DIFFRACTION-LIMITED OBSERVATIONS OF BINARY STAR SYSTEMS

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ABSTRACT

A speckle interferometer is described which has been used to measure the separations and position angles of binary star systems. The present instrument uses an image intensifier to enable the enlarged stellar images to be recorded on cine-film. The exposure time is typically 8 msec and the camera can be operated at up to 20 frames per second. The instrument incorporates a means of calibrating the magnitude difference of the binary star systems.

A pair of achromatising lenses have been designed which will correct the radial chromatic dispersion in the speckle patterns and allow exposures to be made in "white" light. A system is under development which uses an image intensifier and a plumbicon television camera to acquire the data and a hard-wired autocorrelator to perform the analysis in real time. With this system the limiting magnitude of the technique should be significantly improved.

1. INTRODUCTION

The technique of stellar speckle interferometry was suggested by Labeyrie[1] and, in principle, allows any arbitrary extended object to be observed at a resolution equal to that of the diffraction limit of the telescope aperture. The short-exposure image of an unresolved star is composed of a random pattern of speckles enclosed in the seeing disk. These speckles are formed by the coherent addition of light from all parts of the aperture, the relative phases and amplitudes of the wavefronts being random, and are of the same order of size as the Airy disk of the telescope. Most of the observations by speckle interferometry have been restricted to simple objects such as binary star systems[2-7] and just-resolvable single stars[8,9] because the high resolution information may be easily extracted by summing the Fourier transforms or autocorrelation functions of a large number of speckle images. The reconstruction of images from speckle data involves more complicated procedures.

A programme of binary star observations by speckle interferometry has been in progress since 1975. The aims of the programme have been to study spectroscopic binary systems with long periods, close visual-binary systems and variable stars. The visual-binary systems were observed because speckle interferometry was considered to be a more accurate means of determining separations than was previously available. Some of the results of this programme have been published in the first of a series of papers[10]. The previously unresolved stars ε UMa, γ Boo and W Sgr have been found to be binary systems and the system σ Sco has been resolved into three components.

2. THE SPECKLE INTERFEROMETER

The speckle interferometer[11] has been designed for use at the Cassegrain focus of any large telescope and is shown schematically in Figure 1.

