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CCD SPECKLE OBSERVATIONS OF BINARY STARS FROM THE SOUTHERN HEMISPHERE

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ABSTRACT

We present 119 position angle and separation measures of 86 double stars observed by way of speckle interferometry with the University of Toronto Southern Observatory 60 cm telescope at Las Campanas, Chile. Speckle interferograms are recorded with a bare (unintensified) front-illuminated CCD in a fast subarray-readout mode. Position angles and separations are determined by a weighted least-squares fitting algorithm applied to the binary power spectra, and the 180° ambiguity in the position angle inherent in this approach is resolved by bispectral analysis. In this configuration the 60 cm telescope exhibits near-diffraction-limited performance. Initial results indicate that our separation measures have a root-mean-square (rms) deviation of 6.6 ± 1.0 milliarcsecond (mas) and our position angle measures have an rms deviation of 1.73 ± 0.26 degrees when judged against the ephemeris positions of a small sample of binaries with previously well-determined orbits. © 1997 American Astronomical Society. [S0004-6256(97)03411-0]

1. INTRODUCTION

In recent years, the large body of speckle measures of Northern binary star systems has produced significant improvements in orbit determinations, stellar masses, and the mass–luminosity relation (McAlister *et al.* 1988; Hartkopf *et al.* 1989; Bagnuolo, Jr. & Hartkopf 1989; Kamper *et al.* 1990; Barlow & Scarfe 1991; Hartkopf *et al.* 1992; Gies *et al.* 1993; Henry & McCarthy 1993; Copenbarger *et al.* 1994; Scarfe *et al.* 1994; Karovska *et al.* 1993; Mason *et al.* 1995; McAlister *et al.* 1995; Hartkopf *et al.* 1996b; Fekel *et al.* 1997). These developments would not have been possible without speckle interferometry and are largely due to the consistent program of speckle observations first by McAlister in the 1970's, and then by the Center for High Angular Resolution Astronomy (CHARA) collaboration under his direction continuing through the present time. With the recent publication of very precise parallax results from the *HIPPARCOS* astrometric satellite, we can expect further progress for many of these systems that will no doubt significantly increase our understanding, particularly of the mass–luminosity relation.

Despite the active speckle interferometry of binary stars in the Northern Hemisphere, the Southern Hemisphere has received slight attention. There is no large body of speckle data on objects south of -30° declination, and consequently there has been no significant contribution to progress on stellar masses and the mass–luminosity relation from the South. This is particularly ironic considering the long tradition of visual double star observations in the Southern Hemisphere by van den Bos, Finsen, Rossiter and others. Indeed, the first interferometric observations of Southern binaries occurred in

the 1950's and early 1960's with Finsen's eyepiece interferometer (Finsen 1954, 1964). However, at the present time only about 8% of all speckle observations of double stars have been made south of declination -30° . The very great majority of these measures have come from the work of the CHARA group who were regularly observing at the Cerro Tololo Inter-American Observatory 4 m telescope from 1988 to 1994 (McAlister *et al.* 1990; Hartkopf *et al.* 1993; Hartkopf *et al.* 1996a).

In 1994, van Altena and his collaborators started a new program of speckle observations of binary stars based at El Leoncito, Argentina (Horch *et al.* 1996). From 1994 to 1996, this was the only large-scale speckle program based in the South, taking some 1800 binary star observations. Most of these data are yet to be published. However, the speckle camera used in this work, which had been provided by J. Gethyn Timothy of the University of New Brunswick, Canada, was recently returned to the Northern Hemisphere. This left the Southern sky without a dedicated speckle program for the first time since 1988.

In February of 1997, we had the opportunity to observe at the University of Toronto Southern Observatory (UTSO) 60 cm telescope at Las Campanas, Chile using a front-illuminated Kodak KAF-4200 CCD. Set inside a Photometrics CH-250 camera head operating at approximately -50°C , subarrays of the chip can be read out quickly enough to record speckle interferograms with the device. This paper describes our observation technique and presents the first set of position angle and separation measures for 119 observations taken during the 1997 February run. By comparing our measures of five binaries that have very well-determined orbits to their orbital ephemeris positions, we derive initial results of our measurement precision.

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FIG. 1. A schematic showing the CCD and subarray strip used in a typical speckle observation at Las Campanas.

2. OBSERVATIONS

CCDs have previously been used for speckle interferometry (e.g., Kluckers *et al.* 1997; Zadnik 1993) but the vast majority of recent speckle data of binary stars has been collected with microchannel-plate (MCP) based cameras, most often intensified CCDs. Bare (unintensified) CCDs have traditionally had two problems as speckle imaging detectors. First, the readout time has been too slow to acquire data at the frame rate necessary to make observing efficient, and second, the read-noise floor of CCDs presents a problem with faint objects where there is insufficient contrast between speckles and peaks in the read noise to perform the standard speckle analysis.

On the other hand, CCDs offer much higher quantum efficiency than MCP-based cameras (which are typically limited by the quantum efficiency of the photocathode), so that as CCDs improve in terms of read noise and speed, they begin to compete with MCP-based cameras in certain speckle imaging situations, specifically those where the number of pixels read out per second (the pixel rate) is lower or where the objects of interest are brighter. There are two situations that can reduce the pixel rate necessary in speckle imaging. The first is good seeing. When the seeing is good, the correlation time of the atmosphere is longer, and it is not necessary to record as many frames per second. The second situation is a smaller ratio between the seeing size and the speckle size. Fewer pixels are then needed in a frame in order to both oversample the speckles and contain the seeing disk. Infrared speckle imaging is an example of both situations, and perhaps not surprisingly, unintensified focal plane arrays have already been extensively used as speckle imaging detectors at these wavelengths. Likewise in the visible, fast, low-noise CCDs can be used as speckle imaging devices not only at sites of superb seeing (where again the correlation time of the atmosphere is longer), but also at smaller telescopes, where the speckles are larger compared to the seeing disk.

