Speckle Interferometry and Speckle Holography with the 1.5 m and 3.6 m ESO Telescopes

J. Ebersberger and G. Weigelt

That great arch-enemy of all observing astronomers, the seeing, *can be pacified with a method called* speckle interferometry. *For some years it has provided us with "real" pictures of close binary systems and even of the surfaces of some stars, e.g. the well-publicized image of Betelgeuze. So far, however, the speckle technique—which is based on very short exposures and very long focal lengths—has been limited to comparatively bright objects. Drs. Johannes Ebersberger and Gerd Weigelt, from the Physics Institute of the Erlangen-Nürnberg University, Fed. Rep. of Germany, review recent speckle work at La Silla. It will be good news to many that they are reasonably confident that objects of magnitude 16 or even fainter may soon be within reach of speckle interferometry!*

The theoretical resolution of a 3.6 m telescope is about *0.03 arcsecond* (at $\lambda = 400$ nm). This limit is caused by diffraction. Of course, ordinary astrophotography does not yield diffraction-limited resolution. The turbulent atmosphere restricts the achievable resolution to about *1 arcsecond*.

However, it is possible to achieve *0.03 arcsecond* resolution if one evaluates *short-exposure photographs* by speckle interferometry or its modification, speckle holography. Speckle interferometry was first proposed by A. Labeyrie (*Astron. Astrophys.* **6**, 85). Up to now speckle interferometry was mainly applied to the measurement of binary stars and star disks. In the future speckle interferometry will certainly also be applied to more complicated objects such as for instance galactic nuclei.

For speckle interferometry it is necessary to evaluate short-exposure photographs, because only short-exposure photographs carry diffraction-limited information. The exposure time has to be about 0.03 sec or shorter in order to "freeze" the turbulent atmosphere. Such short-exposure photographs, called speckle interferograms, consist of many small interference maxima, called "speckles". The size of each speckle is in the case of a 3.6 m telescope about 0.03 arcsecond. Speckle interferograms are the diffraction patterns of the refractive index variations in the atmosphere. The life time of the fine structure of a speckle interferogram is about 0.03 sec. A typical speckle interferogram is shown in the upper part of figure 2.

Why is it possible to extract by speckle interferometry high resolution information from speckle interferograms? Figure 1 gives the answer. The two stars of a close binary star produce at the same time nearly the same speckle patterns or point spread functions. This fact is called the space-invariance (isoplanicity) of the atmospheric point spread function. If the separation of a binary star is closer than 1 arcsecond, then the total speckle pattern consists of *two identical, overlapping* speckle patterns.

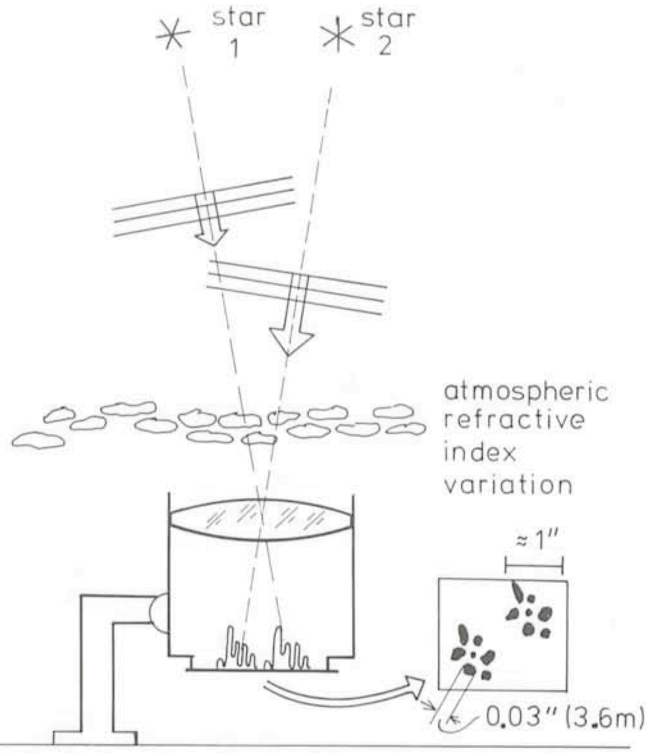

Fig. 1: *The two stars of a close binary star produce at the same time nearly identical speckle patterns. This is due to the fact that the light from both stars propagates through nearly the same part of the atmosphere.*

This knowledge is the key for extracting high resolution object information. In the case of a more complicated object, the total produced speckle pattern is equal to the convolution of a single star speckle interferogram and the object intensity distribution.

