MEASUREMENT PRECISION OF THE YALE-SAN JUAN SPECKLE INTERFEROMETRY PROGRAM

E. P. HORCH, T. M. GIRARD, W. F. VAN ALTENA AND R. D. MEYER
Department of Astronomy, Yale University
P.O. Box 208101, New Haven, CT 06520-8101 USA

C. E. LOPEZ
Observatorio Astronómico "Félix Aguilar"
Av. Benavidez 8175 Oeste, 5407 Marquesado, San Juan, Argentina

AND

O. G. FRANZ
Lowell Observatory
1400 West Mars Hill Road, Flagstaff, AZ 86001 USA

Abstract. We present an update on our progress in taking speckle observations of double stars from the Southern Hemisphere. The work here includes a measurement precision study, where we compare some of our measures to ephemeris positions of binaries with very well-determined orbits.

1. Introduction

In the talk that opened this meeting, Dr. McAlister showed that there is still a large disparity in the number of speckle measures of southern double stars compared with northern ones. As late as 1988 there were almost no speckle measures of double stars south of $-30°$ declination (Hartkopf 1992). Since that time, the situation has improved somewhat with the publication of three large sets of position angle and separation measures from data taken at the Cerro Tololo 4-m telescope (McAlister, Hartkopf & Franz 1990, Hartkopf *et al.* 1993, Hartkopf *et al.* 1996), but a large imbalance favoring the Northern Hemisphere objects still persists today.

By way of example, Figure 1 shows a situation typical of the kind of data that exist for many of the far southern double stars today. This object,

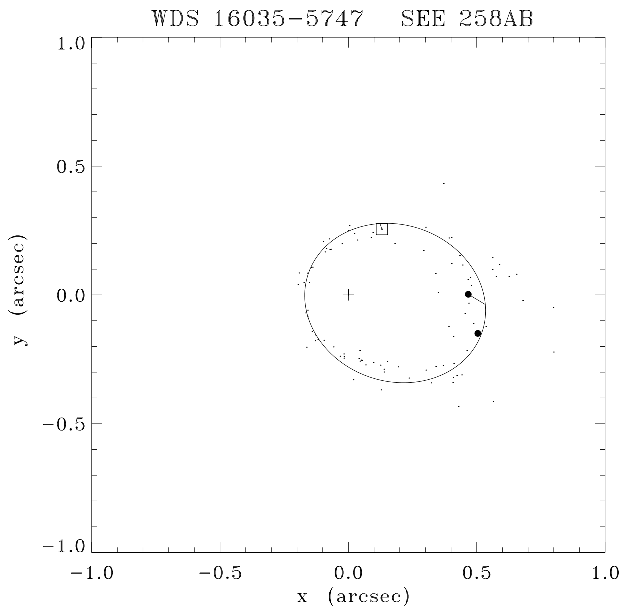

Figure 1. Measures and orbit of See 258 AB.

See 258 AB, has visual data dating back to the turn of the century, which are represented by dots in the figure. van den Bos published an orbit of See 258 AB in 1961 that, according to *The Fourth Catalog of Orbits of Visual Binary Stars* of Worley and Heintz (1983), is a "grade 1" or "definitive" visual orbit with semi-major axis of 0.366 arc seconds and period of 26.93 years. (The curve in the figure is the orbit of van den Bos.) Also plotted in the figure are all published speckle measures of See 258 as of this writing, a grand total of three, two from the 1970's plotted with filled circles (Morgan *et al.* 1978, Bonneau *et al.* 1980) and a third measure enclosed in a box, which is our recently published measure (Horch *et al.* 1996). Despite the fact that the system is easily resolvable with speckle interferometry even with small telescopes, there is virtually no data on this well-known system with the speckle technique.

