FIVE YEARS OF DOUBLE STAR INTERFEROMETRY AND ITS LESSONS

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I. INTRODUCTION

With nearly 1500 diffraction limited measurements of high accuracy to its credit, speckle interferometry must now be considered an established and productive method for performing binary star astrometry. This paper will attempt to give an explanation of the technique from the perspective of a binary star observer along with a general summary of the accomplishments that have given speckle interferometry its present respectability. Some recommendations aimed at increasing the effectiveness of the method will also be made. Speckle interferometry has provided valuable information on stellar diameters, and tantalizing results are beginning to appear for a variety of faint objects, but only the application to the measurement of binary stars will be considered here.

II. BINARY STAR SPECKLE INTERFEROMETRY

The rapidly changing fine structure visible within an image of a highly magnified star has been known for decades and is related to "the image within the image" utilized by visual observers to measure very close double stars, but it was not until 1970 that Labeyrie[1] pointed out that this fine structure carried information at spatial scales as small as permitted by classical optics. Thus the "speckles", as Labeyrie called them in analogy to a related phenomenon arising in coherent optics, have diameters essentially equal to the Airy disk. The minimum resolvable angle obtained from speckle interferometry has been found to agree very closely to the resolution set by the well-known Rayleigh criterion where the smallest resolvable separation of point sources Θ_s is given in radians by

$$\Theta_s = 1.22\ \lambda/A$$

where λ is the central wavelength of the observed passband and A is the telescope aperture. Since Θ_s for the largest telescopes is 0.02 arc-second, speckle interferometry was seen by Labeyrie as having strong potential for performing binary star astrometry.

Several reviews[2,3,4] of speckle interferometry have been published which contain numerous references to theoretical papers, but it seems appropriate to include here a brief discussion of the theory of speckle interferometry in the particular context of binary star astrometry.

As shown schematically in Figure 1, turbulence in the atmosphere results in instantaneous phase fluctuations across the otherwise plane incoming wavefront of a distant star. These fluctuations have characteristic size on the order of ten centimeters so that the aperture of a large telescope is filled with many such perturbing cells. At any instant a particular cell will be in phase with a number of other cells randomly distributed across the telescope aperture and interference will

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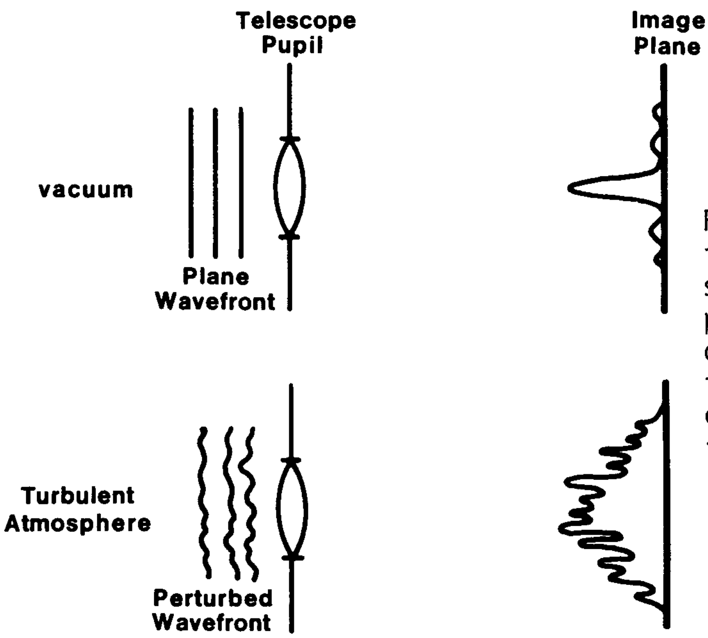

FIGURE 1 (Left) - The formation of the image of a distant point source is shown schematically for the cases of a non-perturbed wavefront giving rise to the diffraction pattern for a circular aperture (above) and of an atmospherically distorted wavefront leading to an instantaneous speckle pattern (below).

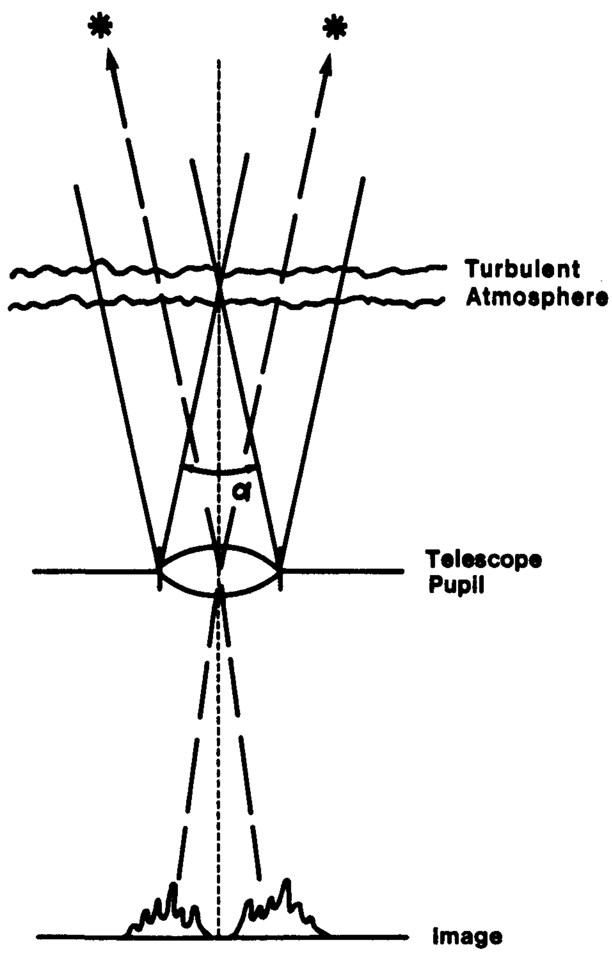

FIGURE 2 (Right) - The condition of isoplanicity is illustrated for two stars whose angular separation is just large enough so that the light from the two stars passes through separate regions of atmospheric turbulence. Thus the two images in the focal plane are completely uncorrelated due to the lack of isoplanicity and cannot be measured by binary star speckle interferometry.

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occur to produce fringes. Since the set of in-phase cells has contributions from parts of the entire aperture, the fringes (i.e. speckles) will have a size near the theoretical diffraction limit of the telescope. Thus the instantaneous speckle pattern results from numerous sets of perturbing cells, each set producing a common phase in the perturbed wavefront and giving rise to a portion of the speckle pattern. The overall size of the speckle distribution, or seeing disk, is dictated by the scale of the turbulence, and since classical photography requires the time averaging of the continuously changing speckle pattern, the telescope aperture is effectively reduced to ten centimeters for purposes of resolution. Visual binary observers do not perform such time averaging in their perception of a close double star and must be performing a mental process analogous to speckle interferometry to achieve resolutions down to below 0.1 arc-second with large refractors. Because the number of speckles scales with the telescope aperture, visual observers accustomed to using telescopes with apertures well below one meter will see considerably fewer speckles than with, say, a four meter telescope.

Binary star speckle interferometry takes advantage of the very high degree of similarity between the speckle patterns of two stars whose incoming wavefronts pass through nearly the same region of atmospheric turbulence. This "isoplanicity" condition shown schematically in Figure 2 then sets an upper limit on angular separations measurable by speckle interferometry at several arc-seconds and perhaps occasionally as large as twenty arc-seconds. The technique thus overlaps into the realm of photographic observations of double stars. The high spatial correlation which is the basis for binary star speckle interferometry is apparent in Figure 3 in a speckle photograph of the binary star 57 Cancri. Very precise measurements of this system could be made by simply deducing the relative separations and orientations of the numerous pairs of speckles arising from the two stars, although such direct measurements become a challenge for close binaries such as Capella (Figure 4) or for systems with non zero Δm's.