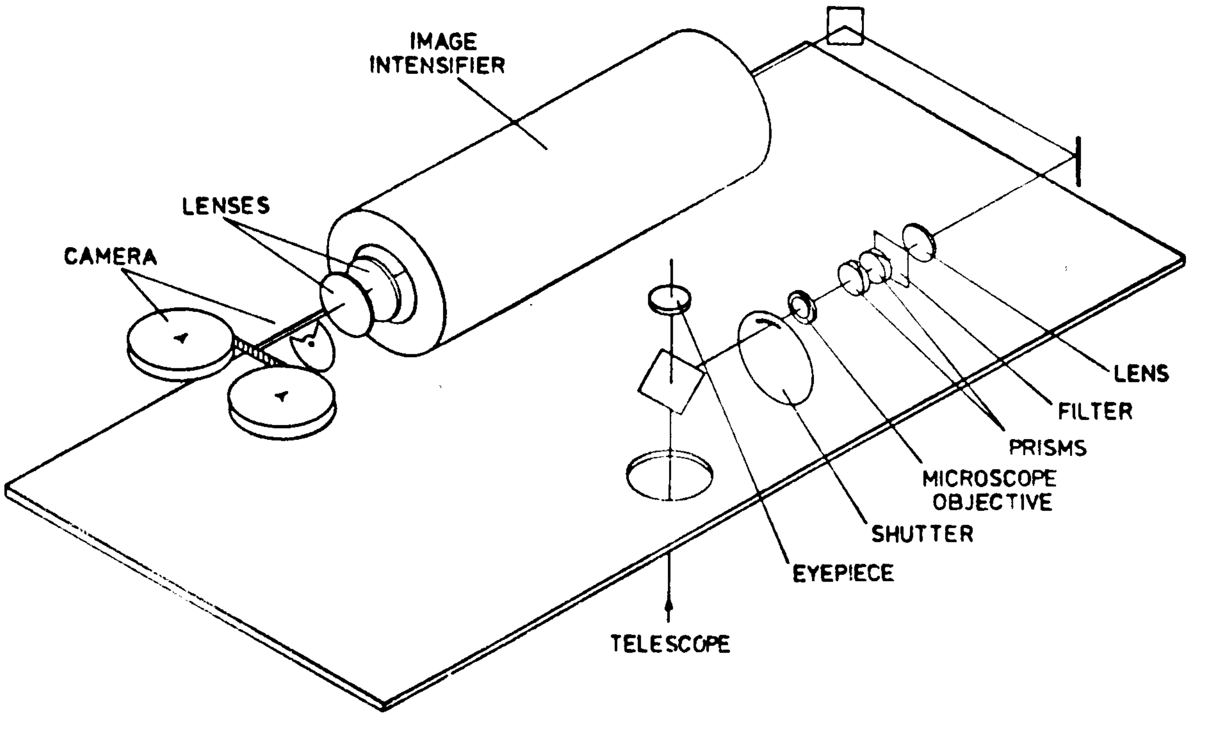

Figure 1. Schematic diagram of the speckle interferometer

The image formed by the telescope is centred in the field-finding eyepiece and then brought into the instrument via a movable mirror. A rotating

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shutter provides exposures in the range 0.002 to 0.01 s depending on the speed of rotation and the angle of the aperture in the shutter. A 5 cm focal length microscope objective collimates the light from the star image and this light passes through a pair of prisms and an interference filter. The nondeviating, but dispersing, prisms may be set from precomputed tables to produce equal and opposite dispersion to that imparted by the atmosphere for stars not at the zenith. A filter of 30 mm bandwidth centred at 520 nm is normally selected for 3 arcsec seeing on a 2.5 m telescope. A doublet lens with a focal length of 60 cm reimages the star onto the photocathode of an image intensifier or an eyepiece via a movable mirror (not shown). A four-stage magnetically focused image intensifier (EMI type 9912) with a maximum light gain in excess of 10^6 and a resolution of better than 40 line pairs per mm is used. A pair of f/1.2 Nikon 35 mm camera lenses working front to front image the output phosphor screen of the image intensifier on the focal plane of a 16 mm Vinten cine-camera. The overall light gain of the system is sufficient to record individual photoelectron events on Kodak Tri-X Reversal type 7278 film. The camera and shutter are driven synchronously at framing rates of up to 20 f.p.s. When the interferometer is used on the 2.5m Isaac Newton Telescope of the Royal Greenwich Observatory the image scale on the 16 mm film is 0.51 arcsec per mm. Observations have also been made on the 1.9 m telescopes of the South African Astronomical Observatory, the Observatoire de Haute Provence, France, and the Helwan Observatory, Egypt.

Three methods of data analysis have been used.

2.1 Analogue Method

In this method the cine film is run through a projector in which each frame is illuminated with coherent light from a laser which is then imaged by a lens onto a second piece of film where the squared modulus of the Fourier transform of the image is recorded. By this means the image power spectrum may be averaged over as many as 10^3 frames. A liquid gate is under construction to reduce the intensity of light scattered from the emulsion surface and initial results indicate that an improved signal-to-noise ratio will be obtainable. An example of the fringes obtained from 700 images of the

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binary star system λ Lupi (m_V = 4.0, separation = 0.302 arcsec) is shown in Figure 2.

Figure 2. Fringes obtained by the analogue method from 700 images of the binary star system λ Lupi.

2.2 Microdensitometer Method

In this technique the density distribution the cine film is digitized by scanning each frame with a PDS microdensitometer. The scanning aperture is 55 μm^2 and up to 1024 density levels are recorded on magnetic tape in an array of 128 x 128 points with a step size of 50 μm (equivalent to 0.025 arcsec). A two-dimensional fast Fourier transform is computed for each frame, the squared moduli of many transforms are co-added and the result is displayed on microfilm. An example of the result is shown in Figure 3 and is the image power spectrum for 48 images of the binary star system ADS 10374 (m_V = 2.6, separation = 0.290 arcsec).

