

Experimental simulation of stellar speckle interferometry

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ABSTRACT. Some results obtained using speckle interferometry in a coherent optical system are shown with a synthetic diffuser generated by an $m \times n$ matrix of random integer numbers with zero average by means of a computer program and a microdensitometer. The photographic emulsion where the pixels are recorded is bleached in order to obtain a phase diffuser which resembles the effects produced by the atmospheric turbulence. The laboratory simulation of this speckles and the optical autocorrelations of both one and two objects are similar to some resolved stellar objects.

RESUMEN. Se muestran algunos resultados obtenidos usando interferometría de moteado en un sistema óptico coherente con un difusor sintético generado por una matriz de $m \times n$ números enteros aleatorios con promedio cero mediante un programa de computadora y un microdensitómetro. La emulsión fotográfica donde son grabados los *pixeles* es blanqueada para obtener un difusor de fase que simula los efectos producidos por la turbulencia atmosférica. La simulación de laboratorio de este moteado y las autocorrelaciones ópticas en uno y dos objetos son similares a algunos objetos estelares resueltos.

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1. INTRODUCTION

In observational astronomy, the limit of angular resolution of stellar objects is of the order of one arc second because of the random fluctuations caused by the refraction index of the terrestrial atmosphere [1]. The phase and amplitude of the wavefront are perturbed thus creating a granular structure known as speckle in the observational plane of the telescope. In 1970, A. Labeyrie proposed and implemented a new method of speckle interferometry to obtain resolutions in the limits of diffraction of the optical system: obtaining the autocorrelation of the object but not its image [2]. This technique has been successfully applied to a great amount of astronomical objects, such as stars and binary stars [3].

The information contained in the speckle patterns is optically decodified using a coherent optical system. The atmospheric model assumed in this method consists of one atmospheric layer [4], with Gaussian distribution in amplitude and phase that attenuates and cut off the high spatial frequencies.

In this work, two different experimental simulations of the effects produced by the atmospheric turbulence are presented, first using glass plates sprayed with silicone and second implementing a phase diffuser generated by a computer program and a microdensitometer.

2. THEORY

The wavefronts in propagating through the atmosphere are distorted because the random fluctuations of the refraction index and the stellar object image at the focal plane of the telescope is greater than the Airy disk of the telescope. The angular resolution is limited for the atmospheric turbulence, the good "seeing", and not by the theoretical diffraction limit of the telescope [5]. It is used the resolution Rayleigh criterion, $\theta = 1.22 \lambda/D$, where θ is the angular resolution, λ the wavelength and D the diameter of the telescope.

The point spread function of the atmosphere is approximately $\lambda/d \cong 1$ arc second, where d is the average size of the "cells" of the order of 10 to 20 centimeters, depending of the weather conditions such as temperature, pressure and altitude of observation. One arc second is the limit imposed by the atmosphere, this means a good seeing, and it is greater than the theoretical Airy disk size λ/d of the telescope ($D \gg 10$ cm). With no turbulence medium, the average size of each speckle is the same that the Airy disk of the telescope. The average size and lifetime of this speckles, which is approximately from 0.1 to 0.01 seconds [1], is determined by astronomical observations and by the atmospheric turbulence [6].

For these reasons, in stellar speckle interferometry is necessary to take short exposure photographs, ≈ 0.01 seconds, to "freeze" the atmospheric turbulence. These are the speckle interferograms.

According to Fourier optics theory, the intensity distribution of each speckle interferogram is equal to the convolution of the stellar object and the point spread function of the atmosphere and telescope. This means

$$I_n(x, y) = O(x, y) * P_n(x, y) \quad (n = 1, 2, \dots, N), \quad (1)$$

where I_n , O , and P_n are the bidimensional intensities distributions of the n -th speckle interferogram of the object, and the instantaneous point spread function of the atmosphere-telescope system respectively. The symbol $*$ denotes convolution.