The practical measurement of speckle photographs takes advantage of the convolution theorem in which the convolution of two functions becomes a simple multiplication of their Fourier transforms. If $O(x)$ is the actual object intensity distribution in one dimension (for simplicity), then the observed instantaneous image intensity $I(x')$ is given by the convolution of $O(x)$ with the instantaneous point spread function $P(x')$ resulting from the combined effects of the telescope and the atmosphere so that

$$I(x') = \int O(x)P(x'-x)dx.$$

Taking the Fourier transform of this equation then gives

$$i(u) = o(u)T(u)$$

where $i(u)$ and $o(u)$ are Fourier transforms of the image and object intensities, and $T(u)$ is the instantaneous optical transfer function. The squared modulus of $T(u)$, i.e. $|T(u)|^2$ is the modulation transfer function (MTF), and it is the average value of this quantity which is normally utilized in binary star speckle interferometry. In speckle cameras which record data on film, a broadened and spatially filtered laser beam is passed through a positive transparency of a speckle photograph and then focused onto a sheet of film. The diffraction pattern thus produced is the Wiener or power spectrum given by

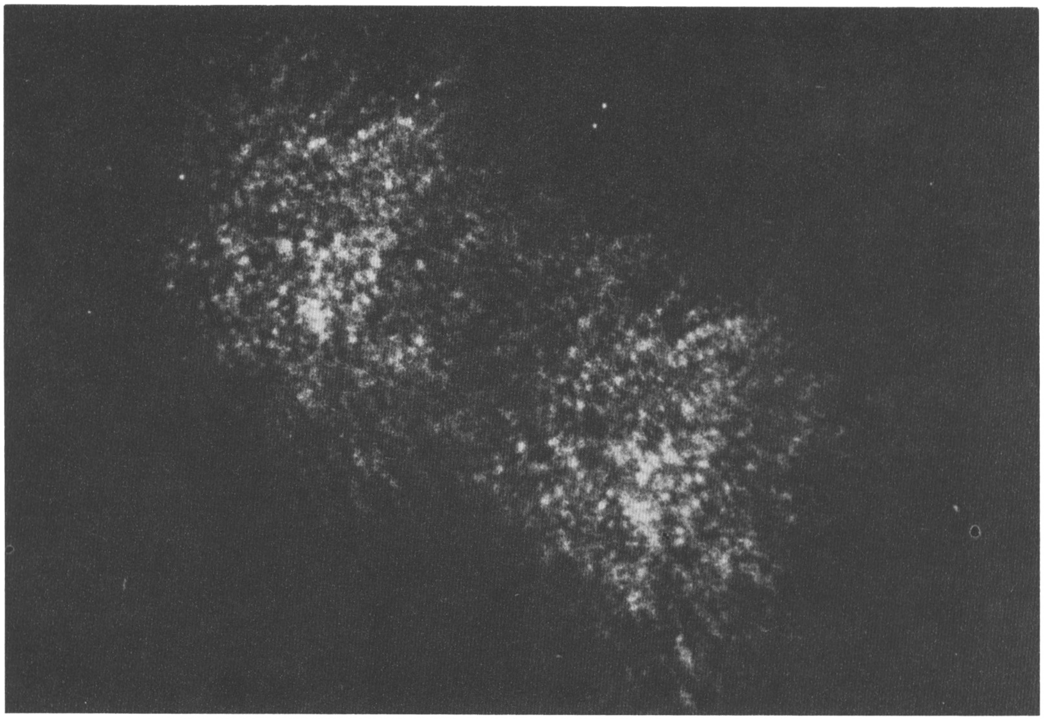

FIGURE 3 - Speckle photograph of the system 57 Cancri taken with the 4 meter Mayall telescope on Kitt Peak. By comparing the speckle patterns of the two components, which are separated by 1.5 arcseconds, one can easily see the high degree of correlation between the component images.

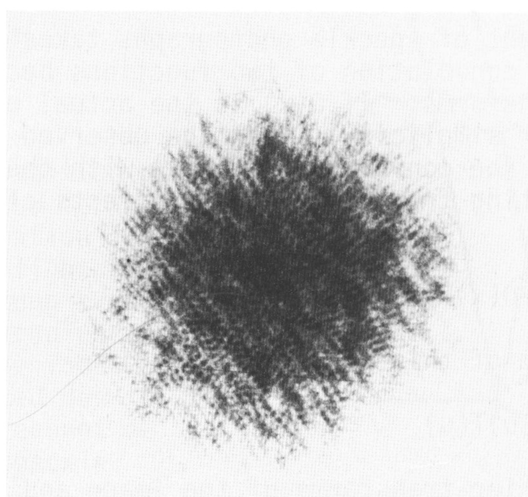

FIGURE 4 - Speckle photograph of Capella taken with the 4 meter Mayall telescope on Kitt Peak. This negative image shows identical but slightly displaced speckle patterns from the two components separated by 0.05 arcsecond.

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$$W(u) = \langle |i(u)|^2 \rangle = |o(u)|^2 \langle |T(u)|^2 \rangle$$

and it can be shown that the average MTF, $\langle |T(u)|^2 \rangle$, is non-zero at the cutoff frequency of the diffraction limit.[3] If necessary, $\langle |T(u)|^2 \rangle$ can be determined by observing an unresolved single star, but for the purposes of measuring binary stars, the average MTF can essentially be treated as a constant and can be ignored except for separations just above the diffraction limit.

In a photographic speckle system, the composite power spectrum is obtained by adding the power spectra of many speckle photographs of a binary star onto a single sheet of film and appears as a set of fringes on a Gaussian-like background. This background is the power spectrum of an unresolved star or equivalently is the average MTF of the process. An example of such a composite power spectrum is shown in Figure 5b. The angular separation of the binary is inversely proportional to the fringe spacing in the power spectrum, and the position angle is given by the fringe orientation. A calibration scheme for the scale and orientation is described in section V of this paper. The effects of measuring fringe locations on a sloping background has been found to be negligible at the level of half percent accuracy and can be compensated for if necessary.[5]

The origin of the fringes in the power spectrum due to the passage of laser light through a speckle photograph of a binary star is completely analogous to Young's classic double slit experiment[6] in that a pair of corresponding speckles acts as a double slit. The multiplicity of such pairs in a single frame all contribute to the same fringe system when the collimated laser beam is focused onto a distant screen. A typical arrangement for this kind of processing is shown schematically in Figure 6.