In speckle interferometry high resolution information is extracted from speckle interferograms by averaging the modulus square of the Fourier transforms of all recorded speckle interferograms. This procedure and the compensation of the speckle interferometry transfer function yield the power spectrum (= modulus square of the Fourier transform) of the object. This is what Michelson observed as "visibility". From there one continues to process the information by performing another Fourier transformation. The outcome is the autocorrelation of the object, with a resolution limited only by diffraction, not anymore by the turbulent atmosphere.

In the following sections some examples of speckle interferometry measurements with the 1.5 m and with the 3.6 m telescope are shown. We describe: (1) speckle interferometry measurement of the close spectroscopic binary Epsilon HYA, (2) speckle interferometry of the newly resolved, close binary Zeta AQR A-C (separation = $0.''064$), (3) speckle interferometry of two faint binaries (brightness $9^{m}.4/9^{m}.6$ and $9^{m}.5/10^{m}.4$; probably the faintest binaries resolved by speckle interferometry up to now), (4) speckle interferometry with a simulated Multiple Mirror Telescope, and (5) reconstruction of a high resolution *image* (instead of the autocorrelation) from speckle interferograms. The latter image-forming method is called *speckle holography*.

Example 1: Speckle Interferometry Measurement of the Spectroscopic Binary Epsilon Hydrae

Spectroscopic binaries are very interesting objects for speckle interferometry, because the combination of speckle measurements and spectroscopic measurements can yield new points in the empirical mass-luminosity relation. One of the spectroscopic binaries that is resolvable by speckle interferometry is Epsilon HYA. At the bottom of figure 2 the reconstructed autocorrelation of Epsilon HYA is shown. The autocorrelation of a binary star consists of three dots. The distance from the centre to one of the off-centre dots is the separation. The separation of Epsilon HYA was measured (epoch 1978.964) to be $0\overset{''}{.}239 \pm 0\overset{''}{.}004$. The position angle was measured to be $141\overset{\circ}{.}7 \pm 2^{\circ}$ (180°-autocorrelation ambiguity). The autocorrelation was reconstructed from 400 speckle interferograms. One of them is shown at the top of figure 2. The speckle interferograms were recorded under the following conditions: 3.6 m telescope; effective focal length = 460 m; exposure time = 0.01 second; interference filter: $\lambda_0 = 550$ nm and $\Delta\lambda = 20$nm; compensation of atmospheric dispersion by non-deviating prisms.

