SPECKLE INTERFEROMETRY AND SPECKLE HOLOGRAPHY; TECHNIQUES AND LIMITATIONS*

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ABSTRACT

We discuss speckle interferometry and speckle holography measurements of double and triple stars. Speckle holography with the ESO 3.6m telescope yielded direct images with a resolution of 0.03 arc second (diffraction limit). Finally we discuss the speckle rotation method, which can be used to reconstruct high-resolution images from Space Telescope data.

(1) INTRODUCTION

Labeyrie's speckle interferometry (Labeyrie 1970, Gezari et al. 1973) yields the autocorrelation of astronomical objects with diffraction-limited resolution, which is about 0.03 arc second in the case of a 3.6m telescope. Since the invention of speckle interferometry, many applications have been reported. Some of the more recent papers are (Arnold et al,), (Balega and Tikhonov 1977), (Beddeos et al. 1976), (Blazit et al. 1977), (Hege et al. 1980), (Lena 1979), (McAlister 1978), (Weigelt 1980), and (Worden et al. 1977).

Usually, speckle interferometry yields the autocorrelation of the object instead of a direct image. Therefore, various authors have developed methods for the reconstruction of direct images from speckle interferograms (Bates et al. 1973), (Bates and Cady 1980), (Ehn and Nisenson 1975), (Fienup 1978), (Knox and Thomson 1974), (Liu and Lohmann 1973), (Lynds et al. 1976), (von der Heide 1978), and (Weigelt 1977). Some of these methods have already been applied to astronomical objects.

In the following sections we describe applications of speckle interferometry and speckle holography. After that, we discuss the speckle rotation method for the 2.4m-Space Telescope.

* Based on data collected at the European Southern Observatory, La Silla, Chile

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(2) LABEYRIE'S SPECKLE INTERFEROMETRY

Astronomical short-exposure photographs are speckle interferograms, which are produced by the atmosphere and the telescope. Speckle interferograms carry diffraction-limited information since individual speckles are as small as the Airy disk of the telescope. This high-resolution information in speckle interferograms can be reconstructed by speckle interferometry (Labeyrie 1970), which essentially is a Fourier analysis of many speckle interferograms. The final result of the speckle interferometry process is the high-resolution energy spectrum of the object or the object autocorrelation. Speckle interferometry can be performed optically or digitally. Up to now most of our speckle data were processed optically (see, for example, Ebersberger and Weigelt 1979, Weigelt 1980), but some of our recent data were processed digitally (Baier et al. 1980).

Our speckle camera consists of a high-gain Varo or EMI image intensifier, a microscope in front of the image intensifier, non-deviating prisms for the compensation of atmospheric dispersion, interference filters for the selection of various wavelength bands, and a pair of f/1.0 Leitz Noctilux lenses to image the phosphor screen on the film of a 16mm-motion picture camera. Until now all data were recorded on 16mm or 35mm film. The advantage of film is its high number of resolvable pixels and the fact that the data can also be processed optically. For digital processing we digitize the speckle data with a TV camera and a digital video memory (512x512 pixels). In the case of faint objects the positions of individual photon events are calculated. The digitized data are Fourier transformed or are autocorrelated with our PDP 11/34.

Fig. 1 is a speckle interferometry measurement of the double star Beta Cephei. The photographs show the 30 original speckle interferograms (1m telescope), the average energy spectrum and the reconstructed autocorrelation. The separation was determined to be 0.25 arc second (Sept. 4, 1977).

Fig. 2 shows a speckle interferometry measurement of the famous central object R136 in the 30 Doradus nebula. The photograph is the average energy spectrum of 4000 speckle interferograms. The fringes indicate that R136 consists of at least two parts. The separation was determined to be 0.46 arc second (Weigelt 1981). Fig. 2 is a preliminary result since only 4000 of the 40 000 recorded speckle interferograms were reduced in this experiment. The sepckle interferograms were recorded with the Danish 1.5m telescope at ESO.

Speckle interferometry yields only autocorrelations instead of direct images. Therefore, all position angle measurements have a 180° ambiguity. This 180° ambiguity can be overcome by the speckle masking method (Weigelt 1977), which can yield direct images of double stars.

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We performed speckle interferometry of double stars with separations between 22 arc second (Weigelt 1979a) and 0.064 arc second (Ebersberger and Weigelt 1979). Objects up to magnitude 13.5 have been easily measured with 1000 speckle interferograms (Weigelt 1981).