Our project examines the small-telescope regime. During

FIG. 2. A four-image portion of a raw data strip. These data are of HR 2411 ($V=5.42$). The bias level has not been subtracted and has average value of approximately 75 ADU. The peak value in the low-level streak between images (barely visible here) is approximately 2% of the peak in the images themselves after bias subtraction.

a run in February of 1997 at the UTSO 60 cm telescope at Las Campanas, speckle observations of 86 double stars with separations ranging from 0.25 arcsec (very close to the diffraction limit of the 60 cm telescope) to about 4.0 arcsec were obtained using a Photometrics CH-250 CCD camera. The sensor is a commercially available front-illuminated CCD with 9 μm square pixels and a 2033 $\times$ 2048 pixel format. The electronics module can readout pixels at a rate of 200 kHz, at which speed the rms read noise is approximately 10 electrons. The pixel data are then stored on a PC with an image processing software package called PMIS ($\copyright$ 1991–1996 GKR Computer Consulting, Boulder, Colorado). Within PMIS, it is possible to construct macros to readout subarrays of the chip, execute charge transfer commands, and operate the camera shutter.

A PMIS macro was developed that collects and stores speckle interferograms in the following way. Suppose that the serial register is located at the top of the CCD array. A long subarray strip is defined with orientation perpendicular to the serial register (along the CCD columns). The position of the strip within the array is chosen such that the image of the star being observed is at the bottom of the strip. The shutter then opens and for a predetermined exposure time (30 ms for all the observations discussed here) the CCD is exposed to light. At the end of the exposure time, the shutter remains open but the charge collected during the exposure is quickly shifted up towards the serial register a certain number of rows. The camera then waits for another exposure time, during which more charge is collected in the bottom of the strip. Then a fast rowshift is again executed, and so on. In this way, we build up a sequence of images of the star along the strip without having to read out the CCD. When the strip is filled with independent speckle patterns, the shutter is closed and the subarray is read out and stored. A schematic of the CCD and subarray strip are shown in Fig. 1. To get more frames, the strip is again filled and read out in the same way. A speckle observation then consists of a certain number of strips, each containing a certain number of independent

speckle patterns. A strip with the shutter closed is always recorded first to act as a “bias strip.”

Because the shutter remains open during the fast charge transfer, some light continues to hit the CCD, which creates a low-level streak between the speckle patterns. The charge transfer between exposures takes about 4 ms for the observations discussed here compared to the 30 ms exposure time, but in fact the average intensity recorded per pixel in the streak is only 2%–3% of the average intensity per pixel in the speckle patterns themselves. This is because the light in the streak is spread out over approximately five times as many pixels as the light in the speckle patterns, so that the effective exposure per pixel is reduced. Nonetheless, the signal level in the streak is estimated and removed from the data in the reduction process, as explained in Sec. 3. Figure 2 shows a four-image section of a raw data strip for an observation of HR 2411.

This method relies on the fact that in most cases, the area in and below the strip does not contain any other significant sources of light. If there is another source inside the strip (above the object of interest), then its signal will be added to that of the object of interest as its specklegrams are shifted through the position of the unwanted object. If there is a source directly below the strip, then the its signal will be shifted up into the strip as speckle patterns from the object of interest are accumulated. These situations can lead to an effect where the unwanted source masquerades as a small-separation secondary in some of the frames. As a consequence, it is not possible after the fact to uniquely determine the position of the secondary of a binary system; the position derived can in principle be due to a secondary of wider separation (with separation vector nearly parallel to the strip) whose signal appears close to the primary due to the shutterless operation. However, while observing, we examine the region around the strip by taking a short full-frame exposure. If no wide companions are noted, we assume that if a secondary is detected, its separation is small enough that both the primary and secondary are located within the same frame.

For our observing run, the typical file consisted of 32 (64×1024)-pixel strips, each containing 32 separate star images. The strips can therefore be divided into 32 (64×32)-pixel frames for a total of 1024 frames per observation. With this configuration, an average of approximately seven frames can be recorded per second. All of the data presented in this paper were taken through a standard V filter under seeing conditions ranging between 1.0 and 1.4 arcsec. An observation of a binary star was always followed with that of a point source located very close in the sky to the binary and chosen from *The Bright Star Catalogue* (Hoffleit & Jaschek, 1982). These point source files provide an estimate of the speckle transfer function for the binary observation that is then used in the reduction process. Although most speckle observers use Risley prisms to compensate for atmospheric dispersion, they have not been used here. For reasonable zenith angles, the elongation of speckles caused by atmospheric dispersion is modest at a small aperture telescope due to the large size of the speckles. The largest zenith angle for the data presented here is 49° . In addition, the point source observations

FIG. 3. A surface plot of the power spectrum of one of the observations of Bu 101 prior to defining the annular region for the power spectrum fit. A strong fringe pattern is clearly visible, as expected for a binary star. The separation of the system was measured to be $0''.384$.

taken after each binary do contain information about the dispersion, and because we use these in the reduction technique, it is possible to overcome the lack of Risley prisms. Our data are also undersampled; the pixel scale is 198.88 ± 0.92 mas/pixel (see Sec. 3.3) while the diffraction-limited spot size is equal to approximately 229 mas for the wavelength of interest ($5550 \text{ \AA}$). Though undersampling complicates the reduction scheme (see Sec. 3.2), it is beneficial in that it reduces the number of pixels that must be read out in a strip, and therefore increases the number of frames the system can record per second. Given this pixel scale, each frame has a field of view of approximately 13×6.5 arcsec.

3. DATA REDUCTION

3.1 Formation of the Power Spectrum and Bispectrum from the Raw Data

To begin the reduction procedure, strips are broken into frames centered on the star image centroids. The frames are then bias-subtracted and the low-level streak caused by the shutterless charge transfer is estimated from the edges of the image and removed. Frames are flat fielded in the standard way with (bias-subtracted) flat-field files. The result is a set of “processed frames” $I_{\text{pr}}(\mathbf{x})$ that can be described as the simple addition of two functions:

$$I_{\text{pr}}(\mathbf{x}) = I(\mathbf{x}) + r(\mathbf{x}), \quad (1)$$

where $I(\mathbf{x})$ is the familiar photon-limited image intensity of the speckle pattern (what would have been obtained in the absence of read noise) and $r(\mathbf{x})$ is the read noise term, assumed to be a random field of normally distributed numbers with zero mean and standard deviation equal to σ_r , the read noise of the detector. The Fourier transform of $I_{\text{pr}}(\mathbf{x})$ is then

$$\hat{I}_{\text{pr}}(\mathbf{u}) = \hat{I}(\mathbf{u}) + \hat{r}(\mathbf{u}), \quad (2)$$

