# Pixel Scale and Orientation of PHARO. II.

Stanimir A. Metchev

*Caltech*

*3 Sep, 2003*

metchev@astro.caltech.edu

## 1. Introduction

An initial determination of the PHARO plate scale is presented in White (2002, Memo I) for one cass ring angle, using a single binary star for calibration observed on Jun 23, 2002. Below I present a continuation of this investigation, and study the dependence of the plate scale and the position angle of the direction north on the array with both $(x, y)$ position on the array, and cass ring angle, using several calibration binaries observed on different nights.

## 2. Observations

Calibration binary star observations were performed during two runs on May 10–11, and July 15–16 with the Palomar 200-inch telescope using PALAO + PHARO, for the purpose of determining the pixel scale on PHARO at the f/29.91 focal ratio. The calibration binaries were selected from the 6th Catalogue of Visual Binaries, so as to have the largest possible separations ($\gtrsim 1''$; to minimize the relative importance of centroiding) and/or accurately determined orbits (grade 1; to minimize uncertainties arising from the orbital solution of the binary). A summary of the observations and the orbital parameters of the observed binary calibrators is presented in Table 1.

The observations were conducted mostly under strong winds or heavy cirrus conditions: factors which should not affect the astrometry however. The seeing was 1–2$''$ in $K_s$, and the airmass ranged between 1.0 and 1.3 for all calibration binary observations. The AO loop rates were between 500 Hz 1500 Hz. Due to problems with achieving AO lock on bright stars during the July 15-16 run, focus offloading from the secondary was turned off. All binaries were observed with the $H$, $K_s$ or Br$\gamma$ filters in PHARO with an ND 0.1% or ND 1.0% filter inserted in front of the array to keep the stars from saturating in the shortest exposures (1.8s). Due to the poor conditions, the AO correction was sometimes inadequate, resulting in poor images. These were excluded from the subsequent analysis, for which we have chosen images in which a diffraction-limited core of FWHM = 3.6 – 4.0 pix was clearly visible. The Strehl ratios were estimated to be between 10 and 60%, varying on a timescale of minutes.

Each binary star was dithered across the array to sample the pixel scale and the array orientation in a number of locations. Five-point dither patterns were used for the purpose of sky-subtraction. Usually the 5-point dithers were done at 5 locations: at the center of the array (where most of the science targets are imaged), and in each of the 4 PHARO quadrants. During the July 15-16 run, the procedure was repeated at all 4 orientation angles (333.5° – N-up, E-left; 63.5° – N-left, E-down; 153.5° – N-down, E-right; and 243.5° – N-right, E-up) of the cass ring, to check for dependence on the cass ring angle.

## 3. Analysis

The relative positions of the binary components were obtained using the IRAF/APPHOT task CENTER, employing the "gauss" centering algorithm. The gauss algorithm determines the centers by iteratively fitting a 1D Gaussian function along both the $x$ and $y$ axes within a specified box size, using a fixed FWHM value. Based on visual inspections of the radial fits to the diffraction cores of the binary components, we adopted a FWHM value of 3.7 pix ($0.093''$) for the $K_s$ and Br$\gamma$ images, and 2.7 pix ($0.068''$) for the $H$-band images. The box size was set 10 pix, and 8 pix, respectively, in accordance with the recommended value of 2.5–4.0×FWHM. The measured separations and orientations were then compared to the predicted values (from the orbital solution at this epoch; using the FORTRAN program ORBITSNICE) to determine both the pixel size and the ring angle of true North.

To obtain the uncertainties in the pixel scale and in the north direction for observation, the error in the mean of the measurements ($\sigma_{\rm mean}$) was added in quadrature to the error in the semi-major axis ($a$; normalized to the measured separation), or to the error in the longitude of the ascending node ($\Omega$), respectively. Note however that the uncertainties in $a$ and $\Omega$ provide only an approximate estimate of the uncertainty in the relative position of the binary.

WDC 20467+1607 and WDC 16147+3352 have grade 4 orbits, and, by definition, do not have published uncertainties in the orbital parameters. These are however longer-period binaries (Table 1), and we thus expect that the relative positions of the components in them are known relatively accurately nonetheless.

## 4. Results

### 4.1. Pixel Scale

The measured average pixel scales for all observations and the respective cass ring orientations are listed in Table 2. The nominally predicted pixel scale 25.10 mas/pix (Hayward et al. 2001) is $3.4\sigma$ lower than the unweighted average ($25.218 \pm 0.035$ mas/pix) of all the pixel scale measurements. The current result is consistent at the $1\sigma$ level with the one in Memo I ($25.168 \pm 0.034$; White 2002).

As found in Memo I, Figures 1–4 show that there is a positional dependence of the pixel scale on the array. The location of each measurement is set as the mid-point between the binary star components, and the size of the symbol corresponds linearly to the measured value. The variations across the array for a single binary and cass ring angle are of the order of tens of $\sigma_{\rm mean}$, and appear linearly correlated with the $x$ and $y$ coordinates in a diagonal fashion across the array for each cass ring angle. The sense of the correlation is preserved between the Jun 23, 2002 (Figure 1) and Jul 16, 2003 (Figure 4) observations of the same binary (WDC 18055+0230) at a ring angle of 63.5°. It is, however, **not** preserved between the Jul 15 and 16, 2003 observations of two different calibration binaries, WDC 16147+3352 (Figure 3) and WDC 18055+0230 (Figure 4), at all cass ring angles.

On the nights of Jul 15 and 16, 2003, the pixel scale experiment was performed at all cass ring angles. It is apparent from Figures 3 and 4 that the sense of the pixel scale variations depends on the cass ring angle: it is approximately orthogonal for cass ring angles at 90° to each other (best expressed in Figure 3). However, for cass ring angles at 180° to each other, the pixel scale dependence on $(x, y)$ position on the array is **nearly the same**.