This digital method has the advantage that photometric information, such as magnitude difference, should be easier to obtain. However, scanning the images with a microdensitometer is very time-consuming and, in practice, the analogue method is used for the majority of the analysis.

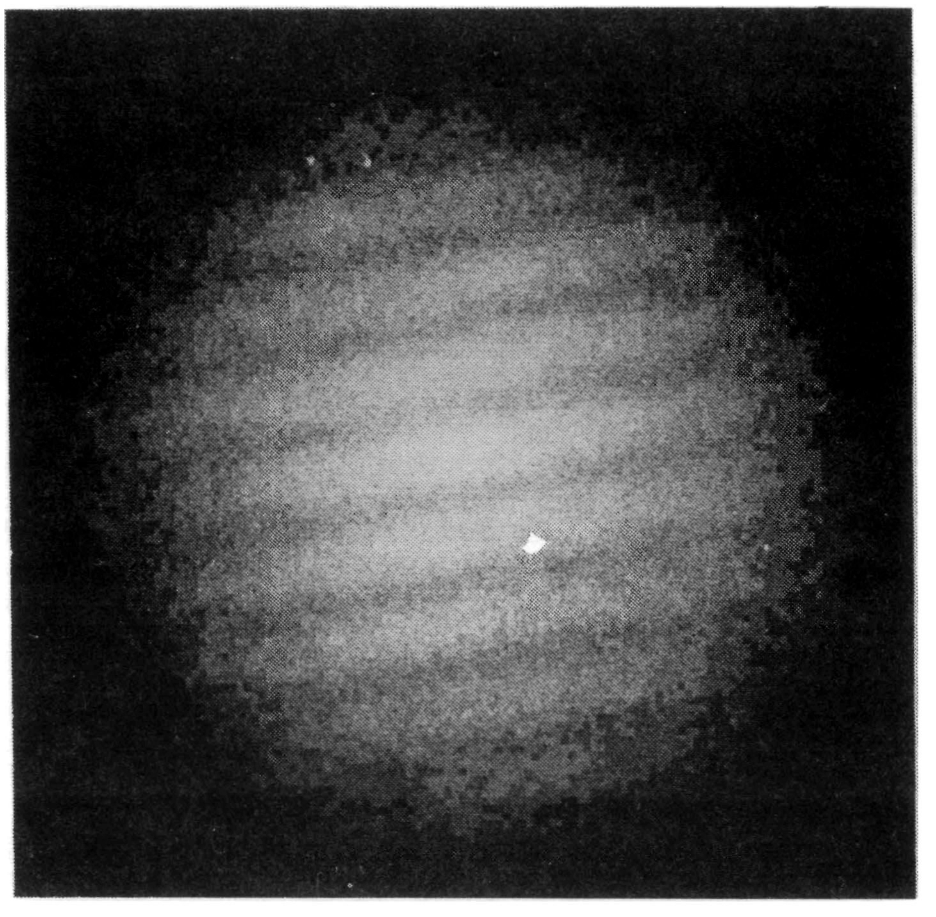

Figure 3. Fringes obtained by the microdensitometer method from 48 images of the binary star system ADS 10374.

2.3 Off-line Autocorrelation using a CCD

The disadvantages inherent in the analogue method, particularly the effects of scattered light, and the long reduction time involved in the microdensitometer approach can be avoided if a CCD and mini-computer are employed to generate the autocorrelation functions of the images. A Fairchild CCD type 202 having a 100 by 100 pixel output field is used to digitize each frame of cine film into two levels and centre-finding logic determines the position of each photoelectron event. The images of bright stars which contain many photons per speckle may be correlated by the same process using clipping as a form of data compression. This is possible since only the position of the speckles is of interest in binary star observations, although photometric information is lost in this process. The output of the CCD is stored in a 10K by 1 bit buffer store and then read via a CAMAC interface into an Interdata 70 mini-computer which is programmed to perform an autocorrelation of this data. The vector autocorrelation involves computing the differences of photon co-ordinates for all possible pairs of detected photons and incrementing memory locations whose addresses are given by the differences. This process is repeated for many images. At present the time required to process one image is of the order of 1 minute.