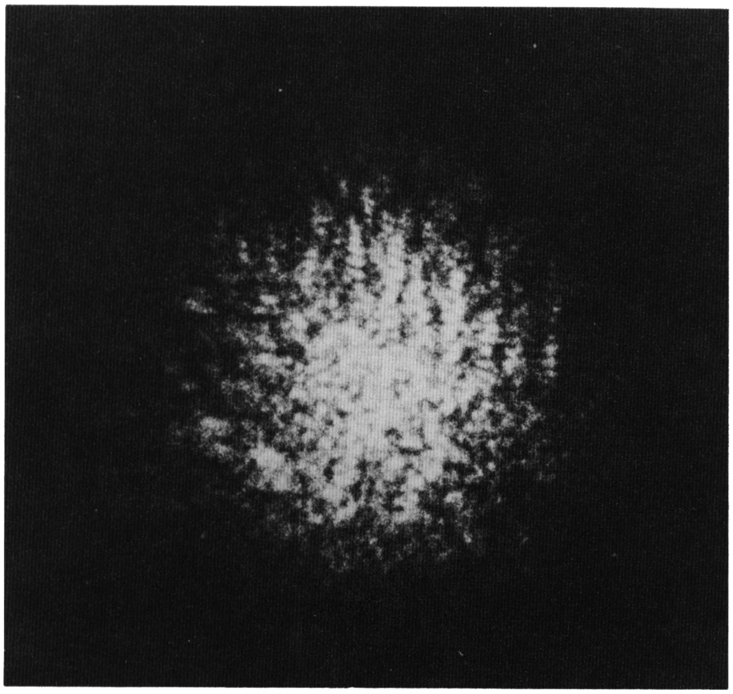
If the composite power spectrum is placed in the film plane of Figure 6, it can be shown that the diffraction pattern produced on the screen is the autocorrelation of the image intensity or

$$C(x) = \int I(x')I(x' - x)dx'$$

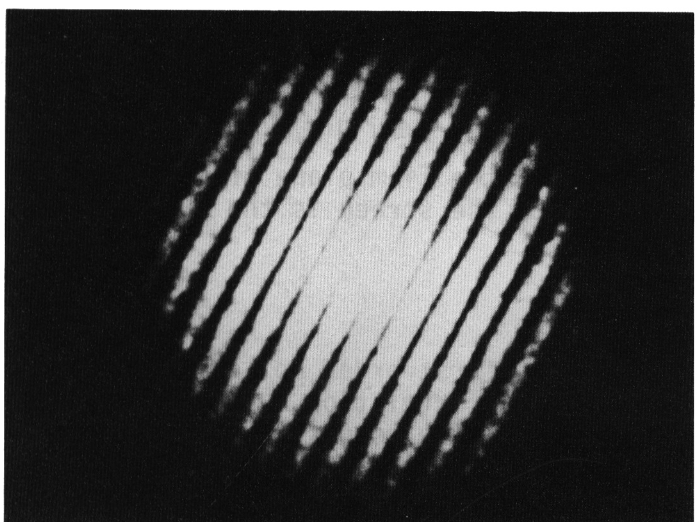
where ρ is now proportional to the spacing of the first order spikes in the autocorrelation. Figure 5c shows such a composite autocorrelation. The binary star parameters can be equivalently measured from either the composite power spectrum or autocorrelation, however for a photographic speckle camera such as that developed at Kitt Peak[7] it should be remembered that an extra and consequently degrading photographic process is involved in going from $W(u)$ to $C(x)$. The processes involved in standard binary star speckle interferometry are summarized in Figure 7.

Any instrument designed to record astronomical speckle patterns must permit exposure times no longer than about 20 milliseconds in order to freeze the atmospheric turbulence and must produce an image scale such that the speckles are well resolved by the detector. The latter requirement implies a high magnification and most speckle cameras have fields of view no larger than ten arc-seconds. A further need for a bandpass width of no more than a few hundred Angstroms to insure high constrast speckles combines with the short exposure and high magnification requirements to produce a low photon flux on the detector even for very bright objects observed with large telescopes. Thus although in principle speckle cameras are rather simple instruments, one encounters a major challenge in selecting the optimum detector configuration.

(A)



(B)



(C)

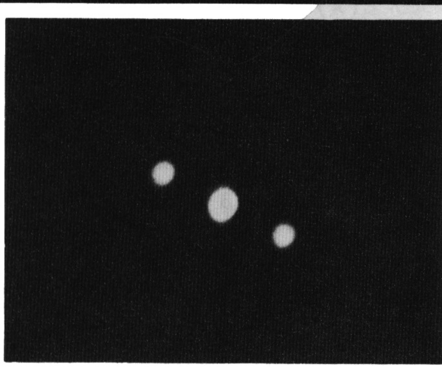


FIGURE 5 - A speckle photograph of κ UMa (ADS 7158) taken with the 4 meter Mayall telescope on Kitt Peak is shown in (A). The system has a separation of 0.27 arcsecond. The composite spatial frequency power spectrum of 50 such exposures is shown in (B), and the composite autocorrelation is shown in (C). Clearly (B) or (C) lead to more accurate determinations of the system geometry than do direct observations of the speckle pattern as in (A).

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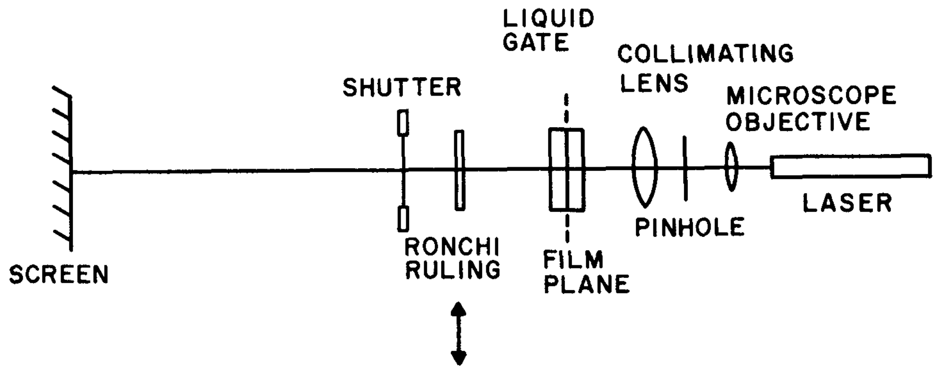

FIGURE 6 - A schematic of a coherent image processor for the analysis of photographic speckle data is shown. The beam from the laser is first broadened and spatially filtered before passing through the film plane. The collimating lens is actually slightly decollimated and focussed on the distant screen where the squared modulus of the Fourier transform of the image in the film plane appears. The film is immersed in an index matching liquid to eliminate diffraction from scratches. A Ronchi ruling may be translated into the beam to produce orientation calibration marks.