Of course the primary motivation for collecting high-quality orbital data on visual binary stars is deriving good stellar masses, and in this regard it is often not so important to derive better orbits because if the parallax of the system is not well-known, parallax error dominates the error in the estimate of the mass. However, in the near future, Hipparcos parallaxes will be made available for a large number of the well-known visual binaries, and then there will be many cases where the error from the semi-major axis estimate will be much more significant. In addition, with smaller and smaller radial velocities being measured every year, there are many "visual" systems that can be observed by means of spectroscopy through at least part of the orbit. These facts make it very important to obtain the best possible astrometry of these systems in order to get the best mass estimates. Due mainly to the more than 20 years of speckle data produced by the Center for High-Angular Resolution Astronomy (CHARA) under the direction of Dr. McAlister, there is a long baseline of high-precision data on all the important systems observable from the Northern Hemisphere, but until recently the southern systems have been neglected. This is why we have started a long-term speckle observing program in the Southern Hemisphere.

2. Update and Current Status

We began taking speckle observations from El Leoncito, Argentina (latitude $-31^\circ\ 48'$) in July of 1994. There are actually two observatories at that location, Carlos U. Cesco Observatory, which is jointly run by the National University of San Juan (Argentina) and Yale Southern Observatory, and the Complejo Astronómico El Leoncito (CASLEO), which is the national observing facility of Argentina. At Cesco Observatory, we use a 76-cm reflector, and at CASLEO, there is a 2.1-m telescope.

Since the beginning of the project we have been using a multi-anode microchannel array (MAMA) detector to record speckle patterns. We have the camera on loan from J. G. Timothy of the University of New Brunswick, Canada. Because this device has a bialkali photocathode, the quantum efficiency in the visible is low compared with most other speckle cameras being used today and there is virtually no detector response redder than about 6000Å. We are hoping to replace the MAMA with an intensified-CCD with a red-extended S-20 photocathode, but at least through the end of 1996 we will continue to use the MAMA.

Absolute scale calibration and orientation measurements are made at least once per observing run with a full-aperture slit mask on the 76-cm telescope. We derive a secondary scale by allowing selected bright stars to drift across the detector with the telescope tracking off. The declination of the star and the diurnal rate are then used to derive the plate scale. While we currently use the aperture mask for primary scale calibration, we have found that the zero point in the position angle is better determined by the drift scans. Up until now, we have not had an aperture mask for scale calibration at the 2.1-m telescope, so we rely on drift scans and observing some stars in common with the 76-cm telescope to fix the scale and orientation there. An aperture mask for the 2.1-m telescope has been constructed, however, and we will begin using it on the upcoming run in October 1996.

As of this writing, the program is now two years old and we have made 1503 observations of 701 double stars. We have observed a total of 81 nights at the 76-cm telescope and 23 nights at the 2.1-m telescope. Eight nights have already been awarded to us at the 2.1-m telescope in the latter half of 1996.

3. Measurement Precision Study

Since our goal is to provide high-quality astrometric data of Southern visual binaries, we have recently completed a measurement precision study to assess our progress in this regard. The idea of the study is straight-forward: we measure position angles and separations of binaries with well-determined orbits, then compare our results to the predicted ephemeris position of the object at the epoch of observation. Originally, we thought that using binaries with grade 1 visual orbits from the orbit catalog of Worley and Heintz (1983) would be sufficient for studying our measurement precision and scale calibration. In this case, we would have many objects from our database to use in such a study. However, after finding many examples like Figure 1 where the visual orbit, although in some sense "definitive," was of insufficient quality to judge the speckle observations, and many other cases in the literature where speckle data has led to a substantial revision in some orbital elements of the binary, we decided against using these objects in our study. Instead, we turned to the much smaller sample of binaries with orbits determined with the highly-weighted inclusion of speckle data. Though there are few such objects that are observable from the Southern Hemisphere, they have some of the highest quality "visual" orbits that exist today.

Between February 1995 and March 1996 we collected 37 observations of 8 objects fitting the above criteria. Those observed with the 76-cm telescope are shown in Table 1 while those observed at the 2.1-m telescope are shown in Table 2. In addition to the orbital elements of these systems, the tables give the *Washington Visual Double Star Catalog* (WDS) number of each object (Worley & Douglass 1984). After taking speckle data with our system, we used a weighted least-squares fitting approach to fit the fringe pattern of the binary power spectra. This is the same technique described in Horch *et al.* (1996), and it yields the position angle and separation based on the orientation and spacing of the fringes.