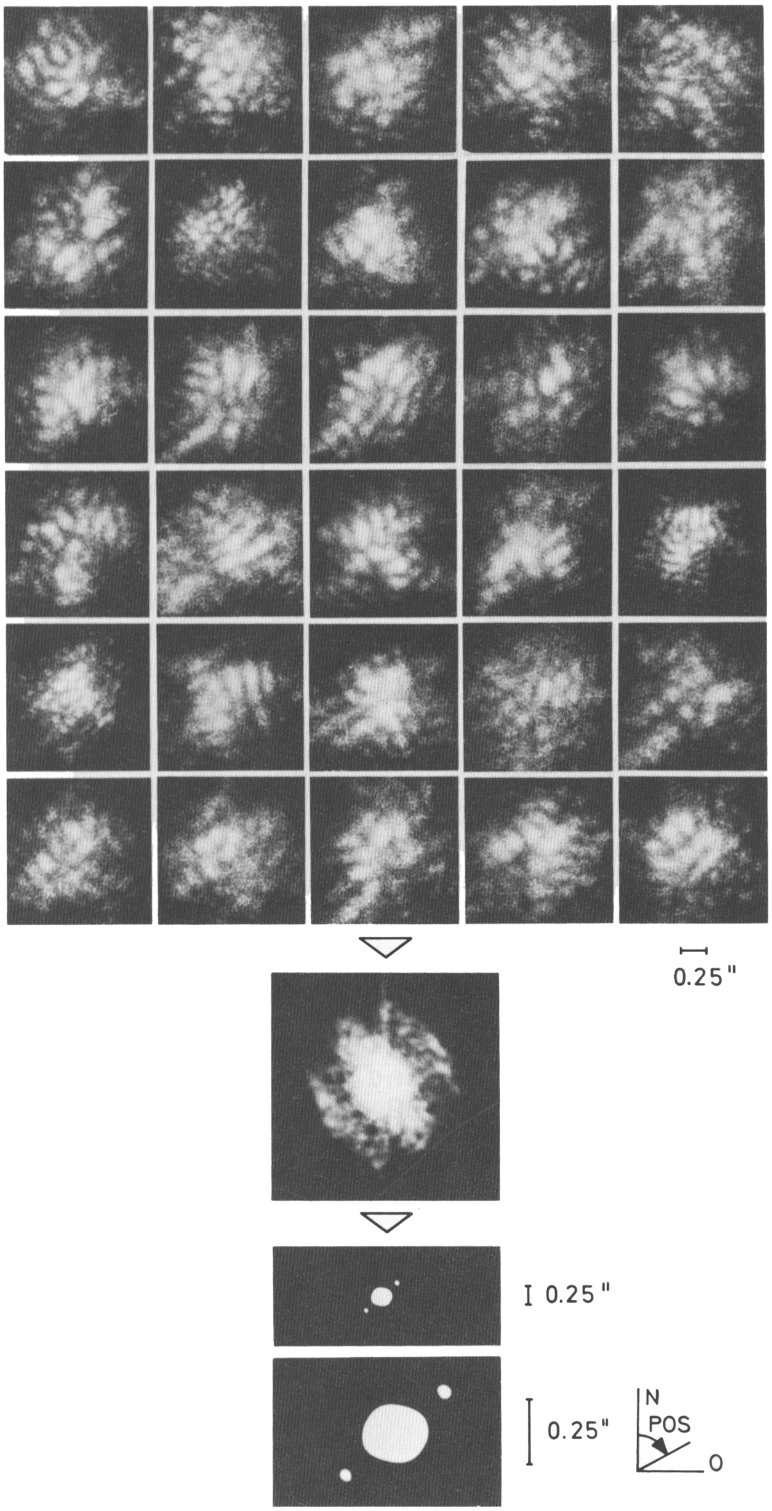

FIGURE 1

SPECKLE INTERFEROMETRY OF BETA CEPHEI. From (Weigelt 1978a).