Planar least-squares fits to the dependence of the pixel scale $\pi(x, y)$ on $x$ and $y$ are listed in Table 3 for all observations. The coefficients $a_0, a_1, a_2$ are all $> 99.5\%$ significant (compared to a model in which the corresponding coefficient is set to 0). From corner to corner, these relations predict a variation in the pixel scale of $\approx$0.30 mas/pix. The uncertainties in the semi-major axes of the binaries are not included in the listed errors for the $a_0, a_1, a_2$ parameters (they would contribute only to the error of $a_0$).

### 4.2. Ring Angle

The ring angle of North is $334.547 \pm 0.108°$ based on an unweighted average of all measurements – $3.4\sigma$ higher than the value found in Memo I from the measurement of WDC 18055+0230 at a single cass ring angle. We confirm that the north direction, similarly to the pixel scale, is dependent on the position on the array, and on the cass ring angle (Figures 5–8).

Once again, we find that the dependence of the north direction on $x$ and $y$ is repeatable for observations of the same binary (WDC 18055+0230) conducted at a cass ring angle of 63.5° a year apart (Figures 5 and 8), however, it is not repeatable between the observations of WDC 16147+3352 and WDC 18055+0230 taken a night apart (Figures 7 and 8. Also, there does not seem to be a one-to-one correspondence between the sense of the dependence of the north direction across the array $\eta(x,y)$ and the cass ring angle (as found for the pixel scale, as well).

Least-squares fits to this dependence are listed in Table 4. The coefficients $a_0, a_1, a_2$ are $> 99.5\%$ significant except where the errors in the coefficients are comparable (within a factor of 2) to their values, in which case the significance is $\lesssim 80\%$. The relations listed in Table 4 predict a variation of $\sim 0.5°$ of the north direction across the array. The uncertainties in the longitudes of the ascending nodes $\Omega$ of the binaries are not included in the listed errors for the $a_0, a_1, a_2$ parameters (they would contribute only to the error of $a_0$).

## 5. Discussion

The unrepeatability of the plate scale and north angle positional dependences between the nights of Jul 15 and 16, 2003, indicates that astrometric observations need to be done on a nightly basis, if an absolute accuracy of better than ±0.15 mas/pix and ±0.25° are desired across the full PHARO field. It is possible that the greater uncertainty in the orbital solution of WDC 16147+3352 (a grade 4 orbit), compared to that of WDC 18055+0230 (grade 1), may be the cause of this effect (although I'm not certain how), since the results for WDC 18055+0230 alone are somewhat more repeatable: to within 0.20 mas/pix in the plate scale, and to within $\approx 0.1°$ in the ring angle. On the other hand, if the observed night-to-night discrepancies are real, it is very probable that any rotation of the Cass ring may have a random effect on the plate scale and north angle orientation (possibly due to loose connections?).

I have written a script 'cal_binary' in the 'macros' directory on ezra2 that performs a 5-point dither pattern at 5 locations on the array, and takes 25 1.8-sec exposures and about 15 min to complete for a single cass ring orientation angle. Having to run this for all orientation angles will take a significant amount of time, although may be an appropriate activity for lapses of heavy cirrus. Another alternative is to take second epoch observations of candidate binaries only at one Cass ring angle, and run the 'cal_binary' script on a calibration binary only for that one angle. One could thus avoid rotating the cass ring when precise astrometry is required, to minimize unwanted random effects.

A further experiment to determine whether cass ring rotations affect the pixel scale in a random way is to return to the same cass ring setting and perform the binary star experiment several times over the course of the night, on a single calibration binary. However, there are other effects that will also likely affect the sense of the pixel scale dependence one the $(x, y)$ position, most notably the orientation of the f/29.91 focal plane with respect to the horizon. That is, the same result may not be attainable at different hour angles. Hence, it may not be possible to improve the accuracy of atrsometric measurements with PHARO beyond $\pm 0.15$ mas/pix.

## REFERENCES

Close, L. M., et al. 2003, ApJ, 599, in press (astro-ph/0309003)

Hale, A. 1994, AJ, 107, 306

Hartkopf, W. I., Maso, B. D., & MacAlister, H. A. 1996, AJ, 111, 370

Hayward, T. L., Brandl, B., Pirger, B., Blacken, C., Gull, G. E., Schoenwald, J., & Houck, J. R. 2001, PASP, 113, 105

Pourbaix, D. 2000, A&AS, 145, 215

Scardia, M. 1979 Astron. Nachr. 300, 307

White, R. 2002, Pixel Scale and Orientation of PHARO Determined from the Binary Star HD 165341. (Memo I)

This preprint was prepared with the AAS LaTeX macros v5.2.