An example of a section through the resulting autocorrelation function is shown in Figure 4. This was obtained by summing the autocorrelation functions of 15 images of the binary star system ADS 10374.

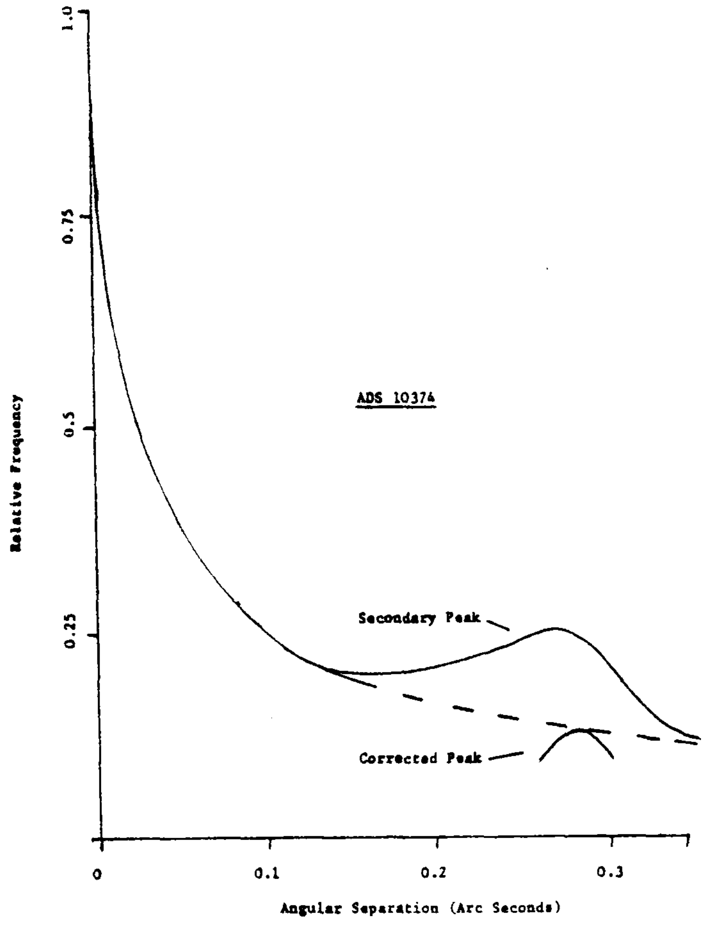

Figure 4. The autocorrelation of 15 frames of the binary system ADS 10374. The corrected peak indicates a separation of 0.285 arcsecs.

2.4 Real-time Autocorrelator

In the off-line CCD and mini-computer system the speed of calculation is limited by the computer access time. It has been shown by Blazit et al[7,12] that it is possible to construct a hard-wired, real-time correlator which can autocorrelate up to 110 photon events per frame at a rate of 50 frames per second. The principal advantage of such a system is the elimination of the cine-film which, in practice, restricts the number of images that may be analysed. We are at present constructing a correlator to perform autocorrelations and cross-correlations of images with a maximum of 512 photon events per image and at a rate of 25 images per second.

Data acquisition will be by means of an EMI image intensifier coupled to a TV system employing a broadcast quality plumbicon camera tube. The raw data will be displayed on a monitor and may be recorded on video tape for further, more complex analysis, e.g. that required to reconstruct images. A form of centre-finding logic will blank the TV output for 2, 3 or 4 pixels in the x and y scan directions after first encountering a photon event. Two modes of operation are envisaged. In the free-running mode the exposure time for the speckle images will be 40 ms, while in the short-exposure-time mode, a shutter synchronised with the TV camera and placed in front of the image intensifier will allow exposure times of 20 ms or shorter. For images with several photons per speckle, a clipping device will digitize the intensity into two levels. The correlator unit will have eleven 512 x 16 bit, semiconductor, random access memories to store the x-y co-ordinates of the photon events in eleven consecutive images. Two 16 bit subtractors will perform the address subtraction operations for auto- and cross-correlation and the results of these subtractions will increment locations in two 8K x 20 bit random access memories. The contents of these two memories will be transferred to another memory which will be used to control a C.R.T. display. The number of photon events per image that may be autocorrelated is critically dependent on the speed of operation of the memories: the 512 x 16 bit RAMs have an access time of 35 ns and the 8K x 20 bit RAMs have a ready-modify-write cycle time of 330 ns. The final auto- and cross-correlations will be stored, for example on disk, via a CAMAC interface.