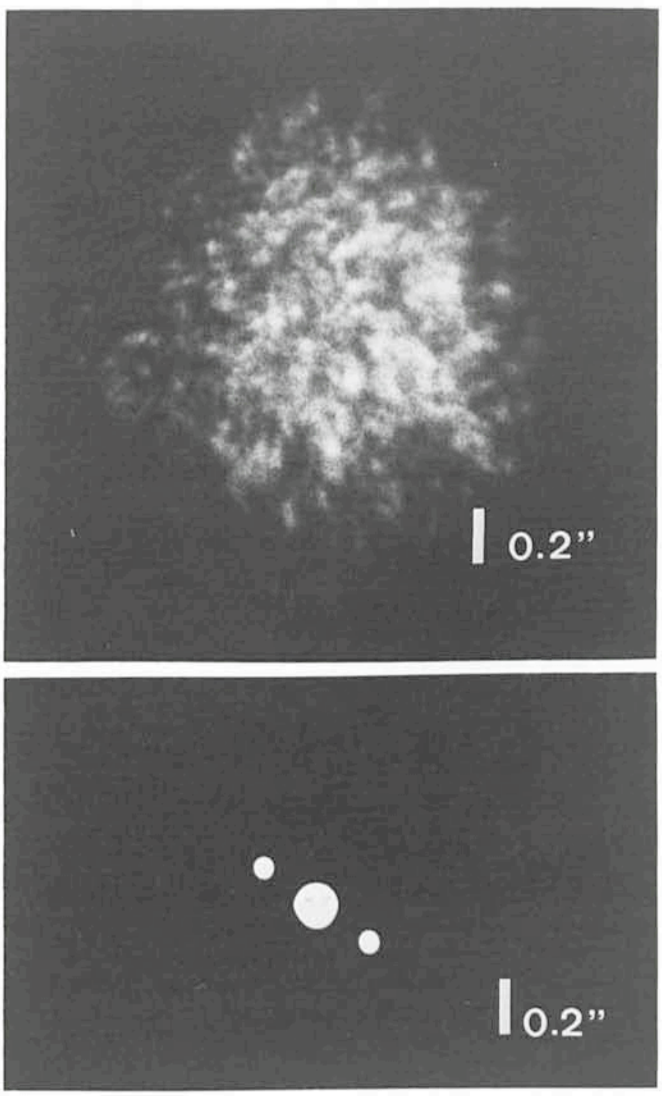

Fig. 2: *Speckle interferometry measurement of the spectroscopic binary Epsilon HYA. The photograph at the top shows one of 400 speckle interferograms recorded with the 3.6 m telescope. The photograph at the bottom is the reconstructed high resolution autocorrelation of Epsilon HYA (separation = $0\overset{''}{.}239 \pm 0\overset{''}{.}004$).*

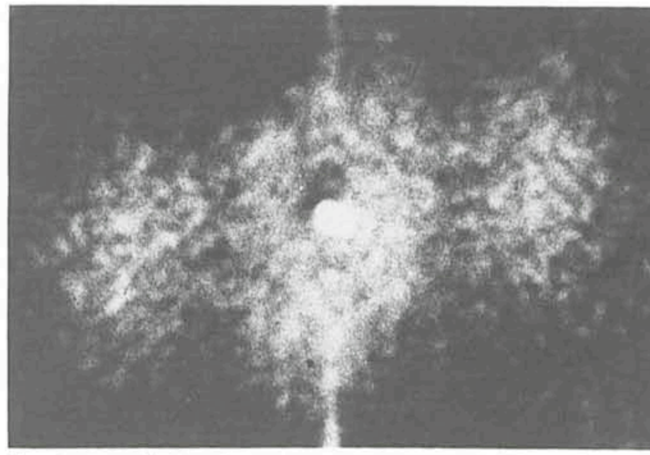

Fig. 3: *Speckle interferometry measurement of Zeta AQR A–C (separation = $0\overset{''}{.}064 \pm 0\overset{''}{.}005$).* Object power spectrum.

Example 2: Speckle Interferometry Measurement of Zeta Aquarii A–C

Zeta AQR A–B is a famous binary star with about 1.7 arcsecond separation. When we evaluated the speckle interferograms of this object we were very surprised. Zeta AQR A was again resolved in two stars having a separation of only $0\overset{''}{.}064 \pm 0\overset{''}{.}005$ (1978.964). Figure 3 shows the power spectrum of Zeta AQR A–C, which was reconstructed from 100 speckle interferograms recorded with the 3.6 m telescope.

Example 3: Speckle Interferometry Measurement of Faint Binaries

In order to study the limiting magnitude of speckle interferometry we recorded speckle interferograms of objects down to $14\overset{m}{.}8$! Most of these measurements have not yet been reduced. Already evaluated are the speckle interferograms of ADS 1865 ($9\overset{m}{.}4/9\overset{m}{.}6$) and D + 14.696 ($9\overset{m}{.}5/10\overset{m}{.}4$). The speckle interferograms of these objects were recorded with the 1.5 m ESO telescope. Separation and position angle of ADS 1865 were measured (1978.956) to be $0\overset{''}{.}214 \pm 0\overset{''}{.}010$ and $181^{\circ} \pm 4^{\circ}$, respectively. Figure 4 a shows the power spectrum of ADS 1865 reconstructed from 500 speckle interferograms. Figure 4 b and 4 c show the power spectrum and autocorrelation of D + 14.696 (1978.956: separation = $0\overset{''}{.}640 \pm 0\overset{''}{.}02$; position angle = $160\overset{\circ}{.}7 \pm 2^{\circ}$). The autocorrelation of D + 14.696 was reconstructed from 400 speckle interferograms. Based on extrapolations we believe that objects of 16th to 18th magnitude may be observable during very good seeing and with a sufficiently large number of short exposures.