where $\hat{}$ denotes the Fourier transform and $\mathbf{u}$ is the Fourier variable conjugate to $\mathbf{x}$. It can be shown that the function $\hat{r}(\mathbf{u})$ is itself a random field of (complex) numbers that are normally distributed with zero mean and the same sigma as $r(\mathbf{x})$. As a result, when the average power spectrum of many

frames is formed, the cross terms vanish and we have the result that

$$\langle |\hat{I}_{\text{pr}}(\mathbf{u})|^2 \rangle = \langle |\hat{I}(\mathbf{u})|^2 \rangle + \langle |\hat{r}(\mathbf{u})|^2 \rangle, \quad (3)$$

where $\langle \cdot \rangle$ denotes the average over many frames. Since the random field $\hat{r}(\mathbf{u})$ has zero mean, the second term on the right-hand side is simply the variance of $\hat{r}(\mathbf{u})$ and has average value σ_r^2 . This means that the CCD power spectrum has a “read noise bias” term that must be subtracted to convert the frames into the familiar photon-limited case. An estimate of σ_r is obtained from the bias strips and then σ_r^2 is subtracted from our power spectra. Of course, the power spectra also contain the classical “photon noise bias” term which is equal to N , the number of photons detected in the frame, and this term is subtracted from the power spectrum in the standard way. Figure 3 shows an example of the binary power spectrum after deconvolution by the point source and prior to the power spectrum fitting discussed in the next section.

To establish the quadrant of the secondary, we form a rudimentary reconstructed image using two “near-axis” subplanes of the image bispectrum. A near-axis subplane of the bispectrum $\hat{C}(\mathbf{u}, \Delta\mathbf{u})$ of an image $I(\mathbf{x})$ can be written as

$$\hat{C}(\mathbf{u}, \Delta\mathbf{u}) = \langle \hat{I}(\mathbf{u}) \hat{I}(\Delta\mathbf{u}) \hat{I}^*(\mathbf{u} + \Delta\mathbf{u}) \rangle, \quad (4)$$

where $\Delta\mathbf{u}$ is some fixed nonzero vector in the frequency plane and $*$ denotes the complex conjugate. Inserting our form for $\hat{I}_{\text{pr}}(\mathbf{u})$ from Eq. (2) into the right side above and carrying out the multiplication, it can be seen that many of the cross terms vanish in the average over many frames to leave

$$\begin{aligned} \hat{C}_{\text{pr}}(\mathbf{u}, \Delta\mathbf{u}) = & \hat{C}(\mathbf{u}, \Delta\mathbf{u}) + \langle \hat{I}(\mathbf{u}) \hat{r}(\Delta\mathbf{u}) \hat{r}^*(\mathbf{u} + \Delta\mathbf{u}) \rangle \\ & + \langle \hat{I}^*(\mathbf{u} + \Delta\mathbf{u}) \hat{r}(\mathbf{u}) \hat{r}^*(-\Delta\mathbf{u}) \rangle + \langle \hat{I}(\Delta\mathbf{u}) \hat{r}(\mathbf{u}) \\ & \times \hat{r}^*(\mathbf{u} + \Delta\mathbf{u}) \rangle, \end{aligned} \quad (5)$$

The three remaining cross terms are nonzero only when the argument of $\hat{r}$ is equal to the argument of $\hat{r}^*$. For nonzero $\Delta\mathbf{u}$, this cannot happen for the last term, and only happens for one value of $\mathbf{u}$ in each of the other two terms, namely, $\mathbf{u} = \mathbf{0}$ for the first term and $\mathbf{u} = -\Delta\mathbf{u}$ for the second one. The value of the bispectral subplane is therefore only affected by the presence of the read noise at two points, where an added term equal to $\hat{I}(\mathbf{0}) \langle |\hat{r}(\Delta\mathbf{u})|^2 \rangle$ is present. $\langle |\hat{r}(\Delta\mathbf{u})|^2 \rangle$ is simply the power spectrum read-noise bias σ_r^2 , and $\hat{I}(\mathbf{0})$ is equal to the number of photons detected in the frame. This value is subtracted from the two pixels in question and a standard image reconstruction from the two bispectral subplanes is performed. This entails photon noise bias subtraction according to the method of Beletic (1989), and then reconstruction of the object phase according to the relaxation method of Meng *et al.* (1990). The phase is then combined with the modulus estimate derived from the power spectrum and inverse-Fourier transformed. The result is a basic reconstructed image that is almost always good enough to immediately read off the quadrant of a double star system.

3.2 Power Spectrum Fitting

Our approach to determining the position angles and separations from the frame data is a weighted least-squares method applied to the object spatial frequency power spectrum. This is the same method described in Horch *et al.* (1996), with a minor modification for application to CCD data. The basic philosophy of the method is different from the CHARA and United States Naval Observatory (USNO) speckle interferometry groups, who both make fits to the autocorrelation data. Though a discussion of the method can be found in Horch *et al.* (1996), we briefly describe how the technique is applied to CCD data below.

Using the point source observed with each binary as an estimate of the speckle transfer function, an estimate of the true object power spectrum can be obtained by dividing the binary power spectrum by the point source power spectrum (a standard Fourier deconvolution). In the absence of under-sampling, this result could then be fit to a function of the form

$$f(\mathbf{u}) = A^2 + B^2 + 2AB \cos[2\pi(\mathbf{x}_A - \mathbf{x}_B) \cdot \mathbf{u}] \quad (6)$$

over some appropriate domain in the frequency plane. A and B represent the intensities of the primary and secondary and $\mathbf{x}_A - \mathbf{x}_B$ represents the vector separation of the binary on the image plane. Equation (6) is simply the power spectrum of two delta functions on the image plane with intensities A and B .