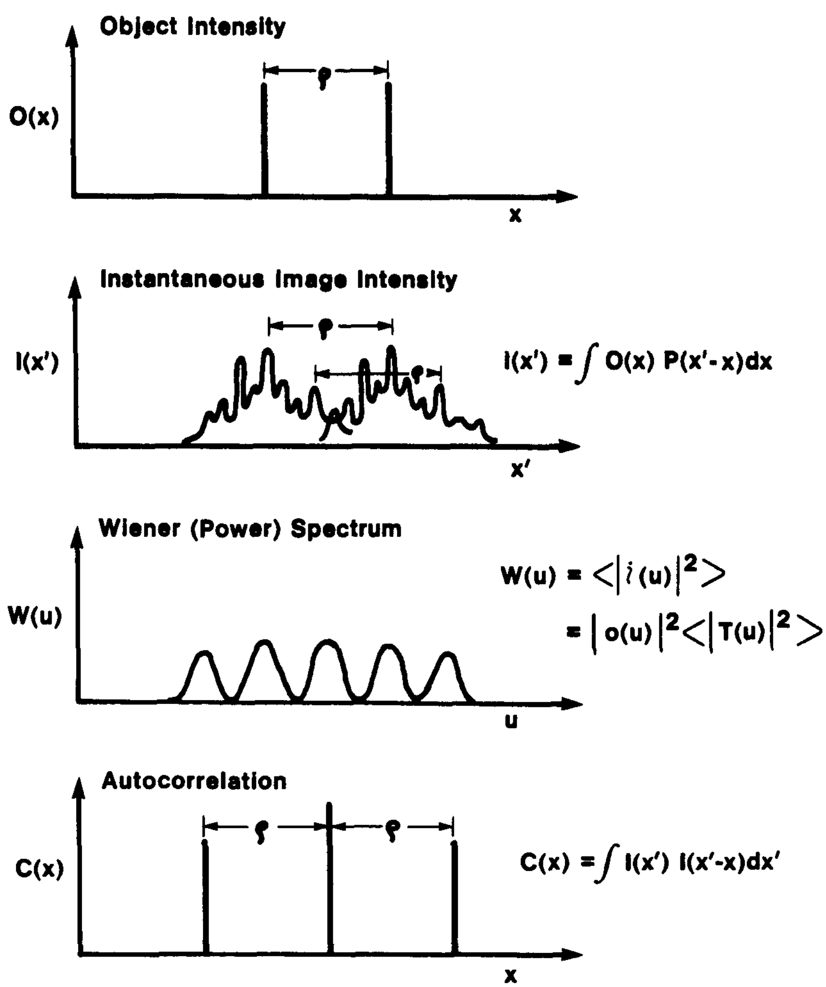

FIGURE 7 - The various processes involved in binary star speckle interferometry are summarized

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All early speckle cameras were based upon intensified film systems[4] similar to that shown schematically in Figure 8, but more recently the trend is toward intensified video systems. [8] The speckle interferometry group at Georgia State University has chosen a dual micro-channel plate intensified CCD array as the detector package for a new speckle camera now being constructed. This configuration is virtually free of the image distortions inherent in electrostatically or magnetically focussed image tubes and in television type tubes and is perhaps the best choice currently available for astrometric measurements using speckle interferometry.

A final necessity for speckle cameras to be used at large telescopes is the ability to compensate for atmospheric dispersion. This dispersion in arc-seconds within a bandpass $\Delta\lambda$ is approximately given by

$$\Delta Z = 5 \times 10^{-4} \Delta\lambda \mathrm{Tan} Z$$

where Z is the zenith distance. Thus for Z = 45° and $\Delta\lambda$ = 200 Å, ΔZ = 0.1 arcsecond so that speckles obtained with a large telescope will be elongated by a factor of four or five times their undispersed diameters. Atmospheric dispersion compensation has normally been accomplished by means of a Risley prism arrangement, although the camera in use by the French observers[9] uses a grating for this purpose as well as for the selection of the bandpass for a particular series of observations.

III. A SUMMARY OF ACCOMPLISHMENTS

Binary star observations are currently being obtained on a regular basis by four groups of speckle observers.[10-13] Table I contains a summary of the results either in print or known to the author in preprint form that have been secured by these four groups.

TABLE I. Results of Binary Star Speckle Interferometry

No. of binaries	358
No. of measures	1366
No. with $\rho \leq 0\overset{''}{.}2$	683(50%)
No. with $\rho \leq 0\overset{''}{.}1$	294(22%)
No. of new binaries	58

Approximately 83% of the measurements from Table I. are from the author's program that has been carried out at Kitt Peak National Observatory since September 1975 with the 4 meter and 2.1 meter telescopes. Table II is a summary of the statistics pertaining only to that program and includes observations made through the spring of 1981.

Half of the measurements obtained have been for systems with separations less than 0.2 arcsecond, and these are the binaries for which speckle interferometry is making its most important contribution. Systems such as ϕ 312, A 1938, ϕ 342, OΣ 175 AB, OΣ 341 AB and A 751, to name a few, have been resolved at separations

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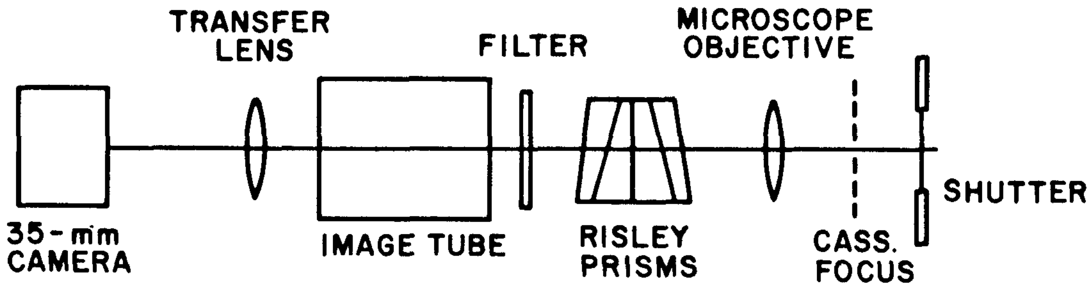

FIGURE 8 - A schematic diagram of the Kitt Peak speckle camera

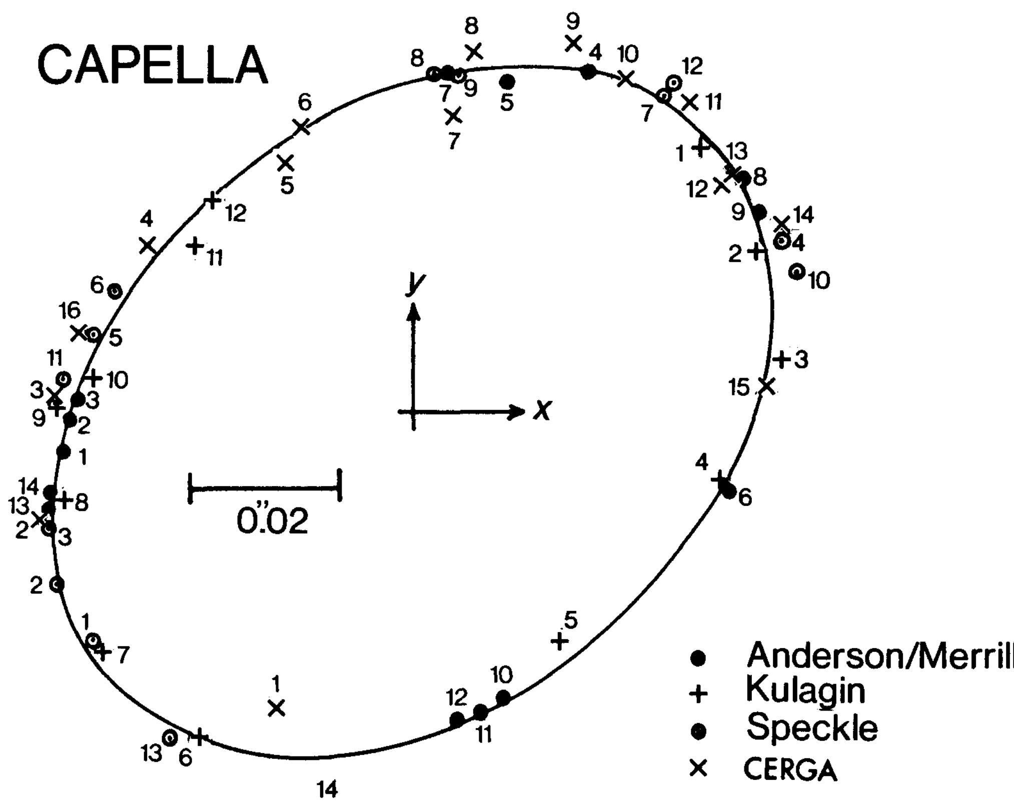

FIGURE 9 - Fifty-six observations of Capella spanning more than 200 revolutions are shown against the newly determined orbit whose elements are given in Table III. Four interferometric techniques contributed to this determination.