Example 4: Speckle Interferometry with Simulated Multiple Mirror Telescopes

ESO and the Kitt Peak National Observatory are studying a large Multiple Mirror Telescope. Therefore we have simulated MMT speckle interferometry. For that purpose we mounted a MMT mask in front of the 1.5 m telescope. The mask consisted of 4 holes. The diameter of each of the four apertures was 50 cm. The goal of these experiments was to collect information about the signal-to-noise ratio and the speckle interferometry transfer function. We have

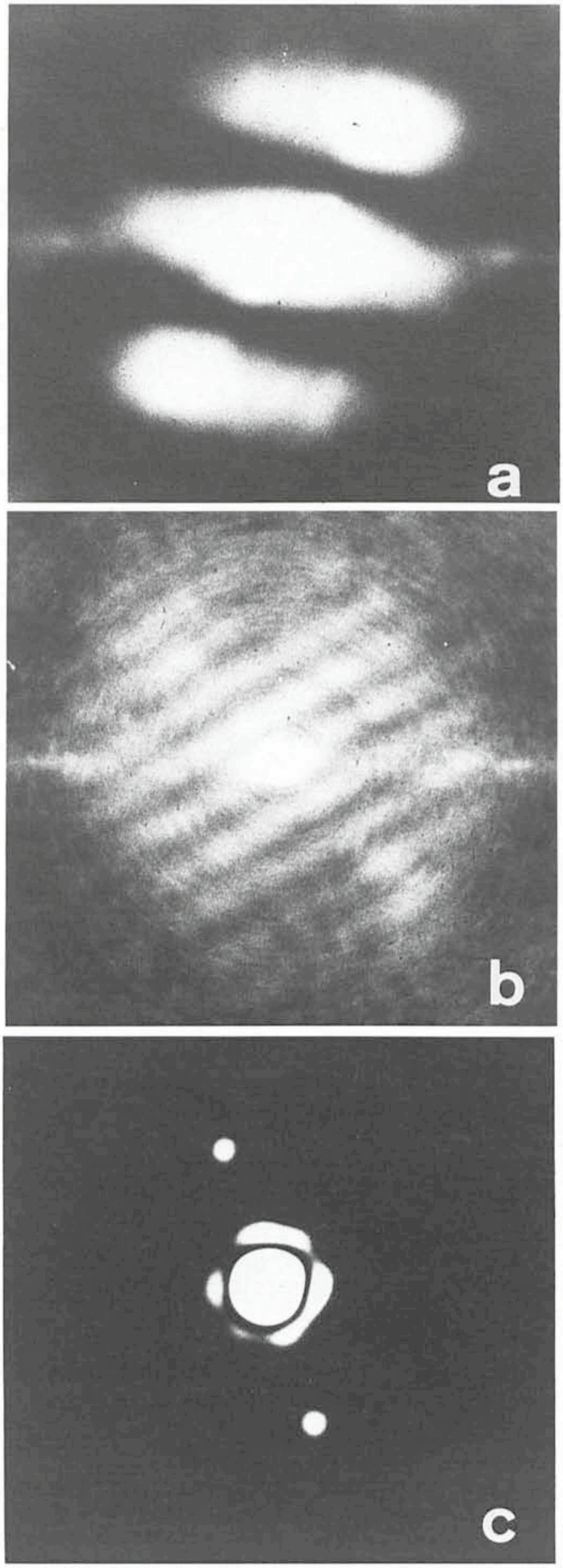

Fig. 4: *Speckle interferometry measurement of the binaries ADS 1865 ($9^{m}.4/9^{m}.6$) and D + 14.696 ($9^{m}.5/10^{m}.4$).*