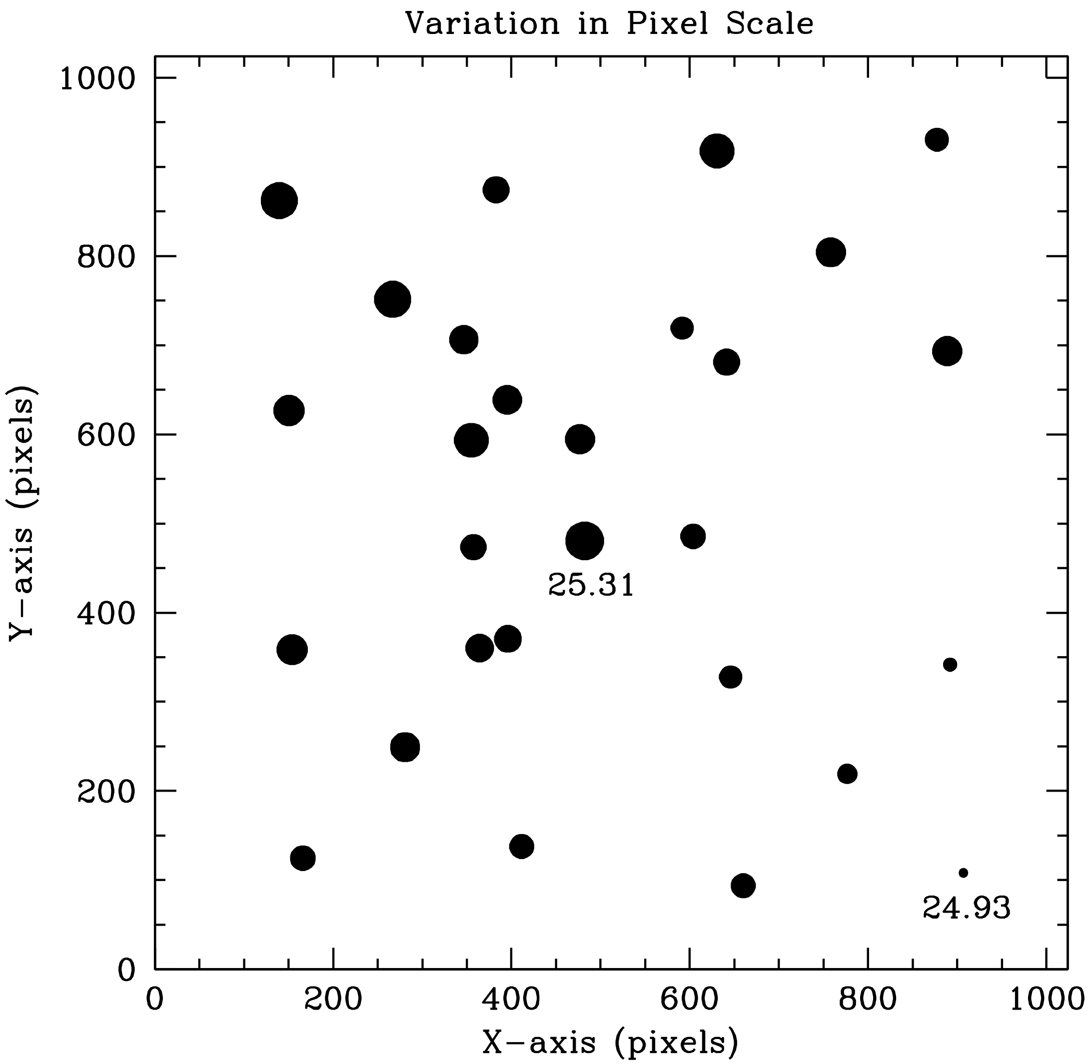


Fig. 1.— Positional dependence of the pixel scale for the night of Jun 23, 2002 (from Memo I). The binary WDC 18055+0230 was observed at angle of 63.5°. The point size indicates the pixel scale, decreasing linearly from the largest value (25.31 mas/pix) to the smallest one (24.93 mas/pix).

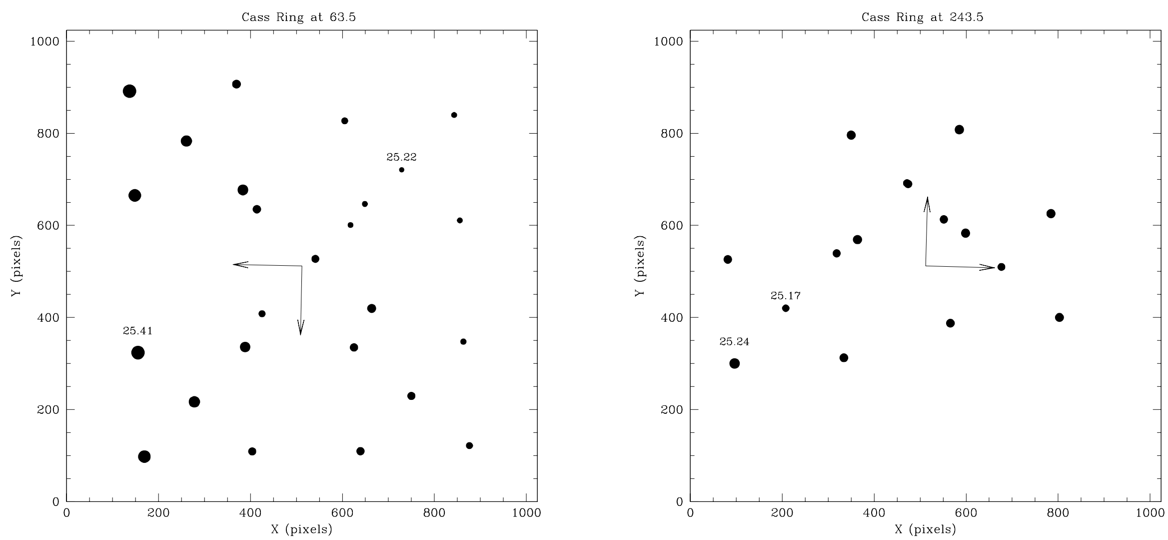


Fig. 2.— Same as Figure 1 above, for WDC 09006+4147 (*left panel*; cass ring at 63.5°) and WDC 20467+1607 (*right panel*; cass ring at 243.5°). The compass arrows correspond to the directions N and E on the array, with E counter-clockwise from N.