Applying the convolution theorem to Eq. (1), we have

$$F\{I_n(x, y)\} = F\{O_n(x, y) * P_n(x, y)\} = F\{O_n(x, y)\}F\{P_n(x, y)\},$$

where F denotes Fourier transform. This can be expressed as

$$I_n(\mu, \nu) = O(\mu, \nu)P_n(\mu, \nu), \quad (2)$$

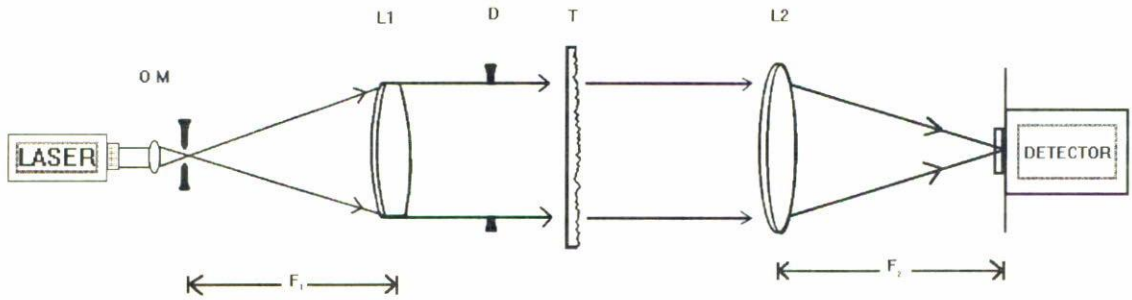


FIGURE 1. Coherent optical system to obtain speckle interferograms. The main parts are: laser, microscope objective (M), pinhole object (O), collimating lens (L_1) with focal length f_1 , turbulent medium (T), and spherical lens (L_2) with focal length f_2 .

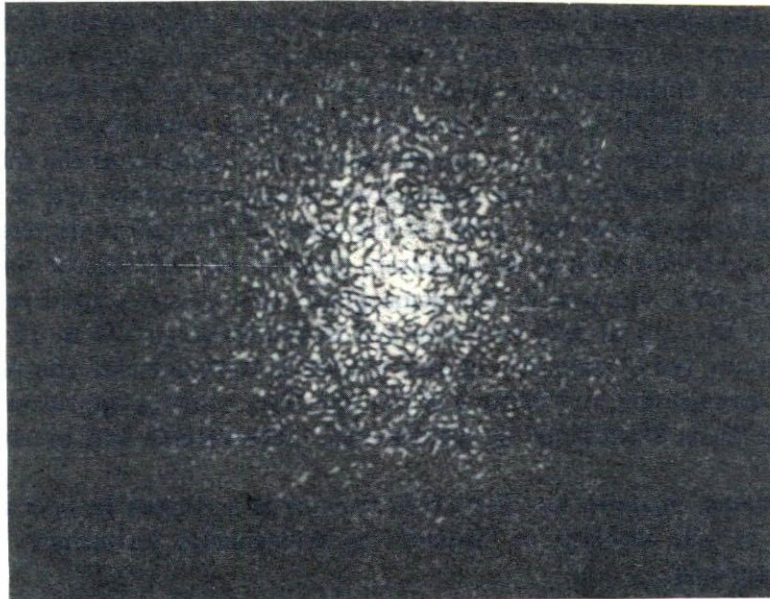


FIGURE 2. Speckle pattern photograph of one pinhole object using a glass plate sprayed with silicone oil as turbulent medium. Lens aperture of L_2 : $D = 4$ mm, focal length $f_2 = 1000$ mm, wavelength $\lambda = 632.8$ nm.

where μ and ν are the spatial frequencies in the Fourier plane.

After taking the square and averaging Eq. (2), we obtain the average power spectrum

$$\langle |I(\mu, \nu)|^2 \rangle = |O(\mu, \nu)|^2 \langle |P(\mu, \nu)|^2 \rangle. \quad (3)$$

All the power spectrum are recorded in the same photographic emulsion to improve the signal-to-noise ratio.

From Eq. (3), we can see that the term $\langle |P(\mu, \nu)|^2 \rangle$ is the transfer function of the whole process in speckle interferometry of non negative functions [7], this means that the transfer function has no zeros for all the spatial frequencies up to the cut off frequency of the telescope, $\nu_a = D/\lambda f$ where D is the diameter of the telescope, λ and f are the

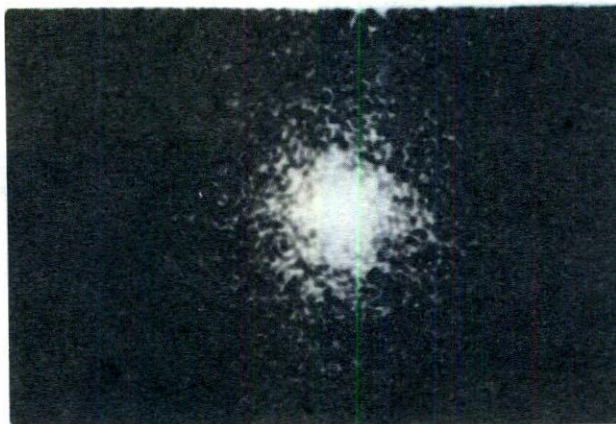


FIGURE 3. Speckle pattern photograph of two pinhole objects separated by $100 \mu\text{m}$ using a plate sprayed with silicone oil as turbulent medium. $D = 4 \text{ mm}$, $f_2 = 1000 \text{ mm}$, $\lambda = 632.8 \text{ nm}$.

wavelength and focal distance of the telescope respectively. Then, it is possible to obtain the object power spectrum

$$|O(\mu, \nu)|^2 = \frac{\langle |I(\mu, \nu)|^2 \rangle}{\langle |P(\mu, \nu)|^2 \rangle}$$

for all the spatial frequencies up to the cut off frequency ν_a limited by diffraction.