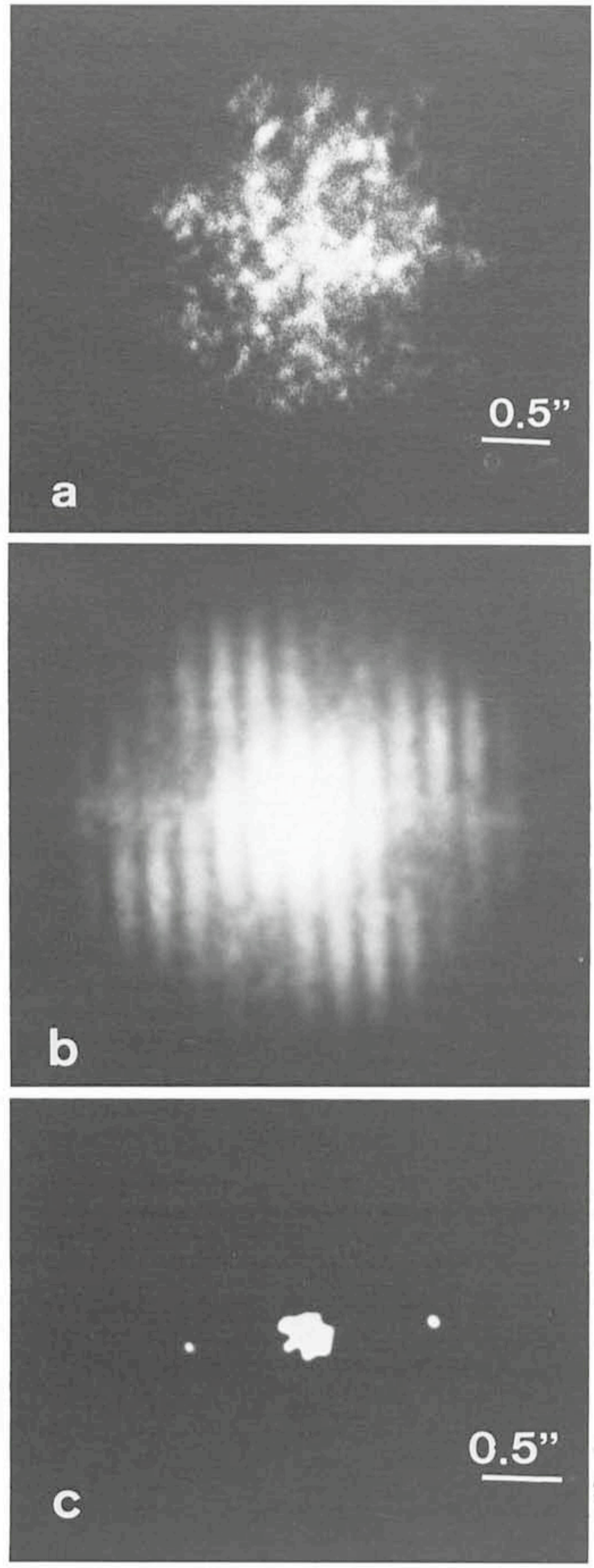

Fig. 5: *Speckle interferometry with a simulated Multiple Mirror Telescope (MMT). Figure 5 a is one of 625 MMT speckle interferograms of Zeta CNC A–B. Figure 5 b shows the average power spectrum of the 625 speckle interferograms and Figure 5 c is the reconstructed autocorrelation of Zeta CNC A–B (separation = $0''.81$).*

found that the S/N ratio of the MMT measurement was nearly the same as in the case of the full aperture.

Example 5: Reconstruction of Actual Images by Speckle Holography

Speckle interferometry yields the high resolution autocorrelation of the object. It is also possible to reconstruct actual images from speckle interferograms. For that purpose one has to record speckle interferograms of the object one wants to investigate, *and simultaneously* speckle interferograms of an *unresolvable* star close to the object. The speckle interferograms of the unresolvable star (point source) are used as the deconvolution keys. It is necessary that the object and the point source are in the same "isoplanatic patch". The isoplanatic patch is the field in which the atmospheric point spread function is nearly space-invariant. We found under good seeing conditions the size of the isoplanatic patch to be as large as 22 arcseconds, which was at the limit of our instrument (article in press).

The technique of using as the deconvolution keys speckle interferograms of a neighbourhood point source is called speckle holography. Speckle holography was first proposed by Liu and Lohmann (*Opt. Commun.* **8,** 372) and by Bates and co-worker (*Astron. Astrophys.* **22,** 319). Recently, we have for the first time applied speckle holography to astronomical objects (*Appl. Opt.* **17,** 2660). Figure 6 shows an application of speckle holography. In this experiment we reconstructed a diffraction-limited image of Zeta Cancri A–B by using as the deconvolution keys the speckle interferograms produced by Zeta CNC C, which is 6 arcseconds apart from A–B.

The measurements reported here are only a small part of the measurements that were performed with the 1.5 m and 3.6 m telescopes. We also measured various spectroscopic binaries, six Hyades binaries, other interesting binaries, the diameter of Mira, the central object of 30 Doradus nebula and other interesting objects. We plan to report these measurements when the evaluation is completed.