One of the most obvious things we noticed about the precision of our measures for the 37 observations in the sample is that it is strongly dependent on the seeing conditions. Figures 2 and 3 show the separation and position angle residuals as a function of seeing full width at half maximum

TABLE 1. Orbital Elements of the Cesco Objects

Parameter	Bu 101 [1]	Sp 1 AB [2]	A 2768 [1]	StF 1728 AB [1]
WDS (α,δ 2000)	07518-1354	08468+0625	10427+0335	13100+1732
P (yr)	23.34	15.0507	80.56	25.804
	±0.17	±0.0064	±0.30	±0.055
a ($''$)	0.573	0.2547	0.3778	0.6684
	±0.010	±0.0009	±0.0014	±0.0013
i ($^\circ$)	79.68	50.01	145.92	90.06
	±0.06	±0.27	±0.78	±0.05
Ω ($^\circ$)	102.5	107.99	56.8	192.34
	±1.6	±0.35	±1.9	±0.24
T_o	1962.381	1991.247	1976.674	1963.468
	±0.039	±0.005	±0.030	±0.021
e	0.735	0.6558	0.546	0.497
	±0.016	±0.0018	±0.001	±0.012
ω ($^\circ$)	71.4	266.10	355.3	101.08
	±1.6	±0.27	±1.9	±0.24

TABLE 2. Orbital Elements of the CASLEO Objects

Parameter	Bu 1163 [2]	StF 2597 [2]	Stt 535 AB [2]	Ho 296 AB [1]
WDS (α,δ 2000)	01243-0655	19553-0644	21145+1000	22409+1433
P (yr)	16.114	425.	5.6998	20.83
	±0.024	±22.	±0.0023	±0.15
a ($''$)	0.1974	1.085	0.2313	0.2907
	±0.0015	±0.024	±0.0005	±0.0002
i ($^\circ$)	116.1	103.05	99.57	140.12
	±2.9	±0.84	±0.18	±0.02
Ω ($^\circ$)	30.38	264.03	203.68	252.37
	±0.70	±0.77	±0.12	±0.23
T_o	1988.860	1974.28	1987.166	1983.557
	±0.014	±0.23	±0.010	±0.004
e	0.927	0.9414	0.4386	0.738
	±0.012	±0.0020	±0.0027	±0.001
ω ($^\circ$)	350.5	327.9	7.02	23.28
	±1.2	±1.7	±0.64	±0.23

[1] Orbital elements from Hartkopf, McAlister & Franz (1989).
[2] Orbital elements from Hartkopf, Mason & McAlister (1996).

(FWHM). When the seeing is better than about 2 arc seconds, the residuals in both coordinates cluster more tightly together than the data with seeing worse than 2 arc seconds, indicating better precision when the seeing is good. There is one data point in the position angle plot which has seeing of about 1.3 arc seconds but a large residual of about $-3°$. This is an observation of Sp 1 AB, which at the epoch of observation had a separation of 0.271 arc seconds, fairly close to the diffraction limit of the 76-cm telescope. For such a small separation, a small deviation in the x- or y-coordinate leads to a substantial difference in position angle. In addition, the magnitude difference is 1.5, which makes the measure additionally challenging near the diffraction limit. The same residual data are plotted in Figures 4 and 5 in rectilinear coordinates (right ascension and declination residuals).

Although the data are few, we can make some preliminary statements about absolute scale calibration at the 76-cm telescope. If we confine the discussion to the data taken under seeing conditions better than 2 arc seconds, there seems to be no reason to suspect a serious problem in the zero point of our position angle calibration; the average of the θ-residuals differs from zero only by 0.1°. The average of the separation residuals is -5.6 milliarcseconds (mas), which is potentially significant. We will continue to monitor this both with future scale calibrations and binary observations.

