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Interferometric apodization of rectangular aperture – Laboratory Experiments

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Abstract. In this laboratory experiment, we study the possibility of producing an apodization of the pupil of a telescope using a classical Michelson interferometer. To simulate the star, we successively used a Laser source, a source of spectral light and a source of white light. Our goal is to study the performance of the assembly with polychromatic light. We present the results of experiments carried out with a rectangular aperture using a HeNe Laser and Na spectral light sources.

Keywords. instrumentation: interferometers; methods: analytical, laboratory; techniques: interferometric.

1. Introduction

The experimental work reported in this poster was made at the École Normale Supérieure of Marrakech, in collaboration with the University of Nice Sophia Antipolis. The goal is to realize an achromatic prolate apodized coronagraph (Aime (2005)), and one of the first steps is to study how the required pupil apodization can be produced by interferometry. Using a classical Michelson interferometer, it is only possible to obtain cosine apodizations, but Pueyo *et al.* (2004) have shown that this technique could be generalized to any apodizing function using deformable mirrors.

The principle of the experimental realization of the interferometric apodization was detailed by Aime *et al.* (2001), and first preliminary results were given by Soummer (2002). The basic principle is to use the Michelson interferometer to project fringes on the entrance aperture of the telescope, therefore producing a cosine transmission. We used a square aperture, and produced the apodization in a single direction.

2. Experimental Assembly

The assembly proposed to carry out the interferometric apodization is represented in figure 1. The Michelson interferometer allows to illuminate the lens L_3 by a coherent superposition of two plane waves of width D and wave vectors $\mathbf{k}_\pm = \frac{2\pi}{\lambda}(\pm\frac{\alpha}{2}\mathbf{x} + \mathbf{z})$. $\alpha = (\widehat{M_1, M_2'}) \ll 1$ is the angle between M_1 and M_2'. The amplitude of this wave at the entrance of L_3 is of the form $2\cos(\frac{\pi\alpha x}{\lambda})$. It equals zero at the edges of the aperture for $\alpha = \lambda/D$. If the quadratic phase term is ignored, the amplitude of the wave in the plane P_2 is given by the Fourier transform of ψ_{L_3} (Goodman (1996)):

$$\psi_{P_2}(x) = \frac{\cos\pi X}{1 - 4X^2} \qquad \text{where} \qquad X = \frac{D\,x}{\lambda\, f_3} \tag{2.1}$$

This shows well that the distribution of amplitude obtained in the plane P_2 is similar to that corresponding to a slit of width D apodized by the function $\cos(\pi x/D)$.

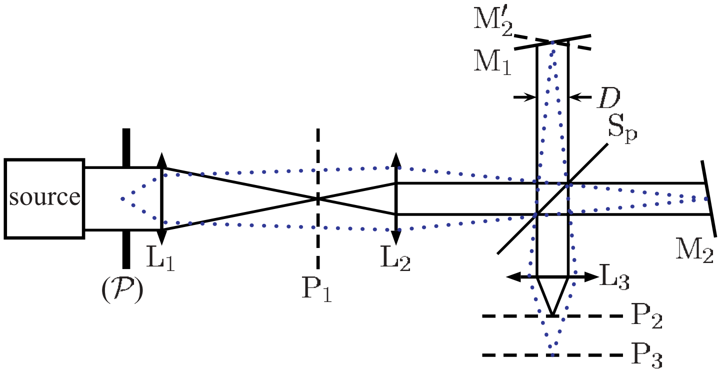

Figure 1. Experimental Assembly. The Michelson Interferometer is represented by the mirrors M_1 and $M_2$and the beam splitter S_p. The lens L_1 represents the telescope of focal plane P_1. The lens L_2 allows to illuminate the interferometer by a plane wave and it forms an image of the entrance pupil $(\mathcal{P})$ of the telescope on the mirror M_2. The lens L_3 transports the final image of $(\mathcal{P})$ to the plane P_3 and the focal plane image of the telescope to the plane P_2. All optical surfaces have a flatness of $\lambda/20$ at 633 nm.