Finally, we would like to thank A. W. Lohmann for initiating the speckle project and for many stimulating discussions. We would also like to thank the staff at La Silla, especially the night assistants, for their valuable cooperation. The development of the speckle interferometer was financed by the German Science Foundation (DFG).

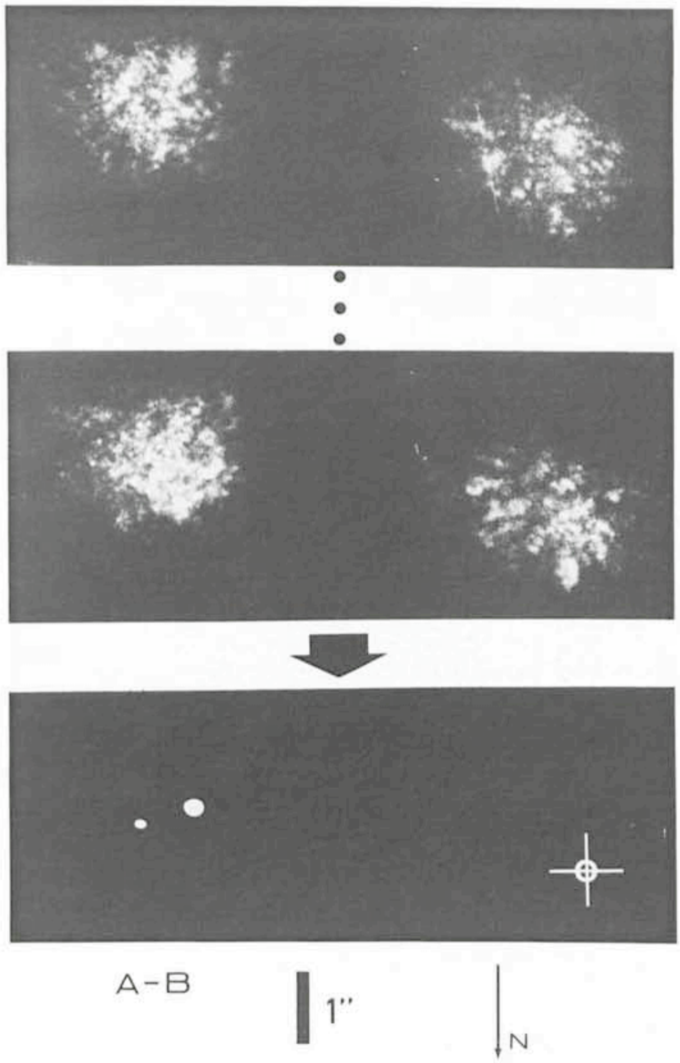

Fig. 6: *Speckle holography measurement of the binary star Zeta Cancri A–B. The diffraction-limited* image *of Zeta Cancri A–B (at the bottom left; separation = 0.″81) was reconstructed from 600 speckle interferograms. The cross at the bottom right has been drawn to indicate the position of Zeta CNC C. Two of the speckle interferograms are shown at the top. The speckle clouds on the left-hand side are produced by Zeta Cancri A–B. The speckle clouds on the right-hand side are due to Zeta Cancri C. The speckle clouds of Zeta Cancri C were used as the deconvolution keys. The speckle interferograms were recorded with the 1.5 m ESO telescope (the photograph in figure 6 is from the article "High resolution astrophotography: new isoplanicity measurements and speckle holography applications", G. Weigelt, submitted to* Optica Acta*).*

Photometric Observations of Minor Planets at ESO (1976–1979)

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The study of the light variation of minor planets allows an estimate of their form and rotation (direction of axis and period). If it is furthermore possible to obtain a measure of their apparent magnitude over as long a time interval as possible, then the knowledge of the albedo and orbit gives the absolute magnitude and dimension. A table exists that connects the diameter and the magnitude/albedo; it has been compiled by the method of least squares applied to asteroids for which the diameters have been determined by other methods.

Minor planet photometry is in itself an important science and many astronomers work in this area only. However, many astrometrists and computers of orbits are overcome by their desire to improve their knowledge about minor planets and begin to do photometric observations. As indicated above, both astrometry and photometry are