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Attainment of Diffraction Limited Resolution in Large Telescopes by Fourier Analysing Speckle Patterns in Star Images*

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Resolution in excess of the limitation set by seeing, and reaching the diffraction value, can be obtained on star features by laser processing the speckle pattern observed in short exposures made with a large telescope. The technique may be considered as an extension of the Michelson stellar interferometry; it is applicable to star diameter measurements and stellar system studies.

Key words: speckle interferometry — Michelson interferometry — image processing — aperture synthesis

It has been known since the work of Fizeau and Michelson that the resolution loss of large telescopes due to atmospheric seeing can be retrieved in some cases by analysing interference effects in the image. Such techniques give direct diameter measurements for several stars, but their possible applications are restricted since small pupils must be used for reasons of phase uniformity. It seems possible to extend interferometer methods in such a way as to use the full aperture of a large telescope, with a corresponding increase in information sensitivity.

"Speckle" refers to the grainy structure observed when a laser beam is reflected from a diffusing surface.

This phenomenon results from interference effects in a coherent beam with random spatial phase fluctuations. The speckle grains can be identified with the coherence domains of the Bose-Einstein statistics. Their analysis in the case of stellar sources is the basis for the intensity interferometer technique (Hanbury Brown and Twiss, 1956).

In large telescopes, the image of point stars also features a speckle pattern, due to seeing induced phase fluctuations on the wavefront (Fig. 1). This phenomenon appears to have been first described correctly by Texereau (1962), on the basis of visual observation and long focus photography. It is rarely seen on star photographs because both a high magnification and a short exposure time are required, but it can be observed visually in telescopes using a strong eye-piece. The minimum grain size of the speckle thus observed is equal to the size of the Airy disk given by the telescope in the absence of seeing and aberrations.

It is therefore conceivable that speckle-affected images contain more information on smaller features than long exposure images with a blurred speckle.

In the simple case of a double star with a spacing smaller than the turbulence angle, the image consists of a superposition of two identical speckle patterns, shifted by an amount smaller than the image size. The resulting image is usually difficult to analyse visually, but its infinity diffraction pattern, produced using a laser beam, shows a set of parallel equispaced fringes whose spatial frequency is proportional to the double star separation (Fig. 2), as shown by Debrus *et al.* (1969).

It is of interest to integrate on a single photographic plate the diffraction patterns of a large number of images: this improves the signal-to-noise ratio in the diffraction pattern. With a uniform star disc as the object, one would obtain an Airy spot as the diffraction pattern.

In the general case these experiments can be interpreted in terms of the diffraction theory. Let $O(\alpha, \beta)$ and $I(\alpha, \beta)$ be the intensity distribution respectively in the object and the image. One observes in the image the convolution of the object

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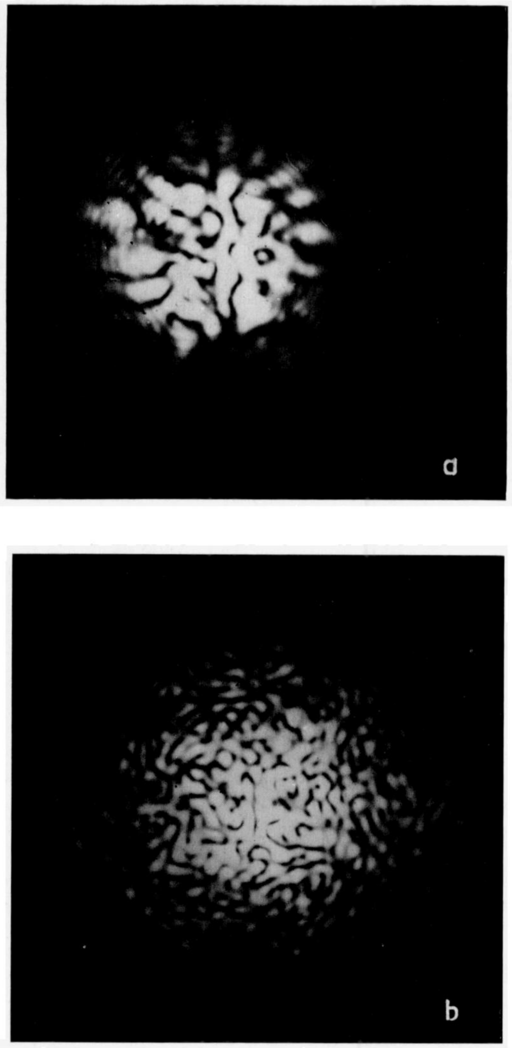

Fig. 1a and b. Simulated image of point star, as it appears in a large telescope, using a fast receiver. a) Aspect in a 2 meter telescope, b) aspect in a 5 meter telescope. The images were obtained at the focus of a low aperture camera (focal length 500 mm, lens free diameter: 2 and 5 mm). Seeing was simulated by introducing a static disturbance in the form of a glass plate sprayed with silicone oil (distance between plate and camera lens: 400 mm)

function with the speckle image of a point object, this speckle being the Fourier transform $p(\alpha, \beta)$ of the perturbated telescope pupil $P(x, y)$:

$$I(\alpha, \beta) = O(\alpha, \beta) \otimes |p(\alpha, \beta)|^2 . \qquad (1)$$