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TABLE II. Binary Star Speckle Interferometry from Kitt Peak

No. of binaries	308
No. of measures	1140
No. with $\rho \leq 0.2$	557(51%)
No. with $\rho \leq 0.1$	247(22%)
No. of unresolved known binaries	183
No. of new binaries	32
No. of observations obtained	7899(~400,000 35mm frames)
No. of observations reduced	5063(65%)
No. of KPNO nights allocated	94(55 on 4 meter telescope)
No. of observing KPNO sessions allocated	32

inaccessible to micrometer observers, and valuable information now exists for portions of visual binary orbits which were previously too close for study. Speckle measurements can reach systems with about four times smaller separations than can visual measurements, a significant gain in itself, but perhaps a more important achievement is the simultaneous improvement in accuracy. Standard calibration procedures have been found to give accuracies to better than 1.0% in angular separation and 0°2 in position angle for separations exceeding about 0.15 arc-second. These values degrade to a worst case of 10% and 5° for observations at the diffraction limit. The Kitt Peak observations from Table II have been found to be free of systematic effects by comparison to orbits of very high reliability[13], and it seems likely that the error estimates which have been made for these measurements are realistic indicators of accuracy.

Another gain which speckle interferometry has made over classical techniques is its capability of resolving close pairs which have significant magnitude differences as large as three magnitudes. This advantage has been offset somewhat by the limitation to stars brighter than about the eighth magnitude, but nevertheless, nearly sixty bright binaries have been newly resolved by the technique. The high resolving power of speckle interferometry has permitted its penetration into the gap which separates visual and spectroscopic binaries, and it is through the direct resolution of spectroscopic systems that the method is making real contributions to the storehouse of fundamental astrophysical data on stars. Combined interferometric studies have been completed for the systems 12 Persei,[14] τ Persei,[15] β Persei AB,C,[16] 51 Tauri,[17] α Aurigae,[18] η Orionis,[19] χ Draconis[20] and ξ Cephei[21]. Observations now being reduced and to be accumulated during the next year should double this sample.

Modern radial velocities are badly needed for many of the resolved spectroscopic binaries and for other systems which could probably become spectroscopic binaries. This is a considerable challenge to spectroscopists since these are long period systems in the spectroscopic sense with consequently small velocity amplitudes. There are numerous newly resolved pairs with early type broad-lined components to further compound the difficulty. In spite of these problems, a sufficient sample of spectroscopic/interferometric binaries exists to enable speckle interferometry to continue to justify the allocation of time on large telescopes for the study of binary stars. The important bonus of improving the orbits of many known pairs should also be emphasized.

With the greatly improved sensitivity to fainter objects that second and third generation speckle cameras are making, there will be a natural tendency to give less attention to binary stars and to turn to faint extragalactic and solar system objects instead. This is unfortunate, particularly in light of the need for data at the low

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end of the mass-luminosity relation, and it emphasizes the need for modern speckle cameras in routine use at medium sized telescopes. These cameras are capable of performing accurate differential photometry on close binary systems - a power probably as important as the high resolution aspects of the technique. The photometric capability has not been a practical goal with photographic systems where, for example, as many as five successive photographic processes are required to go from a sample of original speckle photographs to a composite autocorrelation with the Kitt Peak speckle camera. This problem vanishes when modern quasi-linear detectors are used to produce data in a digital form, and differential photometry is a major goal for the new Georgia State University speckle camera. One irony for speckle interferometry is that it is capable of measuring large Δm's more accurately than small ones.[22]

IV. COMPARISON AMONG SPECKLE OBSERVERS

There are, unfortunately, few binaries with enough observations by more than one speckle group to permit an extensive study of systematic differences among observers. The best such object is Capella for which the American and French speckle results can be extensively compared with the original Mt. Wilson series of measurements during 1920-21, the special periscopic interferometer measurements from Pulkovo during 1968-69, and the first results from the long baseline interferometer under development in France by Labeyrie and his collaborators. These 56 observations have been used to determine a new orbit shown in Figure 9 based entirely on the interferometric measurements that now span, albeit irregularly, nearly 60 years and more than 200 revolutions of the system.[18] The new orbit has very small errors associated with the elements, perhaps qualifying it as the most accurately determined apparent orbit yet made. The new elements are in excellent agreement with those of Finsen,[23] as is shown in Table III, which were based on a combination of interferometric and spectroscopic data then available. Finsen's orbit did not include speckle observations which now account for one fourth of the Capella data, and it is intriguing to note that the newly determined period agrees with Finsen's value, which was derived only from radial velocities, to within five minutes in time or within one part in 30,000!

The very high accuracy of the elements of Capella's orbit give it the unique potential for serving as a calibration object for binary star observers, but it should not be used as the only source of calibration during an observing run. This is because a single measurement of Capella can be made with accuracies only of perhaps 3% in separation and 1° in position angle where wider systems, as mentioned

TABLE III. Orbit Elements for Capella

	Interferometric Solution[18]	Finsen's Solution[23]
P	$104^{d}.0237 \pm 0^{d}.0002$	$104^{d}.0204 \pm 0^{d}.0014$
T	1936.4581 ± 0.0001	1936.4588 ± 0.0002
e	0.0*	0.0*
a	$0''.0547 \pm 0''.0001$	$0''.0541 \pm 0''.0003$
i	$136^{\circ}.64 \pm 0^{\circ}.10$	$137^{\circ}.05 \pm 0^{\circ}.61$
ω	0.0*	0.0*
Ω	$40^{\circ}.22 \pm 0^{\circ}.15$	$40^{\circ}.42 \pm 0^{\circ}.26$

* adopted

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above, can be measured with considerably better precision. It would be unfortunate to degrade all measurements in a series by limiting the calibration procedure to Capella.

A useful outcome of the new Capella study is the summary of residuals given in Table IV. Table IV. shows no evidence for systematic effects among the four Techniques as might be expected from a combined least-squares solution. The

TABLE IV. Residuals to the Orbit of Capella

$\langle\Delta\theta\rangle$	$\langle\Delta\rho\rangle$	N_{obs}	Source
-0°06 ± 2°14	+0″0001 ± 0″0021	56	Combined interferometric data
+0.16 ± 1.61	-0.0004 ± 0.0006	14	Mt. Wilson only
-0.74 ± 1.83	-0.0011 ± 0.0016	12	Pulkovo only
+0.45 ± 2.02	+0.0011 ± 0.0013	14	All speckle only
-0.19 ± 2.82	+0.0004 ± 0.0032	16	Long-baseline only
+0.67 ± 1.59	+0.0014 ± 0.0012	9	KPNO speckle only

Techniques all have roughly comparable accuracies of ±0.002 arcsecond in either coordinate. The surprising result from Table IV is that the original Mt. Wilson measures have the best internal consistency and that the long baseline interferometer results appear to be the poorest in accuracy. The latter result is probably due to the experimental nature of the measurements while the former result may be the high weight the Mt. Wilson measurements inherently receive due their time leverage in the solution. Solutions based upon various subgroups of the observations show small deviations from the solution based upon the entire sample of observations, but these deviations still do not imply significant systematic effects in the case of Capella.