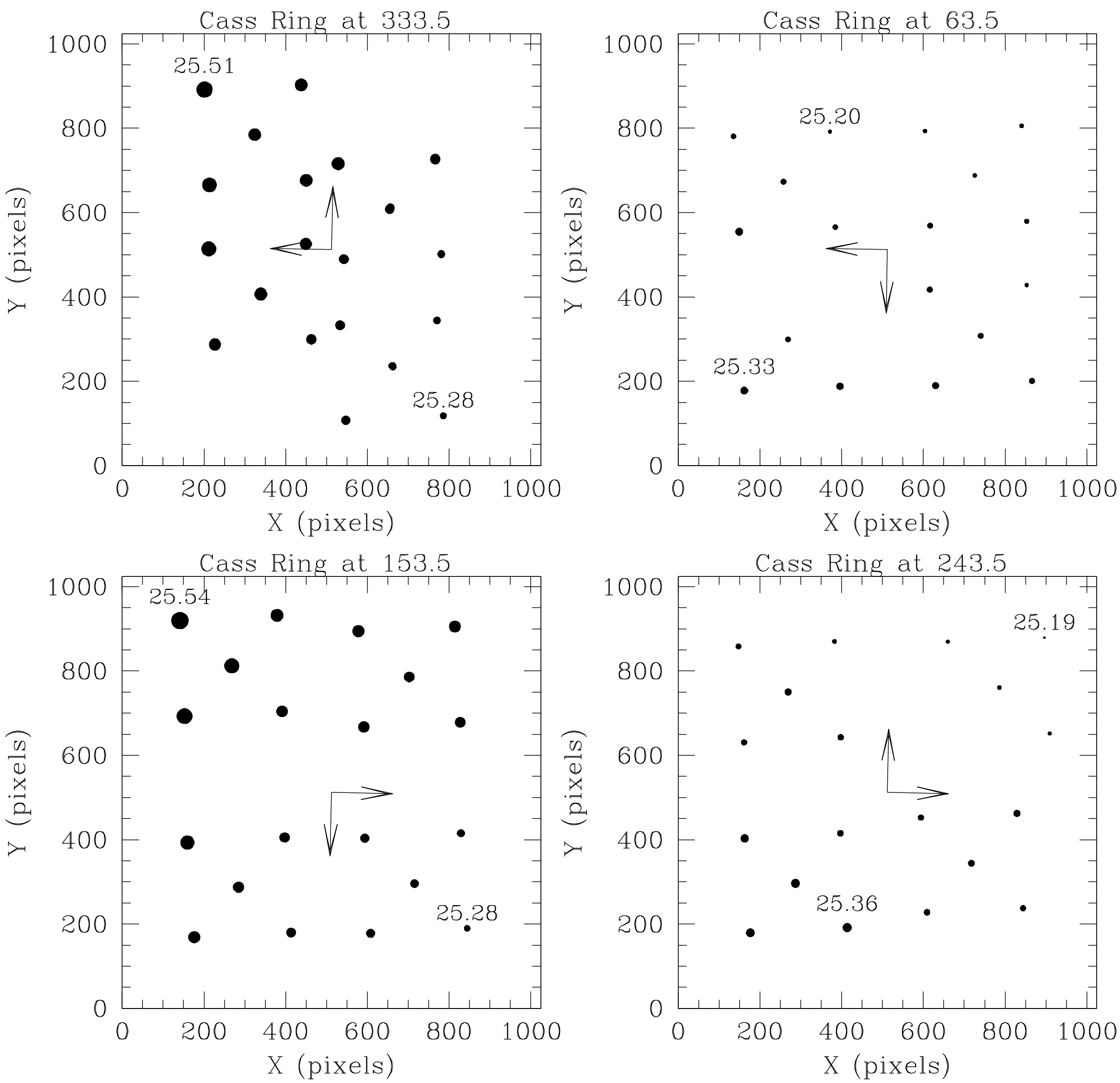


Fig. 3.— Positional dependence of the pixel scale for the night of Jul 15, 2003. The binary star WDC 16147+3352 was observed at all 4 nominal cass ring angles.