The weighting scheme for the fitting is chosen to approximate a χ^2 minimization method. If we define the image power spectrum $\hat{\Phi}_I(\mathbf{u})$, where $\mathbf{u}$ is the two-dimensional vector that describes the frequency plane, and we assume that $\hat{\Phi}_I$ is normalized to 1 at $\mathbf{u} = \mathbf{0}$, then the power spectrum that we form from our speckle data frames is actually the so-called “unbiased estimator” of the image power spectrum given by

$$Q_2 = |\hat{I}(\mathbf{u})|^2 - N = |\hat{I}_{\text{pr}}(\mathbf{u})|^2 - N - \sigma_r^2, \quad (7)$$

where again N is the number of detected photons in the frame. It can easily be shown that Q_2 is related to $\hat{\Phi}_I(\mathbf{u})$ by the following:

$$\langle Q_2 \rangle = \bar{N}^2 \hat{\Phi}_I(\mathbf{u}), \quad (8)$$

where $\bar{N}$ is the average number of detected photons per frame. It can also be shown (e.g., Dainty 1984) that the variance in Q_2 (in the absence of read noise) is given by

$$\text{var}(Q_2) = \bar{N}^2 + \bar{N}^2 \hat{\Phi}_I(2\mathbf{u}) + 2\bar{N}^3 \hat{\Phi}_I(\mathbf{u}) + \bar{N}^4 \hat{\Phi}_I^2(\mathbf{u}). \quad (9)$$

Since the read noise and photon noise are uncorrelated, we assume that the variance of our “processed frames” may be obtained simply by adding the above variance and that of the read-noise power spectrum (this amounts to adding their standard deviations in quadrature),

$$\begin{aligned} \text{var}(Q_2)_{\text{pr}} = & \bar{N}^2 + \bar{N}^2 \hat{\Phi}_I(2\mathbf{u}) + 2\bar{N}^3 \hat{\Phi}_I(\mathbf{u}) + \bar{N}^4 \hat{\Phi}_I^2(\mathbf{u}) \\ & + \text{var}(|\hat{r}(\mathbf{u})|^2). \end{aligned} \quad (10)$$

We use Eq. (10), the (normalized) point-source power spectrum, and the average number of photons per frame to calculate the variance expected as a function of $\mathbf{u}$ for the point-

source observation. A second calculation is performed for the binary observation. The variance in the read-noise power spectrum is calculated from the bias strip in both cases. These two functions are then used to estimate the variance in the division of the binary power spectrum by the point-source power spectrum and a smoothed version of this final variance function is then used to weight the least-squares fitting procedure on the frequency plane.

Equation (10) is valid only in the region outside the low frequency seeing peak in frequency space, so typically we mask this region off before performing the fit. Likewise, $\hat{\Phi}_l$ is only nonzero inside the diffraction limit of the telescope, so the region outside the diffraction limit is also masked off. This defines an annulus in the frequency plane as the fitting domain. To minimize the effect of undersampling, we decrease the outer radius of the annulus to a value slightly smaller than the Nyquist frequency of our power spectra. This may reduce the precision of the measures obtained, but was judged an acceptable cost for insuring that undersampling does not play a large role in the measurement process.

Before using the method on real data, we tested it on simulated speckle data using the speckle data simulation program of Horch (1994), modified to include read noise for application to the CCD problem. In numerous different simulated CCD observations, we found that the fitting method always gave excellent estimates of the secondary position and intensity. Furthermore, the final reduced χ^2 value output by the program was always near one, even when read noise was a significant contributor to the frame images. The method is not a true χ^2 minimization, because the variance function used to weight the least squares is only an estimate of the variance based on photon and read-noise statistics, but it should be very similar to a χ^2 minimization in the limit of a perfect detector.

An added complication in our data is the fact that the speckles are undersampled. The effect of this is to alias high-frequency components of the Fourier transform of a frame image to lower values. However, this may be estimated in a deterministic way by convolving the trial fitting function with the pixel response function and the speckle profile, and then performing the aliasing pixel by pixel in the frequency plane. For most CCDs, there is no detailed information about the sensitivity within a pixel, but for the Kodak KAF-4200 chip, such a subpixel sensitivity map has recently been measured by Kavaldjiev & Ninkov (1997). This sensitivity map has been included in our undersampling correction. The power spectrum fitting algorithm then finds the best-fit *undersampled* binary power spectrum given the input pixel map, the shape of a speckle, and the annular fitting domain described above. For the speckle profile, we used a somewhat broadened Airy profile (not diffraction-limited) in order to account for broadening due to atmospheric dispersion and optical degradation of the profile by the telescope. With atmospheric dispersion, the speckle images will be broadened in one specific direction only (along the vector pointing to the zenith), while a symmetric broadening is assumed. Nonetheless, we have decided that at this early stage to keep the undersampling correction as simple as possible.

TABLE 1. Scale and orientation results for the 1997 February run.

Method	Zero Point Angle (°)	Scale (mas/pixel)
Aperture Mask, β CMa	—	199.53 $\pm$ 0.05
Aperture Mask, δ CMa	—	198.23 $\pm$ 0.31
Aperture Mask, average	—	198.88 $\pm$ 0.92
Star Trails	15.03 $\pm$ 0.02	—
Astrometry of Trapezium	15.0 $\pm$ 0.2	200.46 $\pm$ 0.82

3.3 Measurement of the Pixel Scale

The typical way to measure the scale of a set of speckle observations is to use an aperture slit mask, which then makes a diffraction pattern at the image plane. For our observations, a slit mask was not available, but there was a multihole (Hartmann) mask used for collimating the telescope. By covering up some of the holes, we were able to make a ‘‘Michelson-type’’ aperture mask with holes corresponding to different baselines inside the aperture. The different baselines produce fringes of a given spacing on the image plane. When the power spectrum of such images is formed, narrow peaks appear corresponding to each baseline whose separation can easily be measured. By combining these measures with knowledge of the wavelength of observation, the pixel scale can then be derived. This was our fundamental method for scale calibration.

Because our observations were taken with a V filter, which is wide by interferometric standards, the separation of the fringes produced by the Michelson mask depends on the color of the star observed, the transmission function of the V filter, and the quantum efficiency of the CCD as a function of wavelength. The latter two effects are small, but the first can be substantial, changing the effective wavelength of the observation by 50 Å or more. We include all three in the calculation of the effective wavelength of the mask observations. The stellar flux as a function of wavelength estimated from Gunn & Stryker (1983) and the standard V filter transmission curve (e.g., Buser & Kurucz, 1978) are combined with the quantum efficiency curve of the chip to obtain the amount of light detected as a function of wavelength. The average over wavelength is then used as the effective wavelength of the observation.