We can also compute the standard deviations (sigmas) of position angle, separation, x and y residuals, to get an idea of the measuring precision so far on the project. These are shown in Table 3 along with the results discussed in the previous paragraph. Our position angle residuals have a sigma of about 1.2°, and the separation residuals appear at this point to have a sigma of about 7.5 milliarcseconds (mas). These numbers can be compared with those quoted by the CHARA group for their observations at the 4-m telescope at Kitt Peak, which are 1.01° in position angle and 3.5 mas in separation (Hartkopf, McAlister & Franz 1989). There are probably two reasons for the difference in precision between the two programs: 1) the size of the telescope aperture (4-m for CHARA versus 76-cm for the work here), and 2) our current detector has lower quantum efficiency than most other speckle cameras as discussed in the previous section.

Since there are only six observations from the 2.1-m telescope in this study, it is too soon to say more than there appears to be no improvement in the measuring precision at the larger telescope, as evident from Figures 2 through 5. In fact, it may be that it is worse, for reasons that are not yet entirely clear. We will continue to take more data of these and other binaries with well-determined orbits to get a better picture of the measuring precision at both telescopes.

4. Work on Systematic Errors

There are three components that contribute to the residuals discussed in the previous section. First, there are random or accidental errors, whose distribution is controlled by photon statistics and the speckle process; there

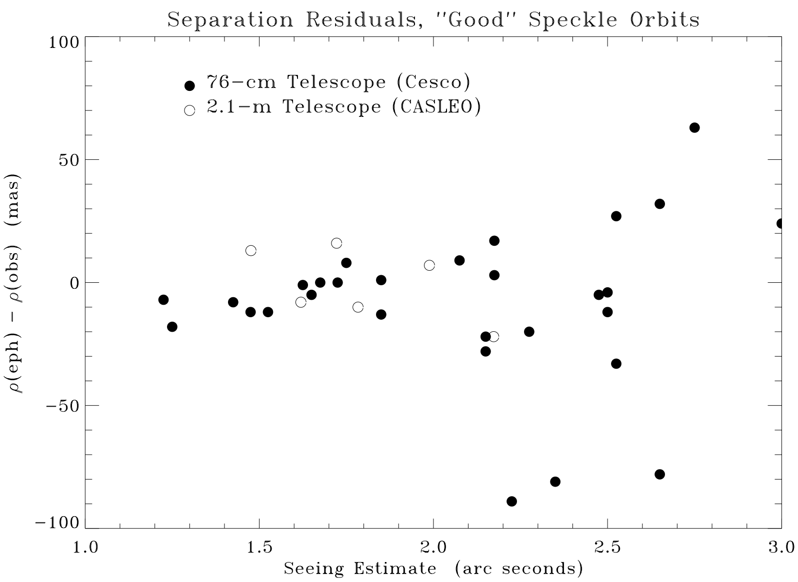

Figure 2. Separation residuals as a function of seeing FWHM.

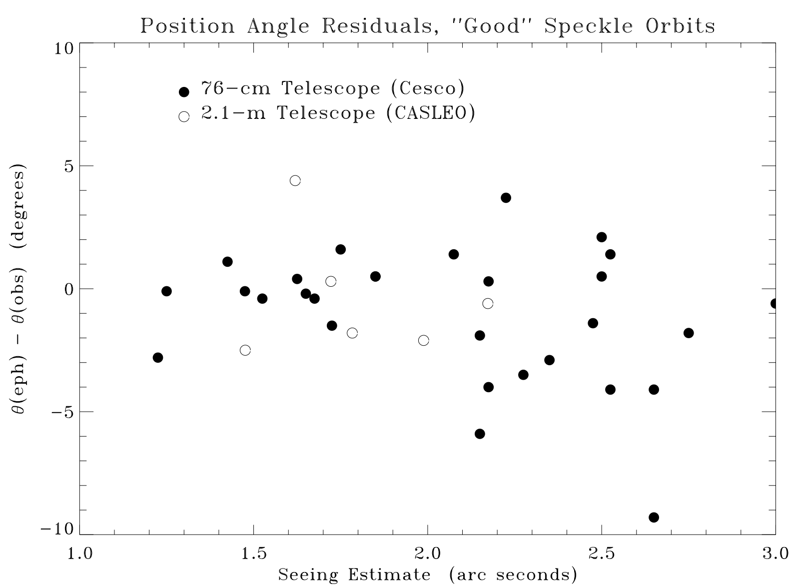

Figure 3. Position angle residuals as a function of seeing FWHM.