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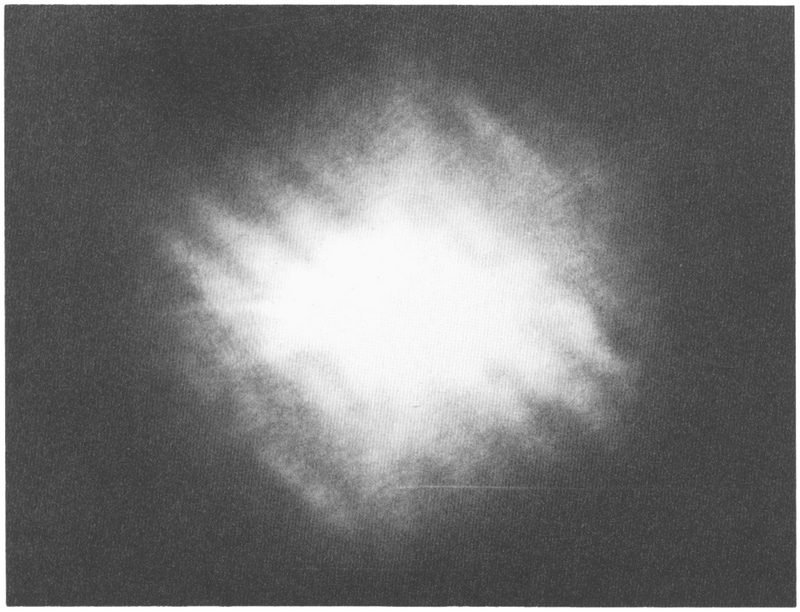

FIGURE 2 SPECKLE INTERFEROMETRY OF THE CENTRAL OBJECT R136 IN THE 30 DORADUS NEBULA. From (Weigelt 1981).

(3) SPECKLE HOLOGRAPHY

Usually speckle interferometry yields the object autocorrelation. Direct images can be easily reconstructed if there is an unresolvable star $\delta(x-x_R, y-y_R)$ near the object, since

$$AC[O(x,y)+\delta(x-x_R,y-y_R)] =$$

$$= \delta(x,y) + AC[O(x,y)] + O(-x+x_R,-y+y_R) + \underline{O(x+x_R,y+y_R)}$$

The object and the δ-star have to be in the same isoplanatic patch. This image reconstruction technique is called speckle holography (Liu and Lohmann 1973, Bates et al. 1973), since the δ-star plays a similar phase-preserving role as the reference beam in holography. The terms $O(-x+x_R,-y+y_R)$ and $O(x+x_R,y+y_R)$ are the desired twin image and the image of the object, respectively. The first applications of speckle holography to astronomical objects are described in (Weigelt 1978b, 1979a, 1980).

Fig. 3 shows a speckle holography measurement of Zeta Aquarii. The photographs show one of the 100 reduced speckle interferograms of Zeta Aquarii A-B (ESO 3.6m telescope), the average energy spectrum of all speckle interferograms (middle), and the reconstructed, high- resolution image of Zeta Aquarii A-C (at the bottom). The separation of the previously unresolved close double star Zeta AQR A-C was determined to be 0.064" (epoch 1978.964). In this experiment the resolution was improved by a factor of about 30. Fig. 4 shows a speckle holography measurement of the triple star ADS 3358. The largest δ-star distance in speckle holography measurements was 10 arc second (Weigelt 1979a).