Two stars (β and δ CMa) were observed using the Michelson mask, detecting three independent baselines in the power spectrum each time. The pixel scales derived from each baseline are systematically different, probably due to imperfect collimation of the telescope and other factors, but if we choose baselines that bracket the region of the frequency plane that we are interested in for our power spectrum fits of binary stars, we obtain an average pixel scale of 199.53 $\pm$ 0.05 mas/pixel for β CMa (an average of two observations) and an average of 198.23 $\pm$ 0.31 mas/pixel for δ CMa (an average of five observations). Since the two values are discrepant, we are forced to assume that the precision of measures of a particular star is not a good estimate of the uncertainty in the determination of the pixel scale. In lieu of any other information, we adopt a final pixel scale which is the simply average of the two values above, 198.88 $\pm$ 0.92

TABLE 2. Orbital elements for the binaries in the measurement precision study.

Parameter	Bu 1032 AB ²	Bu 101 ³	Sp 1 AB ²	A 2768 ¹	STF 1728 AB ¹
WDS (α, δ 2000)	05387-0236	07518-1354	08468+0625	10427+0335	13100+1732
P (yr)	155.3	23.314	15.0507	80.56	25.804
	± 7.5	± 0.018	± 0.0064	± 0.30	± 0.055
a (")	0.2642	0.6000	0.2547	0.3778	0.6684
	± 0.0052	± 0.0013	± 0.0009	± 0.0014	± 0.0013
i (°)	160.4	80.386	50.01	145.92	90.06
	± 7.2	± 0.055	± 0.27	± 0.78	± 0.05
Ω (°)	136.	102.698	107.99	56.8	192.34
	$\pm 25.$	± 0.094	± 0.35	± 1.9	± 0.24
T ₀	1997.	1985.844	1991.247	1976.674	1963.468
	$\pm 24.$	± 0.015	± 0.005	± 0.030	± 0.021
e	0.051	0.7512	0.6558	0.546	0.497
	± 0.015	± 0.0018	± 0.0018	± 0.001	± 0.012
ω (°)	18.	72.73	266.10	355.3	101.08
	$\pm 37.$	± 0.11	± 0.27	± 1.9	± 0.24

¹From Hartkopf, McAlister & Franz, 1989.²From Hartkopf, Mason & McAlister, 1996.³From Hartkopf, 1997 (private communication).

mas pixel. It is unfortunate that we do not have mask data of more stars to more precisely measure the pixel scale; this contributes to the uncertainty of all the separations that we derive in Secs. 4 and 5.

The detector zero-point angle relative to the celestial coordinate system was derived from star images trailed across the CCD with the telescope tracking off. We took a set of star trails typically once per night, with each set containing images of 5, 10, 15, 20, 25, and 30 s trails. The angle between the trail line and the pixel axes was then measured for the longer (20, 25, and 30 s) trails. This yielded a value of $15.03 \pm 0.02^\circ$.

Because of the large format of our detector, it was possible to check our pixel scale and zero point angle angle by

FIG. 4. Separation (ρ) residuals as a function of ephemeris separation for the measures presented here of binaries with speckle orbits. From smallest to largest separation, the objects are: Bu 1032 AB, Sp 1 AB, STF 1728 AB, Bu 101, and A 2768. The shaded region on the left side of the figure marks the region below the diffraction limit of the telescope.

FIG. 5. Position angle (θ) residuals as a function of ephemeris separation for the measures presented here of binaries with speckle orbits. From smallest to largest separation, the objects are: Bu 1032 AB, Sp 1 AB, STF 1728 AB, Bu 101, and A 2768. The shaded region on the left side of the figure marks the region below the diffraction limit of the telescope.

observing a field of stars and using astrometry available in the literature to derive another estimate of these values. For this purpose we chose the Trapezium (θ^1 Ori). Using the astrometry of van Altena *et al.* (1988), we derive a pixel scale of 200.46 ± 0.82 mas/pixel and a zero-point angle of $15.0 \pm 0.2^\circ$. The detector zero point angle is in perfect agreement with the value determined from the star trails, though of lower precision. The pixel scale value is slightly higher than that derived from the mask data, but the 1σ error bars of the two estimates do (barely) overlap. We therefore conclude that there is no major discrepancy and will use the mask value for derivation of all measures discussed in this paper, since the mask files were analyzed with a power spectrum approach in much the same way as the binary stars. Table 1 shows a summary of the pixel scale and zero-point angle results.

The large field of view presents a potential source of error in the pixel scale in the form of optical field angle distortion (OFAD). If present, OFAD changes the value of the pixel scale depending on where within the field of view the star is observed. To guard against this, we tried to limit our field of view to a 1000×1000 pixel area centered on pixel (1500,1500) on the CCD. (Because of the length of the sub-array strips, it is not possible to place objects on the top half of the array, and pixel (1500,1500) is therefore the center of the available area for positioning stars.) All measures presented in this paper have image centroids within the (1000

TABLE 3. Summary of residuals, speckle orbits.

Average Residual (obs - eph)	RMS Dev. from Ave. Residual
$\overline{\Delta\rho} = +5.0 \pm 1.4$ mas	$\sigma_\rho = 6.6 \pm 1.0$ mas
$\overline{\Delta\theta} = +0.04^\circ \pm 0.38^\circ$	$\sigma_\theta = 1.73^\circ \pm 0.26^\circ$
$\overline{\Delta x} = -2.8 \pm 1.6$ mas	$\sigma_x = 7.3 \pm 1.1$ mas
$\overline{\Delta y} = -5.3 \pm 1.8$ mas	$\sigma_y = 8.3 \pm 1.3$ mas

TABLE 4. Double star speckle measures.