And Fourier transforming the power spectrum of the object, we obtain the spatial autocorrelation of the object

$$F^{-1}\{|O(\mu, \nu)|^2\} = \text{AC}\{O(x, y)\},$$

where AC denotes autocorrelation.

3. LABORATORY SIMULATION

The first simulation of speckle interferometry was done utilizing a glass plate sprayed with silicone oil to simulate the seeing [2]. Later, the experiment was repeated to simulate the turbulent atmosphere but with a piece of shower glass that acts like phase distortion plate [8].

A similar experiment was done in this work. The points objects were two pinholes of $25 \mu\text{m}$ illuminated by a He-Ne laser of 5 mW at wavelength of 632.8 nm, and a glass plate sprayed with silicone was used to simulate the turbulent atmosphere between two spherical lenses (Fig. 1).

The speckle images of the objects were recorded on a photographic emulsion at the focal plane of the lens L_2 .

The spherical waves coming from the object are collimated by the lens L_1 . These plane waves are randomly perturbed in amplitude and phase crossing the turbulent medium (the glass plate). Each speckle interferogram is taken moving the glass plate in one direction

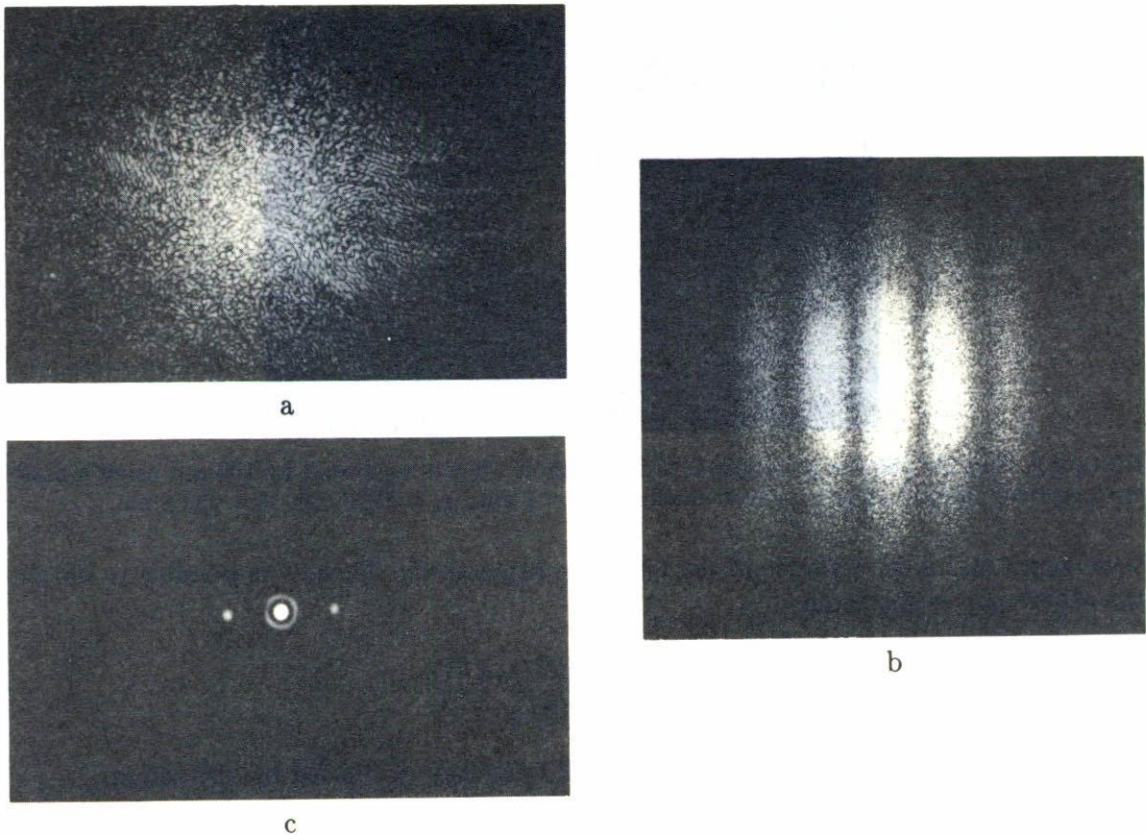


FIGURE 4. a) Speckle pattern of two objects, b) power spectrum, and c) autocorrelation.

with a micrometer. Figures 2 and 3 show the speckle photographs using one and two objects. Figure 4 shows the speckle interferometry process technique.