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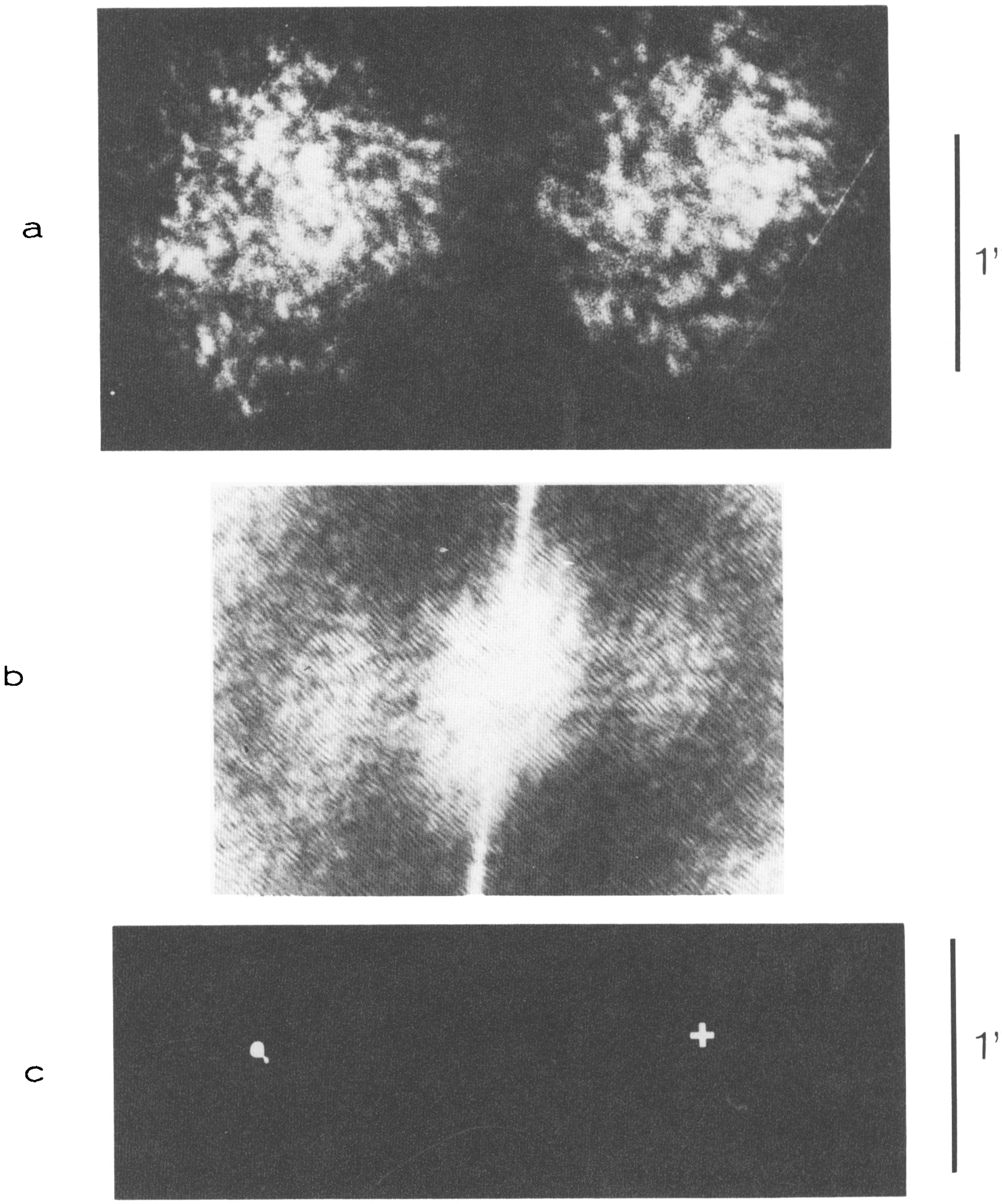

FIGURE 3 SPECKLE HOLOGRAPHY OF THE TRIPLE STAR ZETA AQUARII A-B-C

a: one of 100 recorded speckle interferograms; b: average energy spectrum; c: reconstructed image of Zeta AQR A-C, 30-fold improvement of the resolution. From (Weigelt 1980).