The source simulates a star which illuminates the entrance pupil $(\mathcal{P})$ of the telescope with a plane wave. The lens L_1 schematizes the telescope of focal plane P_1. The two arms of the Michelson have the same length. M_2' is the image of M_2 by the beam splitter S_p; it forms a small angle α with M_1. The lens L_2 allows to illuminate the interferometer with a plane wave. It forms also an image of $(\mathcal{P})$ on the mirror M_2. The lens L_3 transports the final image of the pupil in the plane P_3. It also transports the focal plane of the telescope in the plane P_2. The interferometer is illuminated with a plane wave. It allows to obtain interferences between two plane waves. The fringes obtained are delocalized and have a period $i = \lambda/\alpha$.

3. Results and Discussion

The experimental tests were carried out successively with a HeNe laser and a sodium (Na) spectral source (figure 2).

3.1. *HeNe Laser Source*

The HeNe laser used has a power of 0.8 mW. It emits a red light of wavelength $\lambda = 632.8$ nm. The quasi-cylindrical beam, of small section ($\phi_0 \approx 2$ mm), is widened using the afocal system made up of L_{0_1}(+5 mm) and L_{0_2}(+100 mm) and represented in figure 2(a).

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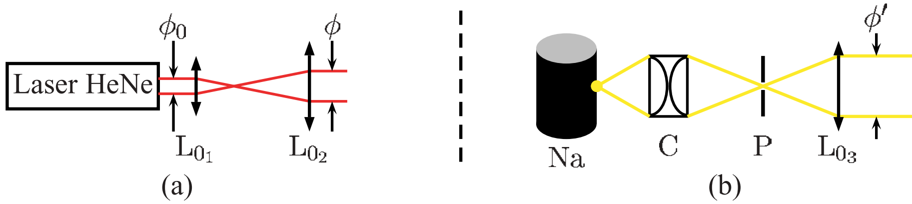

Figure 2. Sources used. (a): the afocal system formed by L_{0_1} (+5 mm) and L_{0_2} (+100 mm) lenses allows to enlarge the quasi-cylindrical beam emitted by the HeNe Laser. (b): the condenser C concentrates the beams coming from the Na Spectral Lamp on a pinhole P($\varnothing = 57\,\mu$m) placed at the first focus of the lens L_{0_3}.

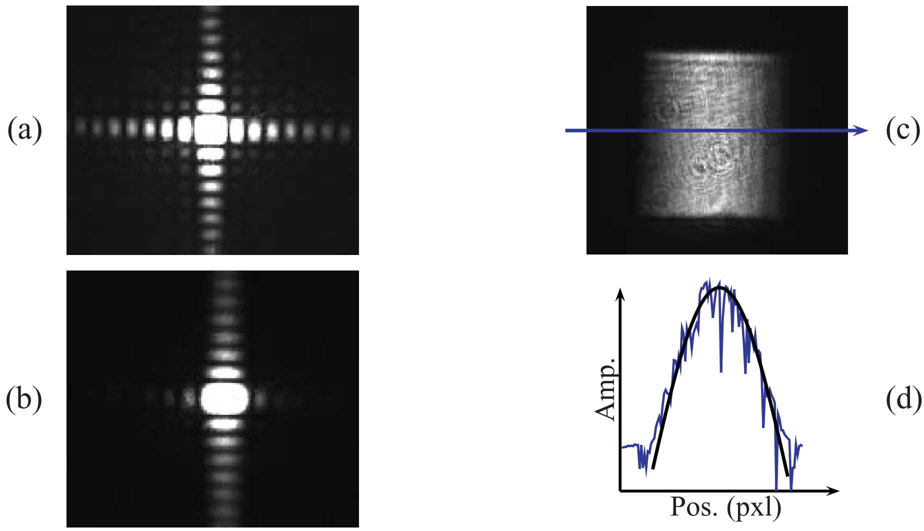

Figure 3. Example of results obtained with the Laser Source. (a): Non-apodized PSF obtained in the plane P_1. (b): Apodized PSF obtained in the plane P_2. (c)&(d) give respectively the distribution of intensity in the pupil plane P_3 and its cut parallel to the direction of apodization.