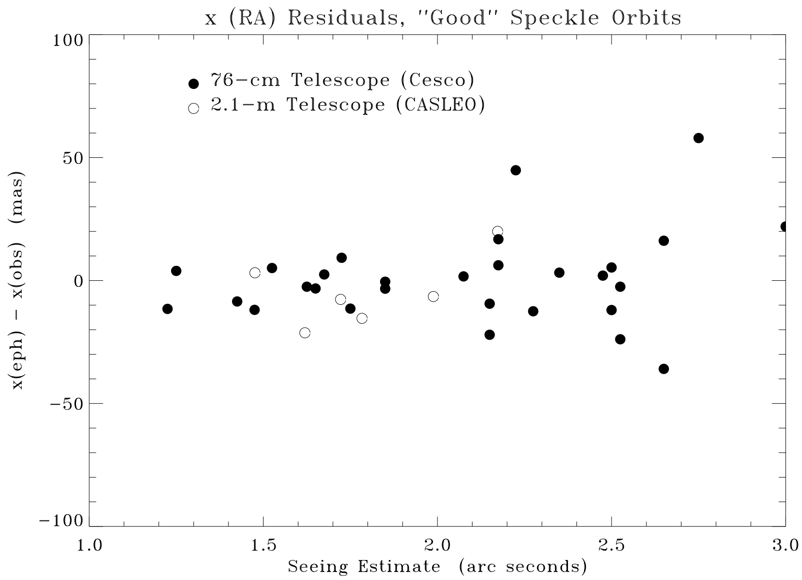

Figure 4. Right ascension residuals as a function of seeing FWHM.

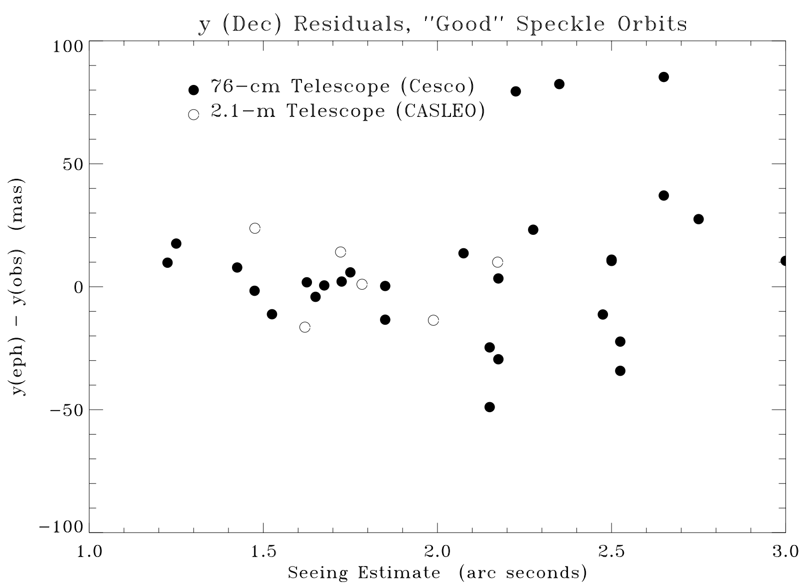

Figure 5. Declination residuals as a function of seeing FWHM.

TABLE 3. Summary of Residuals, 76-cm Telescope (Cesco)

Seeing $\leq 2''.0$	
$\overline{\Delta\rho} = -5.6 \pm 2.2$ mas	$\sigma_\rho = 7.5 \pm 1.5$ mas
$\overline{\Delta\theta} = -0.12^\circ \pm 0.33^\circ$	$\sigma_\theta = 1.16^\circ \pm 0.24^\circ$
$\overline{\Delta x} = -2.7 \pm 2.0$ mas	$\sigma_x = 7.1 \pm 1.4$ mas
$\overline{\Delta y} = +1.3 \pm 2.5$ mas	$\sigma_y = 8.6 \pm 1.8$ mas

are systematic errors induced by the telescope and camera system or the analysis routines; finally there are errors in the orbits themselves, although we have selected the objects so that these errors are as small as possible. The analysis presented in the previous section does not correct for systematic errors. We are continuing to examine the possibility of systematic error generated by change of focus, wavelength of observation, and optical field angle distortion. So far, we have found no evidence for any measurable change of scale as a function of telescope focus or wavelength, but we have found evidence for a small amount of field angle distortion caused by the magnification element in the speckle camera.