The system β Cephei is a more typical example of a close binary amenable to study by speckle interferometry, and it is the most commonly observed object available for studies of systematic effects. Beta Cep has been measured on 25 occasions between 1971.48 and 1979.47 during which the separation decreased from 0.26 to 0.20 arcsecond and the position angle has changed by about 2°. These observations are shown in Figure 10.

In order to approximately remove the small amount of orbital motion, straight lines were separately fit in x and y as functions of time to the samples of Kitt Peak and French measurements. Table V shows the results of the average residuals thus determined. The French measurements, the three latest of which have not been

TABLE V. Residuals to the Motion of β Cephei

$\sigma_{\langle\Delta x\rangle}$	$\sigma_{\langle\Delta y\rangle}$	$\sigma_{\langle\Delta\rho/\rho\rangle}$	$\sigma_{\langle\Delta\theta\rangle}$	# Obs	Source
0″0022	0″0009	0.007	0°38	9	Kitt Peak
0″0049	0″0033	0.017	0°78	9	French

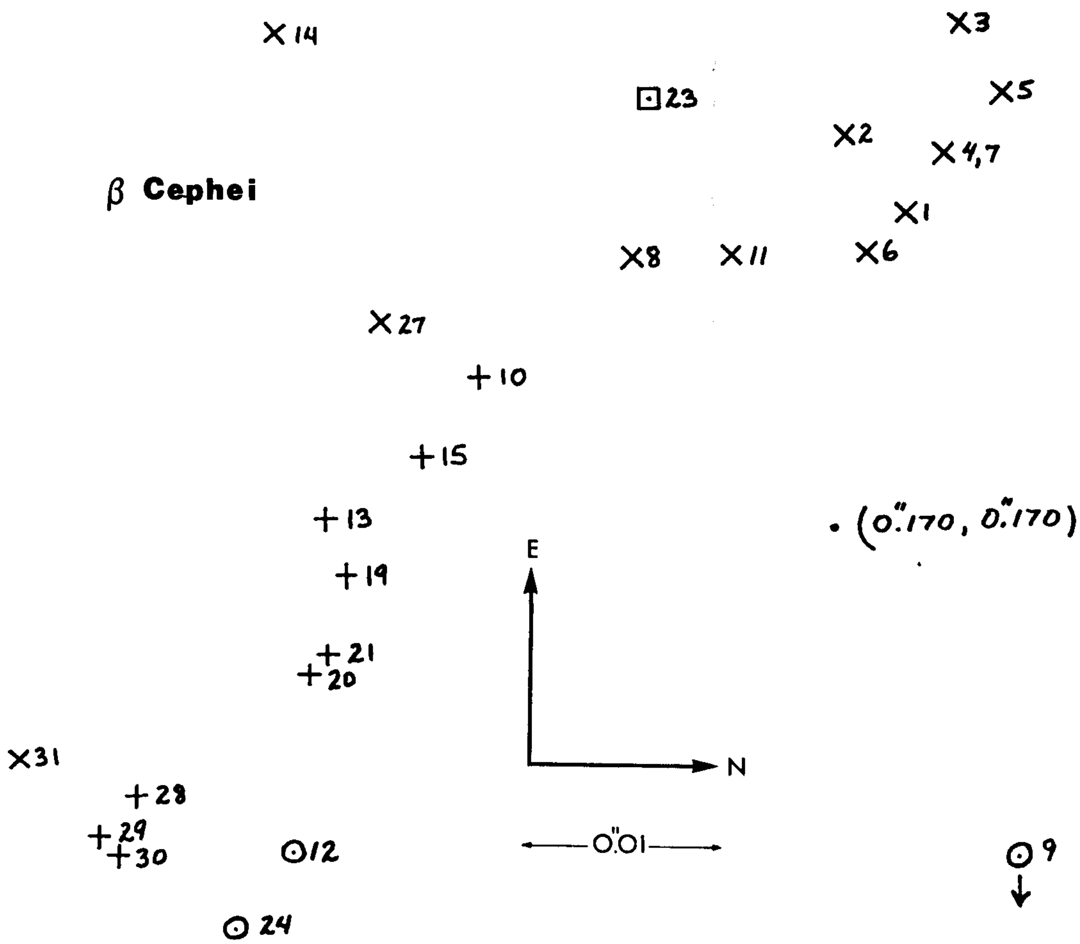

FIGURE 10 - Observations of β Cephei by four groups of speckle observers are shown for the interval 1971 - 1980. The symbols are for French (X), German (⊡), British (⊙) and Kitt Peak (+) speckle observations.

included here due to the non-linearity of motion over the long time base, show greater scatter than the Kitt Peak measures which are themselves near the level of precision claimed for the calibration procedure.

Where observations from the two samples overlap in time, systematic discrepancies can be directly sought. Thus for a French observation on 1978.3947[24], or just 0.15 year before the next Kitt Peak measure of β Cep[13], the separation is found to be 11% larger than would be expected from the trend in the Kitt Peak data. A British measure on 1977.8811[12] is found to be 3% smaller and a German measure on 1977.674[11] is 13% less than expected. This last observation was made with a one meter telescope and so was operating closer to its diffraction limit than for the other measures. These few examples show that there are systematic differences between speckle observers, and since these differences seem well above the precision with which a composite power spectrum or autocorrelation can be measured, it seems likely that the source of these discrepancies is in the calibration techniques used by the various observers. The author has the impression, which cannot perhaps clearly be supported from the data, that the systematic effects are not constants when any two observers are compared, but it seems that some measurements within a sample are simply more reliable than others in a way which is not always in agreement with the error estimates.

V. RECOMMENDATIONS

The results obtained in the decade since Labeyrie first proposed speckle interferometry have clearly established it as a valuable technique capable of making major contributions to binary star astrometry and in the near future, hopefully, to binary star photometry as well. As in every field, there is always room for improvement, and a particular shortcoming of speckle interferometry continues to be the paucity of users of this powerful method. As mentioned in Section III., binary star speckle interferometry would benefit greatly from the addition of a long-term continuing program at an institution which can allocate more frequent observing opportunities on a two meter class instrument.

While we await that very desirable development, there are ways in which existing programs can improve the reliability of their product, and an increase in communication and cooperation is certainly appropriate. For example, it is often more than one or two years after they are obtained until speckle observations appear in print. In the meantime, it would be very helpful if observers would use the "Circulaire d'Information" of Commission 26 to notify colleagues of newly resolved pairs or systems which are quickly changing aspect and are in need of special attention. Observers should attempt to observe not only their own discoveries but also the systems first resolved by others. It has been unfortunate that no other speckle observers have published measures of, for example, the Hyades spectroscopic binary 51 Tauri which has now been observed through one half revolution or the similarly rapidly moving system η Virginis which may be exhibiting a submotion due to an unresolved 70 day spectroscopic companion. The Kitt Peak observations of these two interesting systems are shown in Figures 11 and 12.