Figure 3 gives a typical example of results obtained with the laser source. The non-apodized PSF, obtained in the plane P_1, is represented in figure 3(a). It corresponds to a typical Fraunhoffer diffraction pattern of a rectangular aperture. In particular, the intensity of the first secondary maximum represents approximately 5.0% of that of the principal maximum. This experimental value is very close to the theoretical value which is 4.7%. Figure 3(b) gives the PSF obtained in the plane P_2 when the value of angle $\alpha = (\widehat{M_1, M_2'})$ is set to the optimal value $\alpha = \lambda/D$. The intensity of the 1st secondary maximum falls to 0.6% of that of the principal maximum whereas the theory envisages 0.5%. Figures 3(c) and (d) give respectively the distribution of intensity in the pupil plane P_3 and its cut parallel to the apodized direction. A fit of the intensity profile, thus obtained, with the function $\cos^2(\pi\, x/b\, D)$ gives $b = 1.14$.

3.2. *Na Spectral Source*

To simulate a star with a Na spectral source, we used the assembly represented in figure 2(b). The condenser C concentrates the beams coming from the spectral lamp on a pinhole P of a diameter $\varnothing = 57\,\mu$m. The pinhole P is placed at the first focus of the lens L_{0_3} which illuminates then the interferometer with a cylindrical beam of diameter ϕ'.

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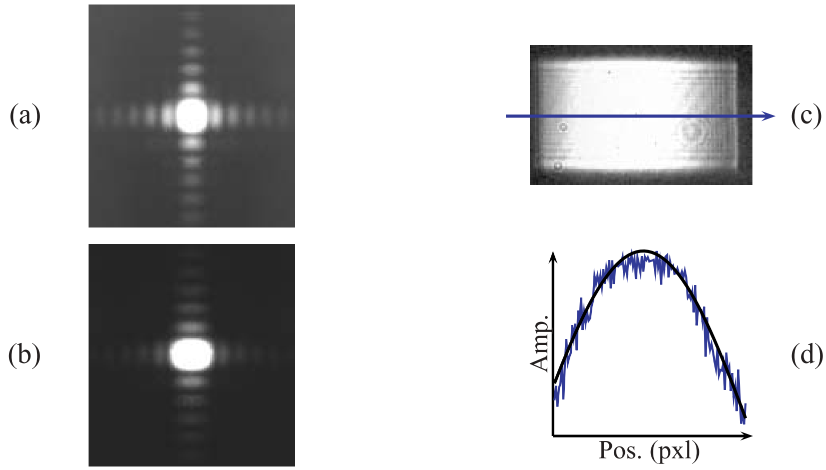

Figure 4. Example of results obtained with the Sodium Spectral Source. The comment is the same than the figure 3.

Figure 4 gives a typical example of results obtained with the light of Na spectral source. It shows the combined effects of the apodization and the resolution of the source (too large pinhole). In fact, it can be noted that despite the fact that the value $b = 1.10$ is close to the optimum one ($b = 1$), the apodization is less effective. This is due to the fact that the Na source is spatially incoherent. Indeed, in the non-apodized PSF, the intensity of the 1^{st} secondary maximum in this case represents almost 8% of that of the principal maximum which is far from the theoretical value. In addition, the apodization disappears almost completely as soon as the diameter of the pinhole P exceeds 0.1 mm approximately. To obtain a better apodization with the Na source, it would have been necessary to use a pinhole with an even smaller diameter. The intensity is then likely to become too low.

4. Conclusion

We showed the experimental realization of the interferometric apodization of a rectangular pupil with a Michelson interferometer. For that we used a laser source then a sodium spectral source. The results obtained with the laser source show a good agreement with the theory. With the sodium source, the main limitation is due to the size of the pinhole, corresponding to a resolved source, for which the apodization effect is degraded.

The study was carried out in the case of only one dimension and has served as a precursor of a new experiment in which a Mach-Zehnder interferometer will be used. As described by Aime (2005), phase plates will be introduced to obtain a prolate apodization.

References

Aime, C., Soummer, R., & Ferrari, A. 2001, *A&A* 379, 697
Aime, C. 2005, *PASP* 117, 1012
Goodman, J.W., *Introduction to Fourier Optics, 2nd edition*, McGraw-Hill, San Francisco (1996)
Pueyo, L., Givéon, A., Littman, M.G., Kasdin, J., & Vanderbei, R. 2004, SPIE 5490, 545
Soummer, R. 2002, PhD thesis, Sophia-Antipolis University, Nice

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