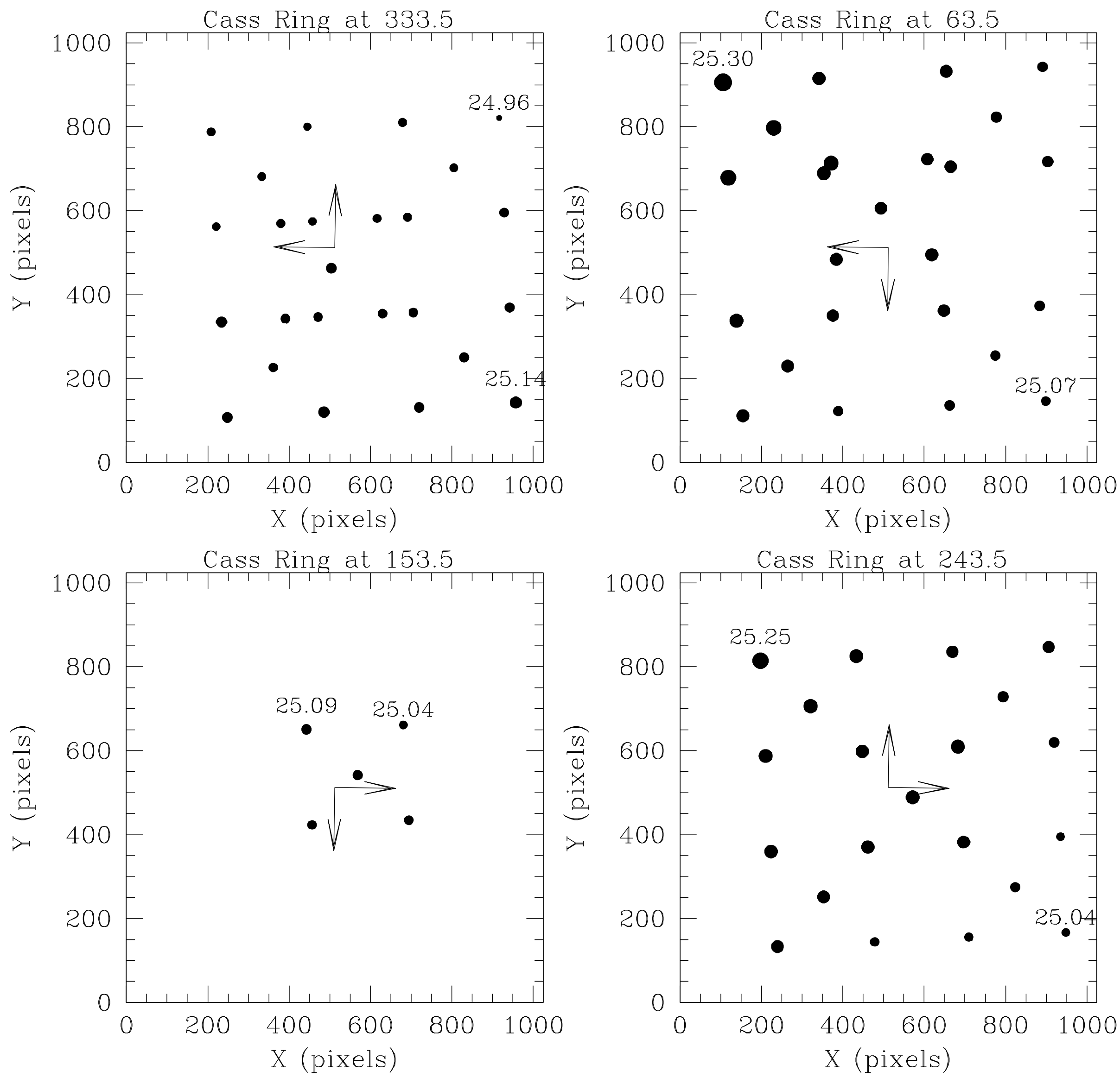


Fig. 4.— Same as Figure 3, but for Jul 16, 2003, and WDC 18055+0230.

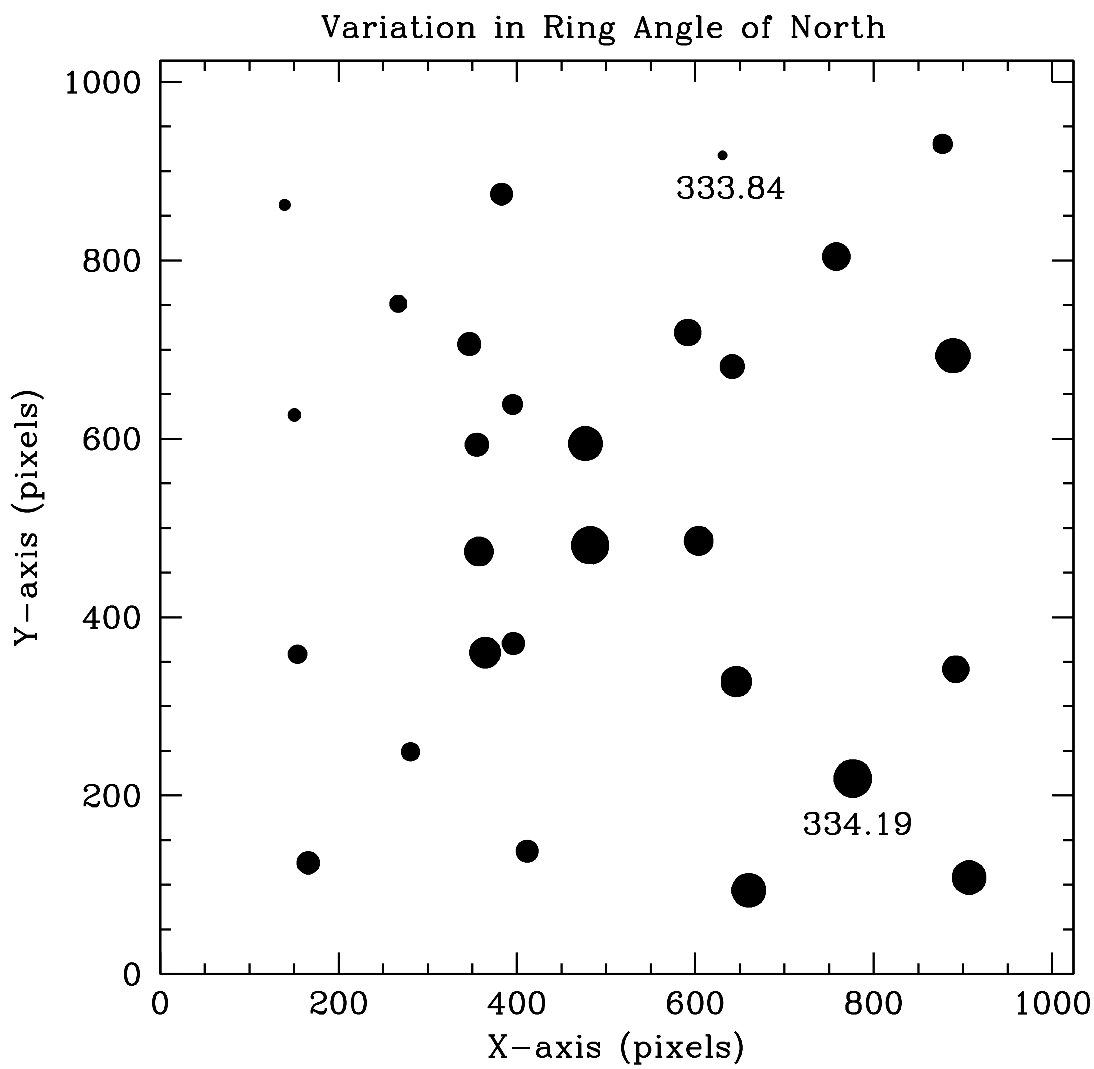


Fig. 5.— Positional dependence of the north direction for the night of Jun 23, 2002 (from Memo I). The binary WDC 18055+0230 was observed at a cass ring angle of 63.5°. The point size indicates the position angle of north decreasing linearly from the largest value (334.19°) to the smallest one (333.84°).