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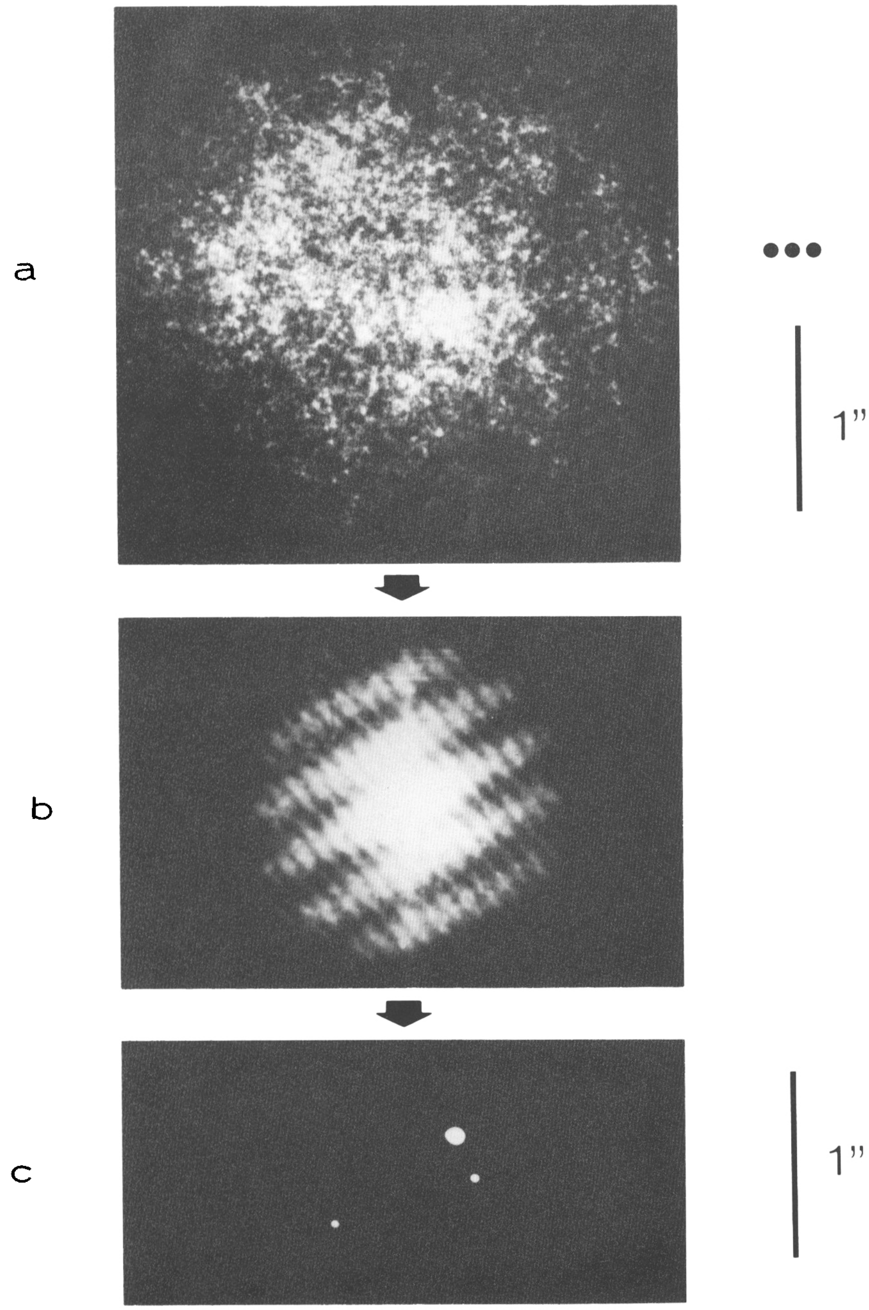

FIGURE 4 SPECKLE HOLOGRAPHY OF THE TRIPLE STAR ADS 3358

a: one of the 240 recorded speckle interferograms; b: average energy spectrum; c: reconstructed, high-resolution image. From (Weigelt 1978b).

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(4) RECONSTRUCTION OF HIGH-RESOLUTION IMAGES FROM SPACE TELESCOPE DATA

The NASA 2.4m Space Telescope will probably be launched in 1985. The size of the aberration point spread function is predicted to be about 0.1 arc second (NASA announcement), which is larger than the diffraction limit $\lambda/D = 0.01$ arc second for $\lambda = 130$nm and $D = 2.4$m. Therefore we have to assume that the quasi-monochromatic point spread function (due to aberrations) will be a small, stationary speckle interferogram. From such speckle interferograms diffraction-limited images can be reconstructed by the speckle rotation method (Lohmann and Weigelt 1979, Weigelt 1979b). In this method the Space Telescope has to be rotated between successive photographs of the same object in order to rotate the ST point spread function and to overcome the zeros problem of inverse filtering. One of the f-ratios of the ST Faint Object Camera is f/288, which is sufficient to resolve the speckle fine structure in the point spread function.

Fig. 5 shows a laboratory simulation of the speckle rotation method. At the top nine aberration-degraded photographs of a single star (left) and a triple star (right) can be seen. The photograph at the bottom shows the reconstructed image of the triple star (right) and the undesired zeroth diffraction order (left) of the speckle holography reconstruction.