It would be very helpful, both as a partial calibration device and as a method of intercomparing the results of different observers, if a small group of binaries with moderate separation was set up as a system of "check stars" which would be frequently measured by all speckle observers. Table VI contains a list of a few recommended objects more or less evenly distributed around the sky at small declinations which are slow moving. Theta Virginis is perhaps an ideal system for this

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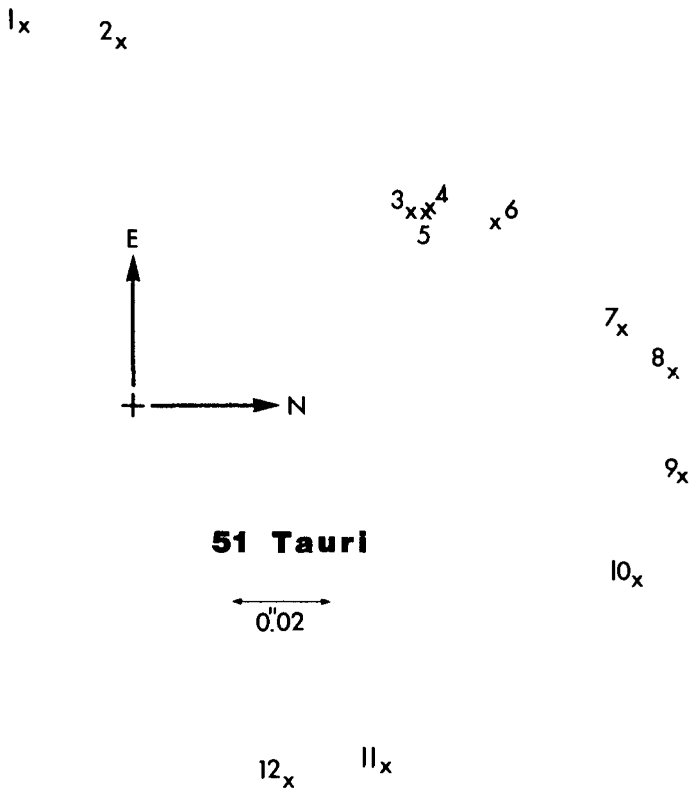

FIGURE 11 - Speckle observations of the Hyades spectroscopic binary 51 Tauri are shown during the interval 1975.716 to 79.774.

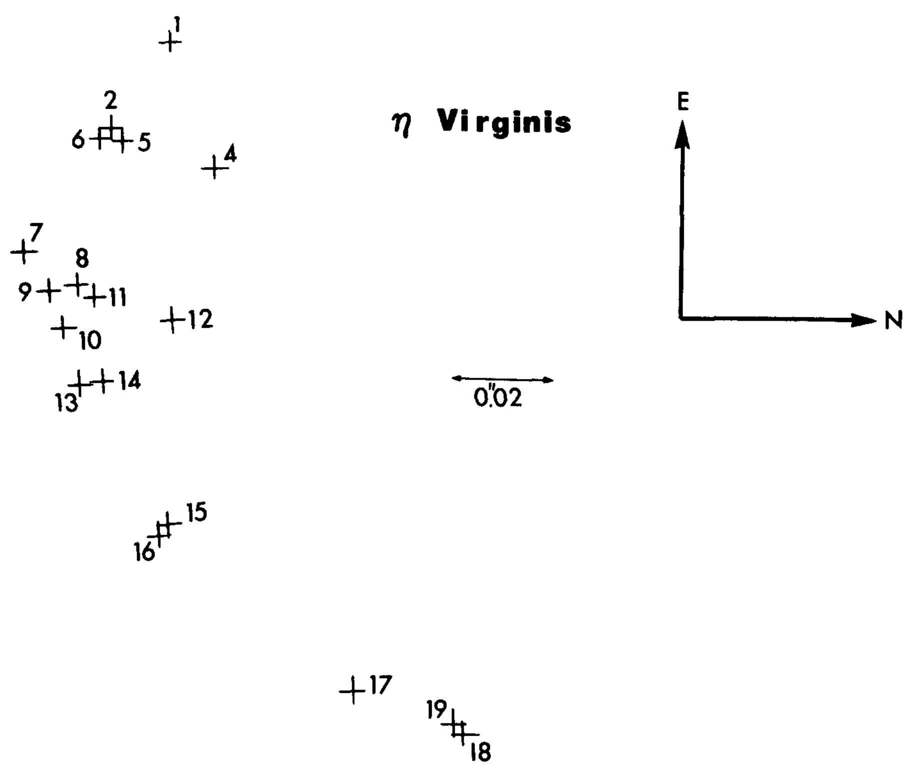

FIGURE 12 - Speckle observations of the previously unknown binary η Virginis. These measures may be showing a submotion due to an unresolved spectroscopic system with a period of 70 days.

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purpose since it has moved only about 2% of its separation in four years. A similar slow moving pair, although at a large northerly declination is ο Andromedae with a separation holding at about 0.34 arc-second.

It must be emphasized that the intent of Table VI is not that is serve as a list of calibration objects, rather

TABLE VI. Check Stars for Speckle Interferometry

	α	δ	<ρ>
Kui 8	$02^h22^m.9$	+01°31'	0".51
φ 325	07 47.9	-05 10	0.37
Θ Vir	13 04.8	-05 00	0.49
φ 332 AB	18 40.6	+05 24	0.16
Kui 89	18 53.8	-12 58	0.23

these systems should be used as secondary checks against some independent instrumental calibration scheme. There are presently no systems in the sky whose instantaneous relative positions are known with enough accuracy to justify their use as calibration objects for binary star speckle interferometry.

Of course, realities of observing at large telescopes, which belong invariably to someone else and for which precious little telescope time can be devoted to cumbersome calibration procedures, may require a compromise with respect to the previous statement. Such a compromise has been followed in the sixth series of measurements from Kitt Peak using the 2.1 meter telescope. For those measurements observations of Θ Vir and ο And were interpolated into the extensive 4 meter telescope results for these two nearly stationary systems in order to place the 2.1 m observations on the same calibrated system as has been established for the larger telescope. Instrumental calibrations at the 2.1 meter telescope were used to check for changes in the scale and orientation parameters within a run at that telescope. This procedure worked reasonably well, but still the results from the sixth series show evidence of less self consistency than in the previous five series.

The calibration scheme in use at the 4 meter Mayall telescope utilizes a double-slit mask which can be mounted at will onto the baffle protruding from the central hole in the primary mirror. When the mask is thus mounted, the telescope is converted into Anderson's version of the Michelson stellar interferometer[25], and speckle photographs such as in Figure 13 then show parallel arrays of fringe filling the seeing disk. The fringe frequency in these arrays is simply a function of the observed passband and the slit separation as projected onto the telescope entrance pupil. Careful measurements of location of this mask in the beam along with estimates of uncertainties in the focal length determined by astrometric measurements of a Pleiades plate led to a conclusion that this method could routinely provide a scale reference accurate to ±0.6% of the separation. The position angle origin was found by comparing the prominent diffraction spikes obtained during a five minute time exposure at the Ritchey-Cretien focus with the mask in place to a trail image on the plate. The direction to the pole can thus be found with an accuracy of about ±0°.2. A power spectrum of 10 calibration exposures in Figure 14 shows very striking fringes which can be measured with high precision. This technique is simple and requires only about fifteen minutes of observing time at the 4 meter telescope. The

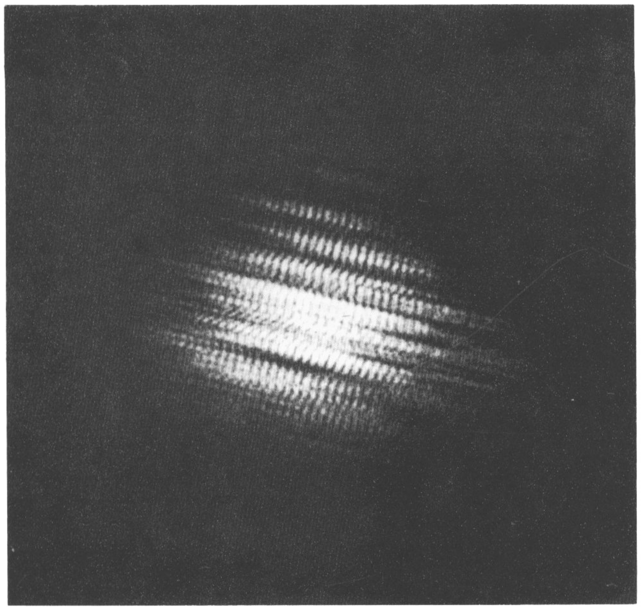

FIGURE 13 - A speckle photograph of an unresolved star taken with a double slit mask in the beam. Numerous parallel fringe arrays can be seen. The fringe frequency is only a function of the wavelength of the observed passband and the slit separation as projected onto the telescope entrance aperture.