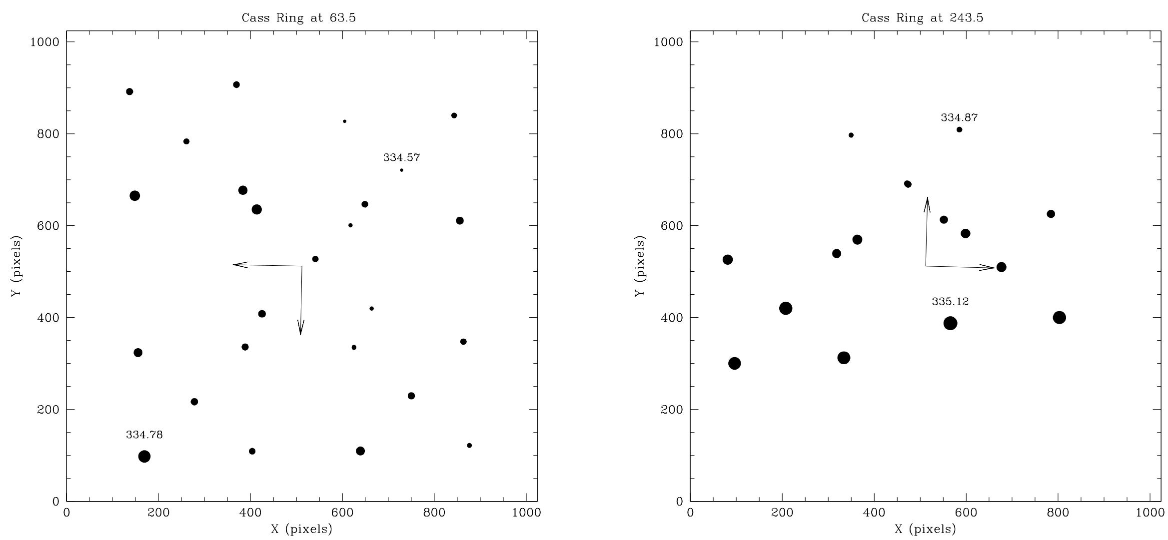


Fig. 6.— Same as Figure 5, but for WDC 09006+4147 (*left panel*; cass ring at 63.5°) and WDC 20467+1607 (*right panel*; cass ring at 243.5°).

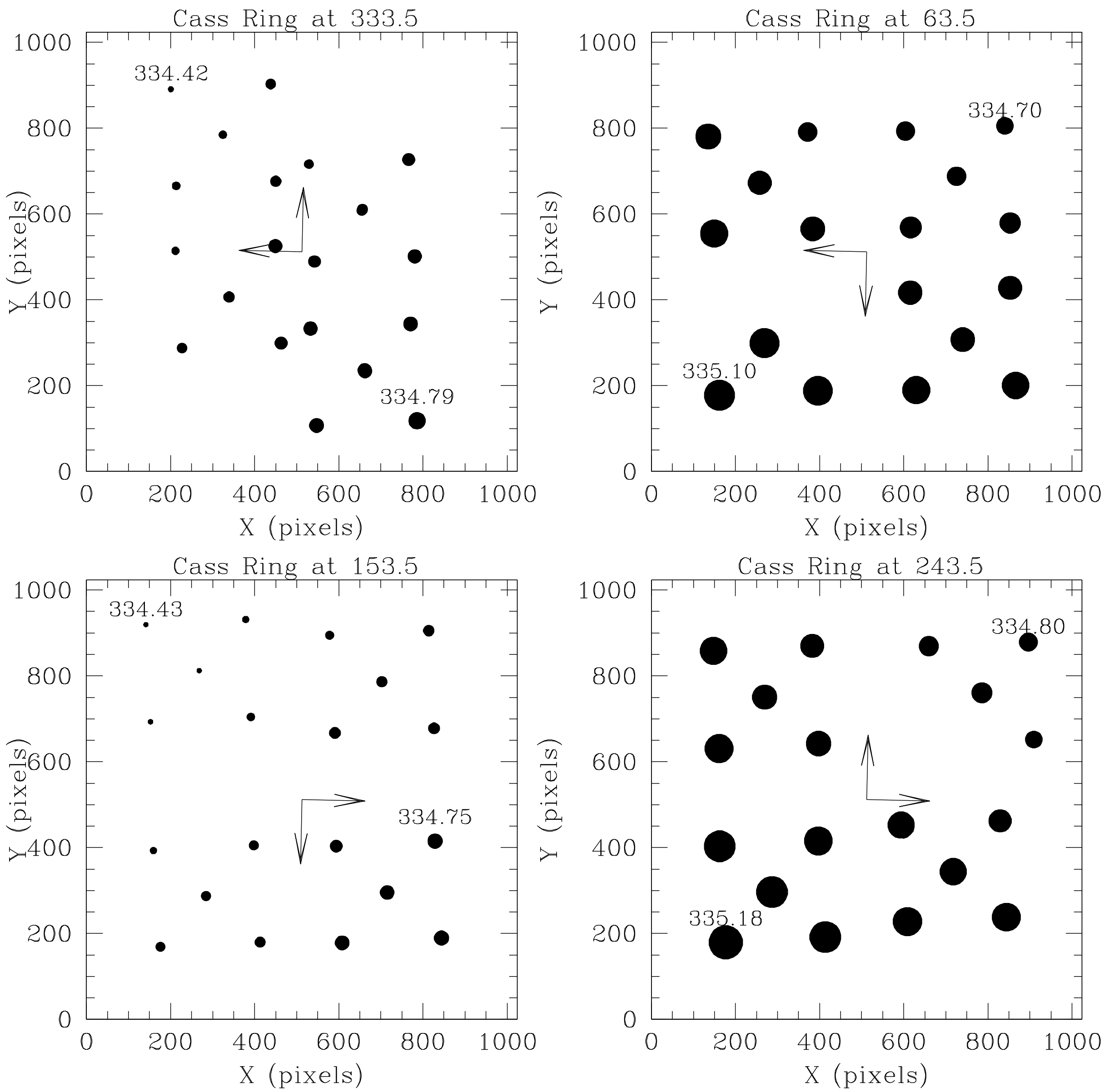


Fig. 7.— Positional dependence of the angle of north for each of the 4 cass ring angles. WDC 16147+3352; Jul 15, 2003.