WDS (α, δ 2000)	Discoverer Designation	HD	DM	Date (1900+)	θ ($^\circ$)	ρ ($''$)
04403 – 5857	HJ 3683	30003	–59°370	97.1005	90.1	3.341
04590 – 1623	Bu 314 AB	31925	–16°1013	97.1005	325.9	0.767
				97.1170	325.9	0.754
05044 – 3529	JC 9	32831	–35°2089	97.0951	306.0	3.134
05132 – 1257	STF 661	33949	–13°1092	97.1224	357.3	2.135
05135 + 0158	STT 517 AB	33883-4	+01°938	97.1224	238.7	0.593
05218 – 2446	HJ 3752 AB	35163	–24°3023	97.1170	93.1	3.412
05231 – 0806	A 486	35261	–08°1105	97.1225	71.3	0.627
05270 – 6837	I 276	36584	–68°375	97.0951	162.4	1.341
05355 – 3316	Hu 1393	37224	–33°2419	97.0951	321.2	0.377
				97.1006	318.0	0.377
				97.1170	318.7	0.373
05387 – 0236	Bu 1032 AB	37468	–02°1326	97.1171	119.2	0.247
				97.1225	120.1	0.261
				97.1225	123.5	0.271
				97.1225	118.0	0.255
05483 – 4855	I 63 AB	39177	–48°1991	97.0952	16.5	1.002
06004 – 3103	HJ 3823 AC	40887	–31°2902	97.0952	7.3	2.438 *
06048 – 4828	Dun 23	41824	–48°2124	97.0952	118.4	2.586
06123 – 2514	B 104	42899	–25°3014	97.0899	184.3	1.067
06214 + 0216	A 2667	44333	+02°1197	97.1171	221.7	0.264
06360 – 3510	I 1118	47229	–35°3008	97.1198	28.3	0.852
06380 – 6132	I 5	48189	–61°688	97.1199	256.8	0.450
06425 – 6145	I 6	49076	–61°706	97.0953	257.3	0.654
				97.1172	256.7	0.644
06552 – 2902	RST 1329	51202	–28°3591	97.0953	36.6	0.741
06573 – 3530	I 65	51825	–35°3233	97.1172	146.2	0.241 *
07018 – 1053	Bu 573	52694	–10°1818	97.1226	299.1	0.838
07033 – 5911	Dun 39	53921	–58°826	97.1199	85.9	1.409
07148 – 1529	Bu 575 AB	56012	–15°1720	97.1226	101.2	0.558 *
07175 – 4659	I 7	57095	–46°3046	97.1227	209.6	0.843
07263 – 2810	See 79	58846	–27°4070	97.1227	305.0	0.755
				97.1227	305.4	0.757
07374 – 3459	Fin 324 AB-C	61330	–34°3755	97.1172	21.0	0.392
07397 – 4317	I 353	61946	–42°3396	97.0900	43.3	0.696
				97.0954	40.7	0.707
07430 – 1704	Hu 710	62351	–16°2093	97.0900	74.7	0.451
				97.1172	76.5	0.437
07468 – 4648	Hu 1428	63449	–46°3421	97.1227	32.6	0.512
07518 – 1354	Bu 101	64096	–13°2267	97.0954	305.2	0.374
				97.1173	307.0	0.384
				97.1173	309.5	0.382
				97.1200	308.1	0.383
				97.1200	308.1	0.376
				97.1227	308.0	0.366
				97.1227	308.9	0.375
08125 – 4616	See 96 Aa-B	68895	–45°3892	97.0955	275.6	0.592
08138 – 3444	I 193	69042	–34°4501	97.1201	102.2	2.374 *
08159 – 3056	Bu 454 AB	69445	–30°5946	97.1173	2.1	1.888
08276 – 2051	B 2179	71581	–20°2538	97.1173	215.9	0.417
08314 – 3642	HJ 4106 AB	72435	–36°4731	97.1228	304.7	4.300
08331 – 2436	Bu 205 AB	72626	–24°7089	97.1201	318.0	0.563
08391 – 2240	Bu 208 AB	73752	–22°2345	97.1174	31.5	1.293
08468 + 0625	Sp 1 AB	74874	+06°2036	97.1174	174.9	0.283
				97.1174	175.4	0.284
				97.1174	175.7	0.285
				97.1201	176.5	0.275
				97.1201	176.5	0.280
				97.1228	173.7	0.273
				97.1228	177.5	0.277
08468 + 0625	STF 1273 AB-C	74874	+06°2036	97.1174	292.7	2.786
				97.1174	292.8	2.796
				97.1174	292.7	2.789
				97.1201	292.9	2.793
				97.1201	292.7	2.797
				97.1228	292.8	2.793
				97.1228	292.8	2.783
09044 – 3306	RST 2599	77920	–32°6023	97.1229	279.7	0.289

$\times 1000$) subarray centered on (1500,1500). We took observations with the Michelson mask and of the Trapezium moving the image around within this 1000×1000 subarray, and we have not observed any obvious systematic change in the pixel scale. Two observations of β CMa were taken outside the 1000×1000 subarray near the edge of the CCD, and these both yield higher pixel scales than the other mask files, so it is possible that OFAD is present at a low level in our data.

4. MEASUREMENT PRECISION STUDY

Five objects from the main list of measures presented in the next section have orbits determined with the heavily-

weighted inclusion of previous speckle interferometry data. These are Bu 1032 AB, Bu 101, Sp 1 AB, A 2768, and STF 1728 AB. We observed each of these objects several times in order to study how our position angle and separation measures compare to the ephemeris positions for these orbits at the epoch of observation. The orbital elements used for this study are shown in Table 2.

Figure 4 shows the residuals of our separation measures when compared to the orbit predictions. The separation residuals have an rms deviation of 6.6 ± 1.0 mas. Figure 5 shows the position angle residuals, which have an rms deviation of 1.73 ± 0.26 degrees. Table 3 shows the averages and rms deviations for polar (ρ, θ) and rectilinear (x, y) coordi-

TABLE 4. (continued)