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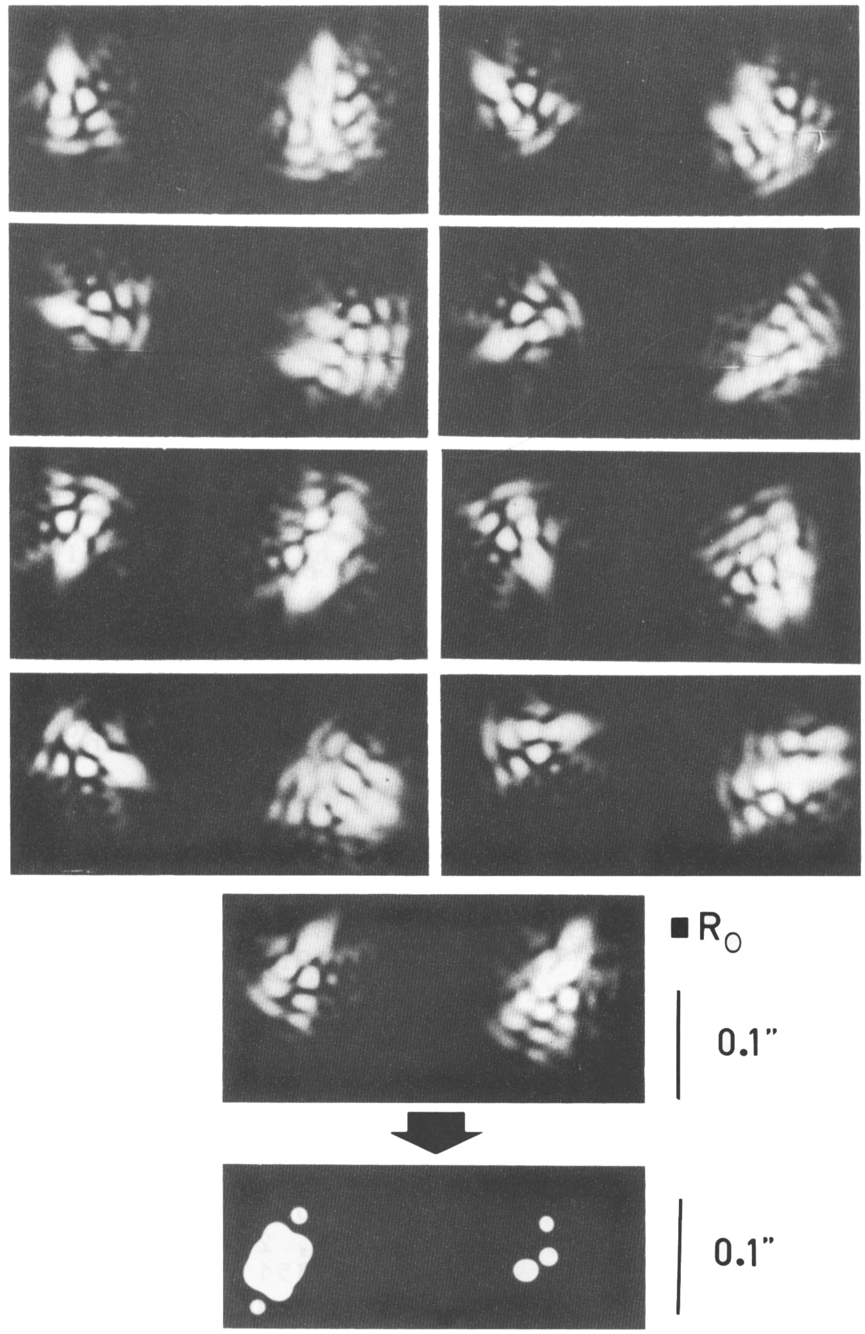

FIGURE 5 SPECKLE ROTATION METHOD FOR THE 2.4m SPACE TELESCOPE

a: nine aberration-degraded photographs; bottom: reconstructed image of the triple star (right).

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DISCUSSION

FEKEL: What is the status of your program, and what kinds of objects are you observing?

WEIGELT: The objects which we have observed up to now are in the following classes. Spectroscopic binaries with known trigonometric parallaxes; all Hyades binaries; and T-Tauri stars, since you can determine the mass if the separation is 50 milli-arc-seconds or closer. We also measure other binary stars which are useful in improving the mass/luminosity relation. Of course, we measure peculiar objects, such as R136 in the 30 Doradus nebula, Seyfert galaxies, and asteroids.

HARRINGTON: Will the engineers let you rotate Sapec Telescope the way you want to?

WEIGELT: Yes, it is necessary for other applications, and it is not difficult to rotate by plus or minus five degrees in short time intervals. If you wait some weeks or days, it is possible to rotate by large angles.

KREIDL: How much information would you lose if you did not rotate the telescope and do one of the following: either mark those zeroes as undefined, or interpolate those values from neighboring points?

WEIGELT: We have already investigated this point, and we find that, if you have no information at some spatial frequencies, you can still do the deconvolution if your object is two stars of the same magnitude. If you have a more complicated object, the deconvolution does not work. It is so easy to rotate the telescope by five degrees, and then you can deconvolve the image. I do not propose to try to deconvolve one photograph, because then it is difficult to tell what is noise and what is object information.

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