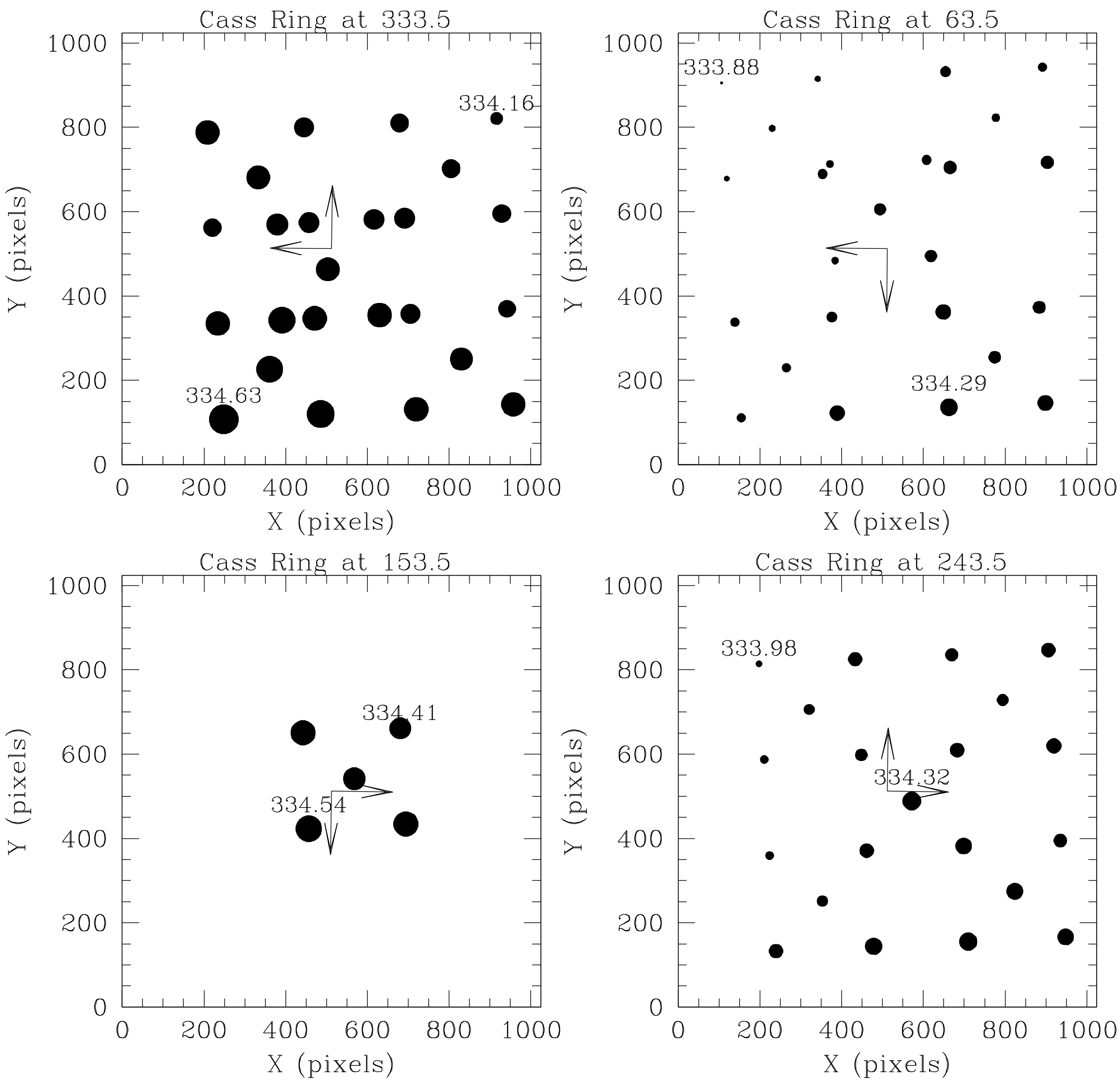


Fig. 8.— Same as Figure 7, but for Jul 16, 2003, and WDC 18055+0230.

Table 1. Observed binaries

| Binary (WDC) | Date (UT) | (year) | $\rho$ (arcsec) | P.A. (degree) | $a$ (arcsec) | $\Omega$ (degree) | $P$ (years) | WDC grade | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 09006+4147 | May 10, 2003 | 2003.3560 | 0.7219 | 13.0340 | $0.6472 \pm 0.0010$ | $204.39 \pm 0.19$ | $21.776 \pm 0.017$ | 1 | 1 |
| 16147+3352 | Jul 15, 2003 | 2003.5370 | 7.0780 | 236.4879 | 5.927 | 16.889 | 888.989 | 4 | 2 |
| 18055+0230 | Jun 23, 2002 | 2002.4764 | 4.3351 | 142.8677 | $4.5540 \pm 0.0052$ | $302.12 \pm 0.097$ | $88.38 \pm 0.017$ | 1 | 3 |
| | Jul 16, 2003 | 2003.5394 | 4.5697 | 140.8363 | | | | | |
| 20467+1607 | May 11, 2003 | 2003.3586 | 9.2023 | 265.7002 | 10.22 | 88.06 | 3249 | 4 | 4 |

References. — 1. Hartkopf (1996); 2. Scardia (1979); 3. Pourbaix (2000); 4. Hale (1994)