WDS (α, δ 2000)	Discoverer Designation	HD	DM	Date (1900+)	θ ($^\circ$)	ρ ($''$)
09152 – 4533	I 11	79900	–45°4982	97.0901	290.3	0.761
				97.1175	290.0	0.764
09217 – 4719	RST 393	81035	–46°5121	97.0902	261.4	0.834
09272 – 0913	A 1588 AB	81728	–08°2678	97.1202	194.8	0.393
09307 – 4028	Cop 1	82434	–39°5580	97.1175	225.9	0.502
09372 – 5340	See 115	83520	–53°2646	97.1229	7.8	0.666 *
09387 – 3937	I 202	83610	–39°5697	97.1202	10.3	0.495
09398 – 5008	RST 4917	83879	–49°4578	97.1229	43.5	0.606 *
09525 – 0806	AC 5 AB	85558	–07°2909	97.1202	64.3	0.580
10043 – 2823	I 292	87416	–27°7171	97.1229	317.2	0.559
10062 – 4722	I 173	87783	–46°5806	97.1175	1.4	0.901
10095 – 6841	I 13 AB	88473	–68°1034	97.1230	112.8	0.645 *
10162 – 5954	Hu 1597	89263	–59°2008	97.1230	93.6	0.299
10191 – 6441	HJ 4306	89715	–64°1248	97.0902	313.3	2.446 *
10193 – 1232	RST 3688	89455	–11°2851	97.1175	334.4	0.261
10238 – 4415	I 208 AB	90201	–43°6224	97.1230	15.3	0.657 *
10329 – 4700	YSJ 1	91504	–46°6205	97.1176	96.9	0.442 *
10361 – 2640	Bu 411	91881	–26°8022	97.1176	312.2	1.271
10370 – 0850	A 556	91962	–08°2963	97.1231	165.5	0.862
10373 – 4814	See 119	92139-40	–47°6042	97.0903	259.2	0.457
10427 + 0335	A 2768	92749	+04°2375	97.1231	272.6	0.452
				97.1231	271.4	0.449
11165 – 4553	HJ 4423	98096	–45°6837	97.1176	275.7	2.542
11210 – 5429	I 879	98718	–53°4498	97.1177	140.4	0.384
11272 – 1539	Hu 462	99565	–14°3326	97.1231	239.3	0.413 *
11336 – 4035	I 78	100493	–30°7175	97.1177	278.4	0.701 *
11529 – 3354	HJ 4478	103192	–33°8018	97.1177	33.6	0.676
				97.1177	32.5	0.651
11554 – 4154	I 80	103567	–41°6849	97.0904	94.2	1.310
11596 – 7813	HJ 4486	104174	–77°772	97.0905	211.0	0.364
12018 – 3439	I 215	104471	–33°8130	97.1178	86.3	0.676
12036 – 3900	See 143	104747	–38°7479	97.1232	68.1	0.817
12301 – 1324	Bu 28	108799	–12°3647	97.1178	334.3	2.010
12318 – 3155	RST 1675	109017	–31°9743	97.1232	304.8	0.815
12421 – 5446	Fin 200	110372	–54°5306	97.0905	265.4	0.403
12567 – 4741	I 83	112361	–47°7972	97.1178	230.2	0.819
13074 – 5952	R 213	113823	–59°4740	97.1178	21.7	0.713
				97.1233	21.9	0.713
13100 + 1732	STF 1728 AB	114378-9	+18°2697	97.1179	12.4	0.281 *
				97.1179	13.0	0.277 *
13229 – 4757	SLR 18	116197	–47°8260	97.1234	242.1	0.706
13351 – 5822	Jsp 588	117945	–57°6143	97.1234	271.8	0.841
13372 – 6142	I 365 AB	118261	–61°3841	97.1179	101.7	0.357
13378 – 3504	See 184	118465	–34°9020	97.1179	301.5	3.341
13520 – 3137	Bu 343	120759	–31°10706	97.1180	304.3	0.290
13535 – 3540	HWE 28 AB	120987	–35°9090	97.1234	307.8	0.973
13550 – 0804	STF 1788 AB	121325	–07°3728	97.1234	97.4	3.594
14077 – 4952	SLR 19	123227	–49°8475	97.1180	314.5	1.295
14153 + 0308	STF 1819	124757	+03°2874	97.1234	204.5	0.902
14411 – 2237	RST 2917	129065	–21°3946	97.1235	170.1	0.379
14543 – 6625	HJ 4707	130940	–65°2914	97.1180	288.5	0.778

Notes to Table 4

WDS 06004 – 3103 = HJ 3823 AC: In this multiple system, our observation failed to detect the closer pair Hu 1399 AB, where the secondary has magnitude 9.2 and approximate separation 0.5 arc seconds.

WDS 06573 – 3530 = I 65: Despite nearly a century of visual observations and a grade 1 orbit in the orbit catalog of Worley and Heintz (1983), ours is apparently the first speckle measure of this system.

WDS 07148 – 1529 = Bu 575 AB: The magnitude difference of the system is listed in the WDS as 0.1. Our reduction does not give the same quadrant as the latest measure in the WDS.

WDS 08138 – 3444 = I 193: A smaller annulus was used in the power spectrum fit due to the faintness of the source. As a consequence, the separation and position angle uncertainties may be larger than other measures.

WDS 09372 – 5340 = See 115: The magnitude difference of the system is listed in the WDS as 0.0. Our reduction does not give the same quadrant as the latest measure in the WDS.

WDS 09398 – 5008 = RST 4917: A smaller annulus was used in the power spectrum fit due to the faintness of the source. As a consequence, the separation and position angle uncertainties may be larger than other measures.

WDS 10162 – 5954 = I 13 AB: Our reduction does not give the quadrant unambiguously. We therefore adopt the quadrant consistent with the latest measure in the WDS.

WDS 10191 – 6441 = HJ 4306: The magnitude difference of the system is listed in the WDS as 0.1. Our reduction does not give the same quadrant as the latest measure in the WDS.

WDS 10238 – 4415 = I 208 AB: A smaller annulus was used in the power spectrum fit due to the faintness of the source. As a consequence, the separation and position angle uncertainties may be larger than other measures.

WDS 10329 – 4700 = YSJ 1: This is the first measure of this system since the discovery measures in 1995 of Dinescu *et al.* (1997). The difference in position angle from their last measure is 2.2° and the difference in separation is 0''.020.

WDS 11272 – 1539 = Hu 462: Our reduction does not give the quadrant unambiguously. We therefore adopt the quadrant consistent with the latest measure in the WDS.

WDS 11336 – 4035 = I 78: The magnitude difference is listed in the WDS as 0.0. Our reduction does not give the same quadrant as the latest measure in the WDS.

WDS 13100 + 1732 = STF 1728 AB: The magnitude difference of the system is listed in the WDS as 0.0. Our reduction does not give the quadrant unambiguously, so we adopt the quadrant that gives a position angle consistent with previous measures in the WDS.

FIG. 6. The measures listed in Table 4 compared with all other measures listed in the WDS Catalog for four binaries with visual orbits from WH. Visual observations are plotted as dots, other speckle observations are plotted as filled circles, and the measures presented in this paper are the open circles. Line segments are drawn from the speckle data points to the ephemeris position derived from the orbital parameters. North is up, east is to the left. (a) AC 5 AB. Only CHARA speckle points are plotted for clarity. Our measure is partially covered by the recent CHARA measure in the upper left. (b) I 879. (c) STF 1819. Once again, only CHARA measures are plotted for clarity. (d) See 119.

nates, where x is the right ascension coordinate and y is the declination coordinate.