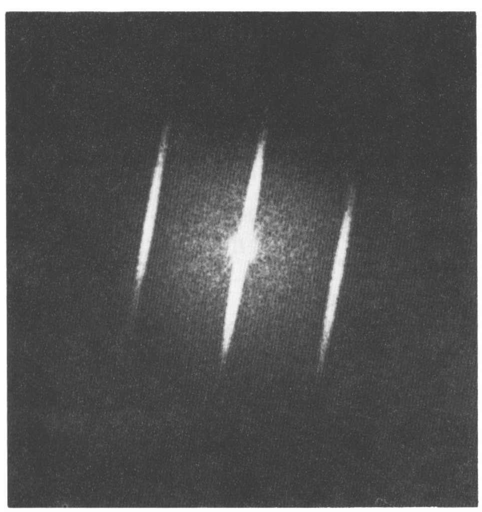

FIGURE 14 - The composite spatial frequency power spectrum of ten such exposures as in Fig. 13. The fringe spacing and orientation of such transforms can be measured to within 1% and 0.2 for calibration purposes.

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telescope must be pointed to the zenith and a ladder propped against the south end of the instrument from which access to the light baffle is obtained by carefully walking on the closed mirror cover.

The primary difficulty in this calibration method was in initially setting it up, and observers using a number of telescopes may be reluctant to do this for every instrument. But no other method seems to produce such consistently reliable results, and once it is established, it is no more awkward to use than any other scheme. The principal criterion for the selection of any method of calibrating speckle data should obviously be its ability to transform the full precision inherent in the power spectrum into the accuracy of the final measurement. This is a goal which has not yet been attained and will be crucial to the success of such problems as the astrometric detection of planets in binary star systems.

VI. ACKNOWLEDGEMENTS

Many readers may note that the title to this paper is an appropriately downward adjusted version of the paper "Twenty Years of Double Star Interferometry and Its Lessons" by W.S. Finsen[26] which was published about the time that speckle interferometry was first being revealed to the world by Antoine Labeyrie. Finsen's name will always be the first to come to mind when the words "double star interferometry" are mentioned, and the lessons by example of careful and steadfast observing which he imparted in his 1971 review will remain the keys to success in this field.

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REFERENCES

1. Labeyrie, A. 1970. *Astr. Ap.* 6, 85.
2. Dainty, J.C. 1975. *Topics in Applied Physics*, Vol. 9. ed. J.C. Dainty (Springer-Verlag: New York). p. 255.
3. Worden, S.P. 1977. *Vistas in Astr.* 20, 301.
4. Labeyrie, A. 1978. *Ann. Rev. Astr. Ap.* 16, 77.
5. McAlister, H.A. 1978. *Modern Astrometry* (IAU Colloquium No. 48). ed. F.V. Prochazka and R.H. Tucker (University Observatory: Vienna). p. 325.
6. Jenkins, F.A., and White, H.E. 1957. *Fundamentals of Optics* (McGraw-Hill: New York). p. 234
7. Breckinridge, J.B., McAlister, H.A., and Robinson, W.G. 1979. *Appl. Opt.* 18, 1034.
8. Hubbard, G., Hege, K., Reed, M.A., Strittmatter, P.A., and Woolf, N.J. 1979. *Astr. J.* 84, 1437.
9. Blazit, A., Bonneau, D., Koechlin, L., and Labeyrie, A. 1977. *Ap. J.* 214, L79.
10. Bonneau, D., Blazit, A., Foy, R., and Labeyrie, A. 1980. *Astr. Ap. Supp.* 42, 185.
11. Weigelt, G.P. 1979. *Opt. Acta*, 26, 1351.
12. Morgan, B.L., Beckmann, G.K., and Scaddan, R.J. 1980. *Mon. Not. R. Astr. Soc.* 192, 143.
13. McAlister, H.A., and Fekel, F.C. 1980. *Ap. J. Supp.* 43, 327.
14. McAlister, H.A. 1978. *Ap. J.* 223, 526.

https://doi.org/10.1017/S0252921100009933 Published online by Cambridge University Press

15. McAlister, H.A. 1981. *Astr. J.* (in press).
16. Bonneau, D. 1979. *Astr. Ap.* 80, L11.
17. McAlister, H.A. 1977. *Ap. J.* 212, 459.
18. McAlister, H.A. 1981. *Astr. J.* 86, 795.
19. McAlister, H.A. 1976. *Pub. Astr. Soc. Pac.* 88, 957.
20. McAlister, H.A. 1980. *Astr. J.* 85, 1265.
21. McAlister, H.A. 1980. *Ap. J.* 236, 522.
22. Dainty, J.C. 1978. *Mon. Not. R. Astr. Soc.* 183, 223.
23. Finsen, W.S. 1975. *IAU Comm. 26 Circ. d'Inf. No. 66.*
24. Bonneau, D., and Foy, R. 1980. *Astr. Ap.* 86, 295.
25. Anderson, J.A. 1920. *Ap. J.* 51, 263.
26. Finsen, W.S. 1971. *Ap. Space Sci.* 11, 13.

DISCUSSION

POPPER: In the abstract of your paper you referred to disturbing discrepancies between speckle results by different workers. In your talk you did not refer to serious discrepancies. Do you no longer consider them to be significant?

McALISTER: I ran out of time. There are discrepancies in the sense that there are isolated observations made by different observers of the same object at similar times for which there is more than the expected disagreement. For Beta Cephei, for axample, a few of the observations are a few hundredths of an arc second off, and that is considerably larger than what the internal errors would suggest. My feeling is that the Kitt Peak observations, because they are made using the same two telescopes at one site, are more amenable to calibration than those of other observers who have to go around to a variety of telescopes. It's not a problem inherent in speckle interferometry, it's a problem dealing with calibration. At this meeting we have been discussing ways of insuring more observations of common objects and more careful calibration procedures.

SCARFE: What are the limitations of speckle work as far as magnitude differences are concerned?

McALISTER: Hege's group has measured a magnitude difference as large as five, which is the kind of goal people are striving for in speckle techniques. The largest magnitude difference we have measured at Kitt Peak has been for 85 Peg, with a delta-m of around three, which I was pleased with for a photographic system.

WORLEY: Are you able to recover any information on magnitude differences?

McALISTER: With the photographic system we have, we have not even attempted to, because there are so many photographic processes involved. It is, of course, possible in principle. It is an important contribution for speckle to make, perhaps as important as the astrometry.

WALKER: Could you briefly describe data storage and the size of the computing facilities needed?

McALISTER: For the film system, which is all I have used so far, the data is stored on 35-mm film, 100-foot rolls, and there is an optical transform apparatus where the film is passed through a laser, so it is rather compact and is as fast as a person can crank the film through. For more modern systems, where the data is digitized, other groups can better comment.

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