanget 1985; Argue \& Irwin

The upper end of this range, say from 5 to 10 arcsec, is accessible to photoelectric photometry by classical methods asing large telescopes in exceptionally good seeing conditions, but is more conveniently done by CCDs which, in addition, yield astrometric information about the system. It is in the range $0.5-5$ arcsec that the CCD, used on a telescope
of moderate aperture, becomes nicely matched to these of moderate aperture, becomes nicely matched to these cedures, it is possible to resolve binaries down to one-half of

in $V$ on the same nights by the Carlsberg Automatic Meridian Circle（CAMC）which is situated nearby on the
mountain．The CAMC results are not obtained in the same way as ours（CAMC 1987）：they are obtained from meridian





 extinction to be lower than ours，suggesting a longer equiva－
lent wavelength for their system．Our $v$ system has already lent wavelength for their system．Our $v$ system has already been shown to be close to the Landolt $V$ system（quoted by
Argue et al．1988）．

## 2．2 Precision of photometry

Some of our nights were of poor photometric quality but， since we were interested also in the astrometry，we continued making observations．On the good nights，such as 1986 July $24 / 5$ ，the internal consistency of a magnitude would be comparable to the residual variance $\sigma_{\mathrm{r}}$ in Table 2 ，namely
0.009 mag in $v$ and 0.008 mag in $r$（its precise value depend－
 would be worse，sometimes much worse．We did not make enough measurements to derive an estimate of the photo－



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 and the second $r$ ．The last column gives the zenith extinction in $V$

 Jacobus Kapteyn Telescope（JKT）．The pixel sizes were nominally 0.3 arcsec for the GEC P8600 chip and 0.4 arc－ sec for the RCA SID 501EX，with field size $3 \times 2 \operatorname{arcmin}^{2}$ in on the globular cluster M13，using Schlesinger＇s relative positions（1934）．The results were as follows：RCA－for $x$ ，
$0.4135 \pm 0.0003$ arcsec，for $y, 0.4132 \pm 0.0001$ arcsec for 43 stars and three frames；and GEC－for $x, 0.3032 \pm 0.0003$ arcsec，for $y, 0.3032 \pm 0.0002$ arcsec for nine stars on two

The filters were Kitt Peak Mould System $V$ and $R$ ，giving instrumental scales $v$ and $r$ which are very close to Landolt＇s was carried out on the twilight sky at the beginning and end of each night．Interference patterns caused by night sky emission lines were never a problem because the exposure
times were short，a few seconds only．Each frame consisted of two exposures，one in each colour and separated by 15 arcsec on the chip．This procedure speeded up the observa－ tions because the readout time was shared between the two exposures，but had the effect of degrading the signal－to－noise





 being finally accepted．Our examination included tests for
pixel saturation and for visible malformation of the image，but even then some frames were allowed to pass，only to be rejected at the reduction stage because of some defect that
had escaped our notice．The most serious problem was

 cured by the use of a more suitable adhesive．This problem is
not likely to recur．

## 2．1 Extinction

## OBSERVATIONS

| Table | Limits in V | Limits in $\rho$ | Proposed | Here |
| :---: | :---: | :---: | :---: | :---: |
| 6 | $9^{m}-12^{m}$ | $0^{\prime \prime} .5-5^{\prime \prime} .0$ | 1353 | 1063 |
| 7 | $9^{m}-12^{m}$ | $5^{\prime \prime} .0-30^{\prime \prime}$ | 804 | 346 |
| 8 | $8^{m}-9^{m}$ | $0^{\prime \prime} .5-5^{\prime \prime} .0$ | 3000 | 729 |