The average position angle residual is very close to zero, but our observed separations are on average slightly larger than the orbital predictions, by 5.0 ± 1.4 mas. It is readily apparent from Fig. 4 that part of this average discrepancy is attributable to the observations of Bu 1032 AB, which is a challenging object for the 60 cm telescope because its separation is very close to the diffraction limit and its magnitude difference is large (2.0). The Bu 1032 observations also increase the rms deviation of the θ residuals. Likewise, Sp 1 AB has a substantial magnitude difference (1.5) and a small separation, and the separation measures are again larger than

expected. Indeed, if these two systems are not included in the calculation, the average separation residual is reduced to -3.1 ± 1.9 mas. This may indicate that there is a small systematic error induced for faint secondaries near the diffraction limit with the power spectrum fitting technique. This is not unreasonable especially given that the observations were taken with no atmospheric dispersion compensation. If the dispersion is slightly different for the binary and the point source calibration object, there will be a change in the position of a weak, widely spaced fringe in the power spectrum, and therefore a change in the derived separation.

Two other sources of error that may be contributing to the larger observed separations are pixel scale measure and un-

undersampling correction. Due to the limited number of observations with the aperture mask, we currently know the pixel scale only to about 0.5%, as discussed earlier. If this pixel scale value is too large by 1σ , a binary with separation 0.3 arcsec would have an observed separation too large by 1.5 mas, or 30% of the average separation discrepancy. As discussed in Sec. 3.2, the undersampling correction applied in our reductions does not account for asymmetries in the power spectrum. This may produce an undersampling correction that is either too small or too large, depending on the geometry of the situation. It may be that with Bu 1032 AB and Sp 1 AB the undersampling correction is underestimated. At this point, having only five binaries with speckle orbits to work with, it is impossible to say conclusively which of these sources of error is dominating. This problem will be investigated further when more data is available.

Nonetheless, the rms deviations of ρ and θ residuals are encouraging. For comparison, the estimated value for σ_ρ is only twice the value obtained by the CHARA group using the Kitt Peak 4 m telescope (Hartkopf *et al.* 1989). The σ_θ result of $1.73 \pm 0.26^\circ$ would be much lower ($1.14 \pm 0.20^\circ$) without the inclusion of the Bu 1032 AB results and one poor measure of Bu 101. These figures strongly support the work of Douglass *et al.* (1997) and Horch *et al.* (1997) in demonstrating that high-precision speckle work is possible at small telescopes.

5. MEASURES

Our main body of position angle and separation measures is given in Table 4. All observations were taken through a V filter. The column headings are as follows: (1) Washington Double Star Catalog (WDS) number (Worley & Douglass 1984) (2000.0 coordinates), (2) the discoverer designation, (3) the HD number, (4) the Durchmusterung number, (5) epoch of observation in fraction of the Besselian year, (6) position angle (θ) in degrees from north (north towards east defining the positive sense of θ), and (7) the separation (ρ) in arcseconds. The position angles in the table have not been corrected for precession, and therefore are appropriate for the epoch of observation listed in column 4. Uncertainties in the position angle and separation measures are not included in the table. An estimate of the uncertainty for the separation measures can be obtained by combining the measurement precision from Sec. 4 with the uncertainty in the pixel scale as follows:

$$\delta\rho = \rho \sqrt{(\sigma_\rho/\rho)^2 + (\delta p/p)^2}, \quad (11)$$

where σ_ρ is the 6.6 mas figure from the measurement precision study, p is the pixel scale value from Sec. 3.3 (198.88 mas/pixel), and δp is the uncertainty in that value (0.92 mas/pixel). For the uncertainty in the position angle, it is reasonable to assume the value of 1.7° from the measurement precision study, since the uncertainty in the detector zero-point angle was very small.

In Fig. 6, we have plotted the orbits for four objects in Table 4 from the orbital parameters that appear in the orbit catalog of Worley & Heintz (1983), hereafter WH. Unlike the objects discussed in Sec. 4, these binaries do not have

FIG. 7. A plot of magnitude difference (as listed in the WDS) versus combined magnitude for all the systems observed during the 1997 February run. Open circles are positive detections (for which measures appear in Table 4) and filled circles are systems whose power spectra were too poor to measure.

orbits determined with the inclusion of speckle data, but they do have orbits determined from visual observations and some recent speckle measures. It is therefore possible to compare our measures to the other recent data and the existing orbit. In the plots, visual observations are marked with dots, previously published speckle measures are marked filled circles, and our measure is marked with an open circle. For speckle points, a line segment is drawn from the orbital ephemeris position to the measure. In Fig. 6(a) (AC 5), the quality of the orbit listed in WH is grade 1 (definitive), though there is a systematic discrepancy between the speckle observations and the orbit. In this case, only the speckle measures of the CHARA group have been plotted for clarity. Our measure agrees well with these points, and in fact is very similar to the recent measure of Hartkopf *et al.* (1997). I 879 [Fig. 6(b)] has a grade 2 orbit from WH, and here there is a large discrepancy between the orbit and the two previous speckle points. Our point again shows good agreement with the previous speckle data. STF 1819 [Fig. 6(c)] has a grade 3 orbit from WH, and a well-defined sequence of speckle observations is available for comparison. See 119 [Fig. 6(d)] has a grade 2 orbit and two previous speckle points. In all four plots, our measure agrees very well with the previous speckle data.

Figure 7 shows a plot of magnitude difference (as listed in the WDS) versus combined magnitude for the 86 systems listed in Table 4 and 13 other systems that we observed in February but either showed no fringes or had a poor quality power spectrum. Most of the systems for which measures were not possible were faint, with combined magnitude around 8. We therefore conclude that the limiting magnitude of our CCD-based speckle work is about 8th magnitude with the current CCD/telescope combination.

6. CONCLUSIONS

We have presented a first set of position angle and separation measures of binary stars using CCD-based speckle interferometry. The observations were performed at the 60 cm

UTSO telescope at Las Campanas, Chile, where due to the small aperture it was possible to record speckle interferograms without atmospheric dispersion compensation. The speckle patterns are captured using a CCD in shutterless charge transfer mode. The faint magnitude limit with the current camera and telescope is about 8th magnitude and the results presented agree extremely well with other speckle observers. An initial study of the precision of our measurement technique shows rms deviations of 6.6 ± 1.0 mas in separation and $1.73 \pm 0.26^\circ$ in position angle when comparing our measures to the ephemeris positions of objects that have extremely well-known orbits.

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