For a more realistic physical situation of the effects produced to a plane wave by the turbulent medium, it was necessary to control the size of the simulated cells implementing a diffuser which was generated by an $m \times n$ matrix of random integer numbers with zero average by means of a computer program of IMSL library. The process to produce this diffuser is shown in Fig. 5.

The matrix of random integer numbers were expressed as density using a microdensitometer in the writing mode, Fig. 6. These values were written on a photographic film, Kodak Linagraph Shellburst film 2476 ESTAR AH BASE, which gives very high contrast, Fig. 7.

In order to obtain this diffuser that produces phase variations on the plane wavefronts coming from the object, the photographic emulsion was bleached using the Kodak Bleach Bath R-10 formula [9].

4. DISCUSSION

The idea of implementing a diffuser that simulates the turbulent medium with the characteristic described above was to have an approximation to the real physical problem: how

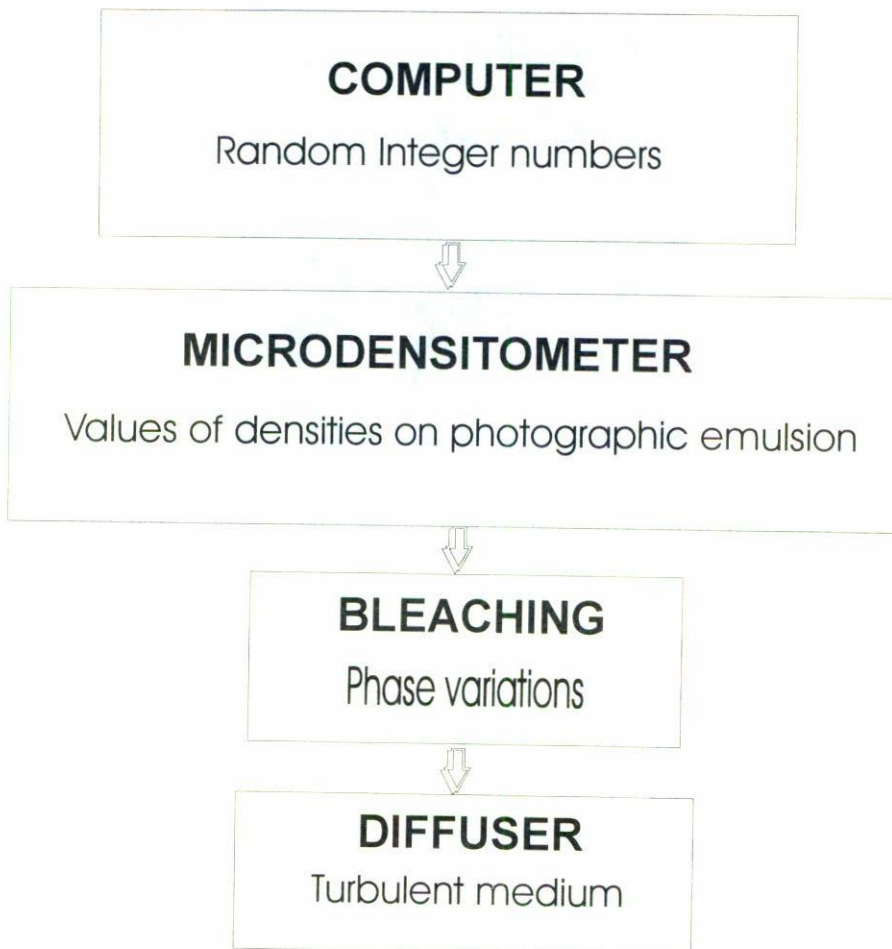


FIGURE 5. Block diagram for the construction of the phase diffuser that resembles the turbulent medium.

to control the size of the atmospheric cells. This is only a preliminary work to simulate optically the atmospheric turbulence. Obviously, this is not the only way that we can do it, there are other atmospheric models, for example: the log normal model [10] in which it is assumed that the log amplitude and phase have Gaussian or normal distributions. Other model of wave propagation in turbulent air has been done by studying the statistical properties of the perturbed complex field [11] in which he find a good approximation for describing the astronomical seeing. And of great interest is the determination of the optical transfer function of atmospheric turbulence [12].