The Fourier transform of this intensity recording is:

$$i(x, y) = o(x, y) \cdot \mathscr{A}\,[P(x, y)] \qquad (2)$$

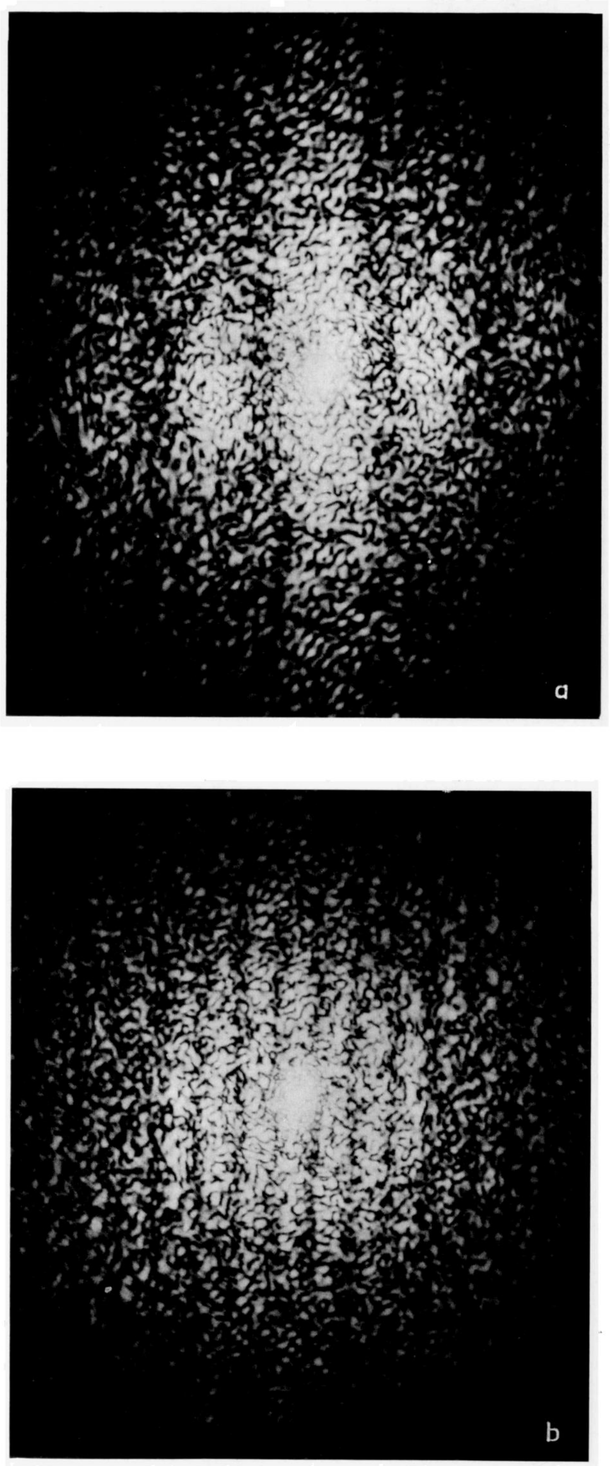

Fig. 2a and b. Fourier transform of simulated double star image, showing characteristic fringes. Turbulence noise, as well as photon noise, can be averaged by compositing a large number of such images. a) Star separation 0.03″, b) star separation 0.1″. Double stars were simulated by double-exposing plates, with a small displacement between exposures and:

$$|i\ (x, y)|^2 = |o\ (x, y)| \cdot |\mathscr{A}\ [P\ (x, y)]|^2 . \qquad (3)$$

$\mathscr{A}$ being the autocorrelation function of $P\ (x, y)$, its squared modulus is the modulation transfer function of the perturbated instrument. This function is not known at every instant but its time-averaged value is a rather well determined and simple function, measurable for given seeing conditions.

It is therefore of interest to add in intensities the Fourier transforms of many instant recordings, for example by multiple exposing a single photographic plate:

$$\Sigma\ |i\ (x, y)|^2 = |o\ (x, y)|^2 \cdot \Sigma\ |\mathscr{A}\ [P\ (x, y)]|^2 , \qquad (4)$$

$$|o\ (x, y)|^2 = \Sigma\ |i\ (x, y)|^2 / \Sigma\ |\mathscr{A}\ [P\ (x, y)]|^2 . \qquad (5)$$

The time-averaged intensity of the pupils's autocorrelation function being known, this gives the intensity of the object's Fourier transform. Losing the phase makes it impossible to reconstruct the object, except if it has a center of symmetry (the Fourier transform of a real centrosymmetric function being a real function). This is the case for double star or limb darkening studies.

Short exposure studies of double-stars, made with a Lallemand electronic camera (Laques, 1966) indicate that the speckle pattern for each star of the pair is identical for stars closer than 2 to 3″. This sets an upper limit for the size of the object to be analyzed.

The number of resolvable points in the object should not be too high, especially for weak objects, because of photon noise. Atmospheric dispersion should be corrected with a prism. Temporal coherence requirements are fulfilled by using a 300 to 3000 Å bandpass filter, since aberration and seeing induced optical path variations are usually smaller than a few wavelengths.

The same principle is applicable in a similar way to long baseline Michelson interferometry, using two large telescopes: in this case two different speckle patterns are superposed, the corresponding beams being at an angle with each other, and fine fringes are observed inside the speckle grains if the beams are coherent. The experiment could be carried out in real time, using a television pick-up tube and a laser-illuminated Eidophor optical transducer.

In the more realistic case of a single telescope, the proposed technique seems capable of giving useful astronomical data on star features, with a resolution reaching 0.02″. Its application requires the largest possible telescope and sensitive image receivers such as image intensifiers or electronographic cameras. The technique appears to be limited to objects brighter than $m = 7$ and it does not seem possible to use it for discriminating faint stars against the sky background.

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