Table 2. Average pixel scale and north direction

| Date (UT) | Binary (WDC) | Cass ring (degrees) | Scale[a] (mas/pix) | North[a] (degrees) | Measurements (#) |
|---|---|---|---|---|---|
| Jun 23, 2002 | 18055+0230 | 63.5 | $25.168 \pm 0.034$ (0.083) | $334.043 \pm 0.099$ (0.093) | 28 |
| May 10, 2003 | 09006+4147 | 63.5 | $25.301 \pm 0.041$ (0.059) | $334.659 \pm 0.19$ (0.049) | 25 |
| May 11, 2003 | 20467+1607 | 243.5 | 25.198 (0.015) | 335.006 (0.074) | 20 |
| Jul 15, 2003 | 16147+3352 | 333.5 | 25.381 (0.057) | 334.631 (0.082) | 87 |
| | | 63.5 | 25.258 (0.030) | 334.909 (0.100) | 62 |
| | | 153.5 | 25.382 (0.060) | 334.615 (0.077) | 60 |
| | | 243.5 | 25.270 (0.040) | 334.979 (0.104) | 55 |
| Jul 16, 2003 | 18055+0230 | 333.5 | $25.067 \pm 0.030$ (0.035) | $334.423 \pm 0.099$ (0.105) | 25 |
| | | 63.5 | $25.155 \pm 0.031$ (0.054) | $334.096 \pm 0.099$ (0.098) | 25 |
| | | 153.5 | $25.072 \pm 0.030$ (0.019) | $334.474 \pm 0.101$ (0.053) | 5 |
| | | 243.5 | $25.143 \pm 0.031$ (0.053) | $334.179 \pm 0.098$ (0.084) | 25 |
| unweighted average | | | $25.218 \pm 0.035$ (0.110) | $334.547 \pm 0.108$ (0.341) | 11 |
| predicted | | | 25.10[b] | 335.8[c] | |

[a]The $1\sigma$ error for the pixel scale and the north direction includes the error in the mean of the measurements, and the error in the semi-major axis (normalized to the binary separation), or in the ascending node of the binary, respectively. The quantities in parentheses represent the observational scatter.

[b]Hayward et al. (2001).

[c]Day crew setting.

Table 3. Pixel scale $\pi(x, y) = a_0 + a_1 x + a_2 y$ mas/pix

| Star WDC | Date UT | Cass ring deg | $a_0$ mas/pix | $a_1$ $\times 10^{-4}$ mas/pix$^2$ | $a_2$ $\times 10^{-4}$ mas/pix$^2$ | Measurements # |
|---|---|---|---|---|---|---|
| 09006+4147 | May 10, 2003 | 63.5 | $25.4283 \pm 0.0182$ | $-2.17 \pm 0.24$ | $-0.341 \pm 0.222$ | 25 |
| 20467+1607 | May 11, 2003 | 243.5 | $25.2054 \pm 0.0144$ | $0.00 \pm 0.18$ | $0.00 \pm 0.23$ | 20 |
| 16147+3352 | Jul 15, 2003 | 333.5 | $25.4312 \pm 0.0083$ | $-2.07 \pm 0.11$ | $0.953 \pm 0.089$ | 87 |
| 16147+3352 | Jul 15, 2003 | 63.5 | $25.3308 \pm 0.0095$ | $-0.487 \pm 0.107$ | $-0.833 \pm 0.122$ | 62 |
| 16147+3352 | Jul 15, 2003 | 153.5 | $25.4090 \pm 0.0098$ | $-1.80 \pm 0.13$ | $1.13 \pm 0.12$ | 60 |
| 16147+3352 | Jul 15, 2003 | 243.5 | $25.3521 \pm 0.0104$ | $-0.551 \pm 0.137$ | $-1.04 \pm 0.15$ | 55 |
| 18055+0230 | Jul 16, 2003 | 333.5 | 25.12450.0151 | $0.0 \pm 0.19$ | $-1.20 \pm 0.20$ | 25 |
| 18055+0230 | Jul 16, 2003 | 63.5 | 25.18660.0147 | $-1.59 \pm 0.19$ | $0.901 \pm 0.181$ | 25 |
| 18055+0230 | Jul 16, 2003 | 153.5 | 25.13330.0715 | $0.0 \pm 0.88$ | $0.0 \pm 0.92$ | 5 |
| 18055+0230 | Jul 16, 2003 | 243.5 | 25.17340.0175 | $-1.55 \pm 0.22$ | $1.18 \pm 0.23$ | 25 |

Table 4. North angle $\eta(x, y) = a + bx + cy$ degrees

| Star WDC | Date UT | Cass ring deg | $a$ deg | $b$ $\times 10^{-4}$ deg/pix | $c$ $\times 10^{-4}$ deg/pix | # meas |
|---|---|---|---|---|---|---|
| 09006+4147 | May 10, 2003 | 63.5 | $334.749 \pm 0.026$ | $-1.22 \pm 0.35$ | $-0.56 \pm 0.32$ | 25 |
| 20467+1607 | May 11, 2003 | 243.5 | $335.254 \pm 0.018$ | $0.24 \pm 0.23$ | $-4.49 \pm 0.29$ | 20 |
| 16147+3352 | Jul 15, 2003 | 333.5 | $334.589 \pm 0.015$ | $2.58 \pm 0.20$ | $-1.59 \pm 0.16$ | 87 |
| 16147+3352 | Jul 15, 2003 | 63.5 | $335.237 \pm 0.014$ | $-2.31 \pm 0.16$ | $-3.63 \pm 0.18$ | 62 |
| 16147+3352 | Jul 15, 2003 | 153.5 | $334.576 \pm 0.010$ | $2.40 \pm 0.13$ | $-1.46 \pm 0.12$ | 60 |
| 16147+3352 | Jul 15, 2003 | 243.5 | $335.250 \pm 0.014$ | $-2.23 \pm 0.19$ | $-3.05 \pm 0.19$ | 55 |
| 18055+0230 | Jul 16, 2003 | 333.5 | $334.696 \pm 0.037$ | $-2.24 \pm 0.47$ | $-3.16 \pm 0.49$ | 25 |
| 18055+0230 | Jul 16, 2003 | 63.5 | $334.090 \pm 0.030$ | $2.35 \pm 0.39$ | $-2.09 \pm 0.37$ | 25 |
| 18055+0230 | Jul 16, 2003 | 153.5 | $334.781 \pm 0.135$ | $-2.45 \pm 1.66$ | $-3.08 \pm 1.74$ | 5 |
| 18055+0230 | Jul 16, 2003 | 243.5 | $334.140 \pm 0.040$ | $2.05 \pm 0.50$ | $-1.60 \pm 0.52$ | 25 |