Most speckle cameras have a very small field of view, a few arc seconds on a side at most, but with our speckle camera we have a much larger field of view, about 15×60 arc seconds at the 76-cm telescope. Even with this large field, we oversample the diffraction-limited point spread function of the telescope by a factor of about 2.7. The large size is also convenient for acquiring targets since we do not have a flexure or atmospheric dispersion model for making corrections to the positions of stars at the 76-cm telescope. We try with each observation to place the star in approximately the same location on the detector, but with such a large field, the position can easily vary by a couple of arc seconds. This makes us especially susceptible to field angle distortion.

We have been able to begin to map out the distortion in our camera both with drift scan star trails and the aperture mask. When using the aperture mask, the slits create a diffraction pattern on the image plane. By moving the pattern around over the full field of view and measuring the change in the derived scale, we can measure the distortion. This work is in progress. The star trails also provide information about distortion, because if distortion exists, the trails will not be straight lines and/or the velocity of the star will not appear to be constant across the detector. Figure 6 shows a long-axis residual plot of many star trails after a best fit line has been subtracted from each trail. The systematic deviation from zero is an indication of distortion. The level of the distortion appears to be small compared to the typical accidental errors of our double star observations,

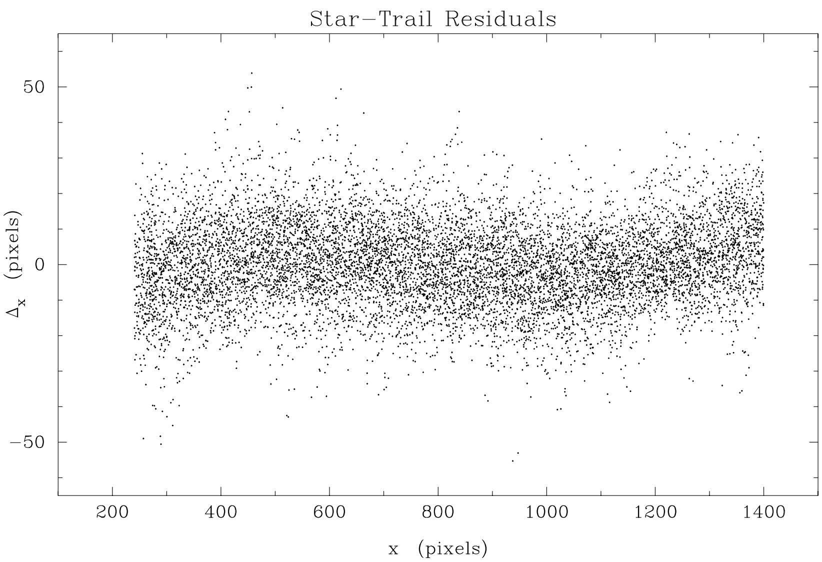

Figure 6. Star trail long-axis residuals.

but nonetheless we are currently trying to model and remove it from our double star measures. We hope that once we do this, the standard deviation values in Table 3 will decrease a little.

5. Conclusions

The Yale-San Juan speckle interferometry program has taken 1500 speckle observations of double stars in the last two years. In our initial measurement precision study, it appears that for data taken under seeing conditions better than 2 arc seconds, the standard deviation in separation residuals is about 7.5 mas, and the standard deviation in position angles is about 1.2° when we compare our measures from the 76-cm telescope to ephemeris positions of binaries with very well-determined orbits.

We would like to thank J. G. Timothy for the loan of the MAMA detector system, and CASLEO for granting us observing time. This work is funded in part by NSF grant AST93-12148.

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