Irwin (1985) has predicted that the precision for $\rho$ will improve with increased $\rho$ and reduced difference in brightness $(\Delta v)$ between the A and B components. Since in general each star was observed only once in each colour, we have no
internal check on the accuracy of $\rho$ within a colour. Instead, internal check on the accuracy of $\rho$ within a colour. Instead,
we have examined the consistency of the separate determinations of $\rho$ in the two colours. As an illustration, Fig. 1 is a plot of $\frac{1}{2}\left(\rho_{v}-\rho_{r}\right)$ against the mean separation $\frac{1}{2}\left(\rho_{v}+\rho_{r}\right)$ for
stars of Table 5. It shows a symmetric error distribution and increased scatter at low separation ( $<1.95$ arcsec). A more detailed analysis of the consistency of $\rho$ as a function of $\rho_{v}$ and $\rho_{r}$ is given in Tables $3-5$, where we have
distributed the data into a $5 \times 3$ matrix having five intervals of brightness difference $\Delta v=v_{\mathrm{B}}-v_{\mathrm{A}}$ and three of angular separation $\rho_{v}$. The tables. Within each interval we have binned the values of $\left|\rho_{v}-\rho_{r}\right|$ according to a quantity $\sigma_{\rho}$ which is
 selected $\sigma_{\rho}$, as nearly as possible, to give a proportion 0.317
of the population of $\left|\rho_{v}-\rho_{r}\right|$ to exceed $1 \sigma_{\rho}$, this being the proportion appropriate to one standard deviation. The
 position angles $\theta$, to be discussed in Section 4.2. Clearly the


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 external accuracy of the individual $v$ magnitudes in our ables. The magnitude differences $\Delta v$ between the comconents ought not to have been seriously degraded by poor
condions, so the theoretical predictions made by Irwin conditions, so the theoretical predictions made by Irwin
ought to apply (Argue et al. 1988): namely that $\Delta v$ should have an internal consistency of order $<0.01-0.02 \mathrm{mag}$ for
components of nearly equal brightness, worsening to 0.1 mag 3 REDUCTIONS Since there is in general considerable overlap between the pair of images in both the $V$ and $R$ passbands, it is necessary
to use point spread function (PSF) fitting techniques to extract the full astrometric and photometric precision (e.g. Irwin 1985). By simultaneously fitting both image com-
ponents it is possible to attain the theroretical limiting accuracy for the random (i.e. photon and readout noise) V
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0 exposure to the next, due to the mirror support problem alluded to earlier and the fact that generally there were no
isolated bright stars suitable to use for a PSF. These problems required a few extra stages in the image processing pathway. An outline of the analysis strategy is presented

As mentioned earlier, eyeball inspection of the data in the frames for which the mirror support problem had caused significant image distortion. However, the residual mirror support artefacts had the effect of causing the PFis vary that an estimate of the PSF had to be made from each individual data frame.

Straightforward isophotal analysis (e.g. Irwin 1985)
suffices to locate the binary star images within their expected locations on the CCD frame (both $V$ and $R$ pairs are present on each frame). Then, by simply summing along the derived major axis direction and by assuming circular symmetry for or each $R$ or $V$ pair. (The values of $s_{V}$ and $s_{R}$ used in Tables 6-10 are the FWHM of these derived image PSFs.) The eyeball filtering at the telescope removed the majority of
those cases in which the PSF was noticeably elongated, and
 with interactively. For a few targets there happened to be an isolated bright star on the CCD frame. These provided an
external check on the reliability of the PSF estimation The multiple-isophote technique discussed by Irwin (1985) was used to generate initial starting parameters for the image components where possible. In cases for which the
image components were not obviously separated (i.e. separaimage components were not obvically less than the Rayleigh resolution limit) the shape of the major axis profile of the blend was used to
derive initial starting parameters. These starting parameters were then fed into the general-purpose maximum likelihood fitting routine described in Irwin (1985). The fitted model
data were then superposed on the CCD data to ascertain the data were then superposed on the CCD data to ascertain the
reliability of the fit. Since there were independent $V$ and $R$ reliabiity of the fit. Since there were independent $V$ and $R$
analyses available for most frames. this also provided an
excellent test of the internal consistency of the analysis.
566 A．N．Argue et al．
Table 3．Internal consistency for $\rho$ and $\theta$ obtained in the two colours $(v, r)$ for stars of Table 6 （having $V \geq 9$ mag and $\rho<5$ arcsec； 1126 stars）．
The stars have been distributed into a $5 \times 3$ matrix with the following elements：five brightness intervals（ $0 \leq \Delta v \leq 0.5$ ，denoted by $0^{m} .5$ ；
$0.5<\Delta v \leq 15 ; \quad 1.5<\Delta v \leq 2.5 ; 2.5<\Delta v \leq 3.5$ and $v>3.5 \mathrm{mag}$ ）and three intervals of separation $\left(0 \leq \rho_{v}<1.95\right.$ ，denoted by $\rho_{v}=1^{\prime \prime} .0$ ；