A computer simulation[13] has shown that the technique should permit measurement of binary stars as faint as about 18th magnitude in an observation time of 35 minutes on a 4 m telescope.

3. MEASUREMENT OF BINARY STAR MAGNITUDE DIFFERENCE

In principle, the magnitude difference between binary stars may be determined from the visibility of the fringes in the Fourier transforms or from the relative heights of the primary and secondary peaks of the autocorrelation function. Unfortunately, these quantities also depend on the contrast of the recorded speckle pattern and are therefore affected by parameters such as the exposure time or the filter bandwidth. A technique of producing artificial binary stars has been developed as a calibration procedure. By introducing one or both of a pair of doubly-refracting calcite prisms into the light path of the interferometer, binary stars may be produced with apparent separations of approximately 0.08, 0.20, 0.28 and 0.48 arcsec. The artificial binary stars are of equal magnitude if the light from the star is unpolarized. Magnitude differences of up to 5 or 6 can be produced by adding a polarizing filter set at an appropriate angle to the optic axis of the calcite. The required angles were determined experimentally to allow for possible imperfections of the calcite or of the filter. The fringe visibility is measured for a calibration series of exposures made at various magnitude differences and under the same conditions as for the binary star observation. Thus the magnitude difference of an actual observed binary star system may be determined. The method does not make allowance for the effects of isoplanicity which lead to an apparent increase in the measured value of the magnitude difference for increasing separation of the binary stars. It is believed that this error is not serious for separations of less than about 0.5 arcsec[14] in typical conditions.

4. SPECKLE ACHROMATIZING LENSES

In white light the speckle pattern of a star image consists of the superposition of monochromatic speckle patterns which differ from each other in two ways. Firstly, there is a difference of scale such that photons of different wavelengths in a particular speckle are separated from each other in a radial direction by an amount proportional both to their distance from the centre of the pattern and to the wavelength difference. Measurements indicate that the typical radial dispersion is about 0.0027/nm. Secondly, the speckle patterns in different wavelengths are not identical, but this decorrelation with wavelength is generally a smaller effect than the radial dispersion. Wynne[15] has designed an optical system of two separated triplets which pro-

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duces an equal and opposite radial dispersion to that of the speckles. The dispersion may be varied by changing the separation of the triplets. Correction of the radial dispersion will allow the use of a filter with wider spectral bandwidth and the observation of fainter stars. A disadvantage of the optical system is that it has zero field of view and therefore will be mainly employed for single, resolvable objects or binary star systems with separations less than about 0.5 arcsec.

5. CONCLUSIONS

A speckle interferometer has been successfully used for observations of binary stars as faint as magnitude 7 and as close as 0.053 arcsec. The technique, which does not require good seeing conditions, yields very accurate values for the separations in observation times of only a few minutes per object. The limiting magnitude of the technique should be significantly improved by the use of a real-time autocorrelator now under construction. This system should enable measurements to be made of diameters and surface features of supergiants and asteroids; observations of features in planetary ring systems; detection of planetary systems in nearby stars; an upper limit to be set to the diameters of quasars and the extension of the mass-luminosity relationship as derived from binary systems.

Acknowledgements

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DISCUSSION

D. G. Currie: Concerning your correction of color effects by a special lens system, it would seem that this corrects the "dispersion" of each speckle, but not the loss of temporal coherence which seems very important in both speckle and amplitude interferometry.

R.J. Scaddan: The second effect you mention is dominant in poor seeing, but there is a real gain in using the achromatizing system in good seeing.

D.L. Fried: I am suspicious of the effect of the chromatic dispersion compensating lens' effect. It seems to me that the same speckle lobe at two different wavelengths "encodes" two different spatial frequencies - there are slight differences between the corresponding speckle lobes at two different frequencies, with these differences carrying the information of interest. I am afraid that using the chromatic dispersion compensating lens will smear the spatial frequency dependence of the power spectrum.