The method of utilizing the microdensitometer and the photographic emulsion has the following very noted advantages compared with the other methods: a) with a sprayed silicon oil glass, b) with a shower glass and c) with a grinded glass. This is because is possible to have control over the atmospheric cell size using one software of the well known IMSL library that generates aleatory numbers matrix with zero average and variance one, with gaussian distribution, and then the microdensitometer's window aper-



FIGURE 6. Photograph of a 100×100 matrix of random integer values of density written with a microdensitometer. The separation between pixels is $100 \mu\text{m}$.

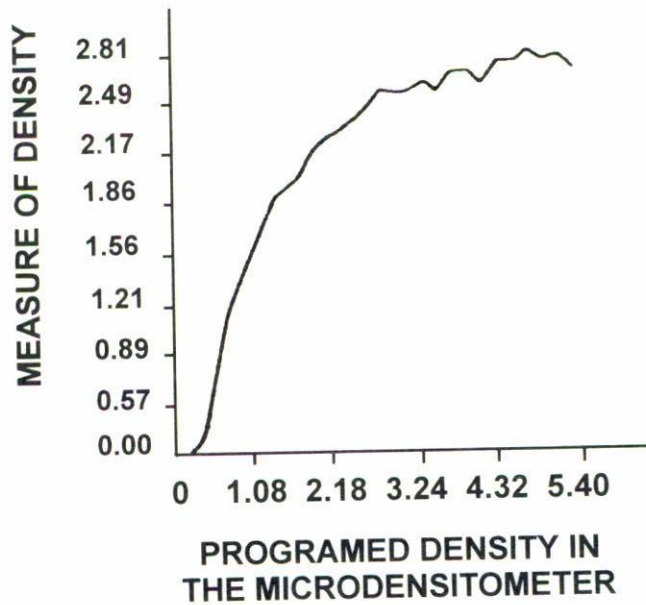


FIGURE 7. Response of the Kodak Linagraph Shellbrust Film 2476 to values of density written by microdensitometer and developed with D-19.

ture can be controlled. This matrix is recorded over the photographic emulsion using the microdensitometer and later this emulsion is immersed in a chemical bath to remove the silver halogens from the emulsion surface, what is so called the bleaching R-10 technique. In this manner, we have a phase diffuser, this means that the incident wavefronts over the emulsion take its shape from passing through it; in other words, we require a transparent diffuser. This situation not appears in other methods above mentioned.

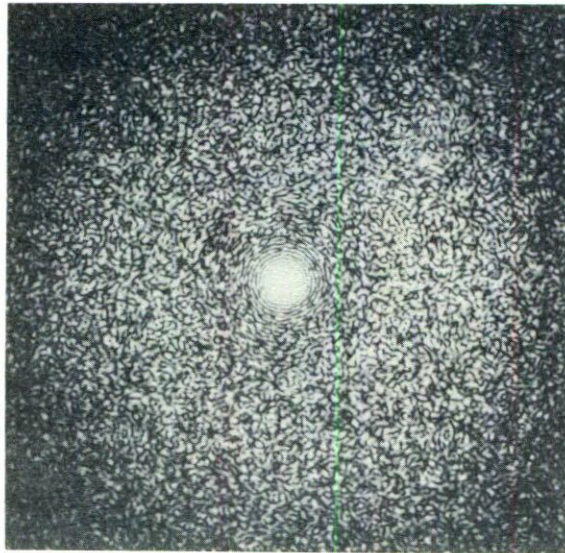


FIGURE 8. Speckle pattern of one object of $25 \mu\text{m}$ obtained with the bleached diffuser.

There is a problem when we use the silicon oil glass plate. It is very difficult controlling the little aerosol drops size, because this is mechanically handled without any precision apparatus to measure and control the drops dimensions that it is no possible manipulate it because this problem is inherent to the experiment. Besides increasing the numbers of the matching diffuser filters, we find a decreasing in the luminous object definition; this means that its transparence is vanished, but actually in the atmosphere it doesn't happens. Something similar occurs with a shower glass, but the problem is more remarkable and coarse.

Working with a grinded polished glass, one can to control the cells size, nevertheless the object definition is loosed, this means that this type of diffuser is not transparent and so it is not convenient use it like an atmospheric diffuser.

We think that with further modeling simulations it should be possible to get a better comprehension of the turbulent medium, and using modern CCD's for register the images, interfaced to a PC in order to processing digitally the images.

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