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instability of the main mirror referred to earlier，and they description of the precision obtained．The results confirm Irwin＇s prediction in giving a fairly smooth increase in $\sigma_{\rho}$ with magnitude difference and with reduction in $\rho$ ．For
binaries wider than 1.95 arcsec the precision in $\rho$ is $0.01-0.04$ arcsec for $\Delta v \leq 3.5 \mathrm{mag}$ ，worsening to $0.04-0.10$ arcsec for larger $\Delta v$ ；for narrower binaries it is $\sim 0.04$ arcsec
for small $\Delta v$ ，increasing to 0.10 arcsec for larger $\Delta v$ ．The inferior precision for the wide binaries in Table 7 （micro－ fiche）arises mainly because these stars had in general been observed only on nights of inferior seeing．
$\rho_{v}=1^{\prime \prime} .0 \quad \sigma_{\rho}=0^{\prime \prime} .041, \sigma_{\theta}=6^{\circ} .90 \quad \sigma_{\rho}=0^{\prime \prime} .052, \sigma_{\theta}=6^{\circ} .00 \quad \sigma_{\rho}=0^{\prime \prime} .090, \sigma_{\theta}=5^{\circ} .00 \quad \sigma_{\rho}=0^{\prime \prime} .094, \sigma_{\theta}=8^{\circ} .00 \quad \sigma_{\rho}=0^{\prime \prime} .445, \sigma_{\theta}=12^{\circ} .40$
 $\qquad$ the $B$ component relative to the $A$ component in the two colours．$d\left(^{\prime \prime}\right)$ thus gives an indication of the consistency of
the astrometry in the two colours for that object．The $\sigma_{0}$ values do not，then，describe a normal distribution，especially

 models of the Galaxy population (Robin \& Crézé 1986; Gilmore, Wyse \& Kuijken 1989), yet double star photometry in
particular has been very slow to materialize. For example, the particular has been very slow to materialize. For example, the
astrometric 'Catalogue des Compositants d'Etoiles Doubles et Multiples' (CCDM, Dommanget 1989) contains over




 be based on the experiences described in this paper.

## 6 OBSERVERS

> The observing schedule was as follows:

 useful consistency check.

### 4.2 Internal consistency of position angle $\boldsymbol{\theta}$

The internal consistency of the $\theta$ determinations in the two colours has been examined in the same way, and the results given in the right-hand columns of Tables 3-5. The $\theta$ values had been output to $1^{\circ}$, so values of $\sigma_{\theta}$ smaller than this are







1986 March - A. N. Argue and D. S. Nithakorn (Institute
f Astronomy). of Astronomy);

1986 April - A. N. Argue, R. Barbier [Observatoire Royal
de Belgique (ORB)], J. Doyle (ORB) and P. A. Wayman
(Dublin Institute for Advanced Studies);




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1987 January - J. Bourgeois (ORB), R. Harmon, D. S. 1987 June - M. Bridgeland (RGO), P. S. Bunclark and M. J. Irwin.

## ACKNOWLEDGMENTS

It is a pleasure to thank J. Dommanget, Observatoire Royal
de Belgique, for selecting our objects for observation and for his continued interest in the programme. We would like to express our gratitude to our collaborators as listed in the previous section, and to our support astronomers, at the telescope, from whom we received essential assistance: R. W.
Argyle, C. D. Pike and D. H. P. Jones. We are also grateful to L. V. Morrison for giving us the standard deviations for the determinations of $V$ by the CAMC in Tables 6-10. We are

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