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Point-diffraction interferometer for atmospheric adaptive optics in strong scintillation

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Abstract

This paper evaluates the performance of a point-diffraction interferometer for closed-loop adaptive optics. A point-diffraction interferometer was built using a modified Mach-Zehnder set-up. The system was used in closed-loop using a SLM to implement a square, 12×12, piston-only segmented corrector with a stroke of $\pm\pi$. Its performance was tested for the case of atmospheric turbulence aberrations. The investigation showed, through simulation and experiment, that the point-diffraction interferometer worked in closed-loop operation in both uniform intensity and scintillated aberrations. Its robustness in the presence of phase discontinuities makes it a promising option for wavefront sensing in strong scintillation.

Keywords: Adaptive optics; Atmospheric turbulence; Wavefront sensing; Scintillation; Optical vortices

1. Introduction

The propagation of light through the atmosphere results in phase and amplitude aberrations in the wave that severely reduce the resolution of ground based imaging systems [1]. As the turbulence strength, or propagation length, is increased the scintillation (intensity fluctuations) becomes stronger and optical vortices begin to appear at nulls of intensity [2]. Adaptive optics (AO) has been used successfully to correct for atmospheric distortions in weak turbulence. In the strong scintillation regime, and especially in the presence of optical vortices, conventional AO systems based on gradient wavefront sensors show a strong decline in performance [3–5]. Although the gradient wavefront sensors commonly used in AO systems, such as the Shack-Hartmann and lateral shear, can detect the presence of vortices, the conventional least-squares reconstructor cannot reconstruct them. In these conditions direct-wavefront sensors such as the self-referencing point-diffraction interferometer (PDI) offer a promising alternative [6]. With such sensors, the reconstruction problem is avoided by measuring phase differences directly. There is now increasing interest in being able to apply adaptive optics image correction in this regime, as it would benefit areas such as line-of-sight optical systems and laser beam propagation.

The performance of PDIs and similar wavefront sensors, such as those using Zernike filters, has been investigated through simulation and experiment [6–11]. However, to our knowledge the performance of a PDI has not been investigated experimentally for propagation through strong atmospheric turbulence. Other atmospheric AO systems using direct wavefront sensing have been shown to work over horizontal propagation paths [12]. In this paper the performance of a PDI, in a closed-loop AO system with a 12×12 segmented wavefront corrector, is investigated for static aberrations corresponding to both weak (phase only), and strong (amplitude and phase fluctuations containing optical vortices) atmospheric turbulence. Results are presented for both simulation and experiment using a liquid crystal SLM as a segmented mirror.

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2. The point-diffraction interferometer (PDI)

The PDI is a simple self-referencing interferometer, that measures the variations in phase across a wavefront. It is set up as a modified Mach-Zehnder interferometer (Fig. 1), where one arm generates the reference wave by spatially filtering the input using a pinhole [13]. A consideration for any PDI is the size of the pinhole. The choice will depend to some extent on the application. Smartt [14] suggests that the diffracting region should not be larger than the Airy disk for an unaberrated wave in the system. For optical testing the requirement of a high accuracy reference wave suggests a pinhole significantly smaller than the Airy disk. In a closed-loop system, an accurate reference is not as critical and a larger diffracting region will allow through more light, but also more of the spatial variations in the original wavefront. For this system a pinhole was chosen with a diameter equal to $1.6\frac{f\lambda}{D}$, where f is the focal length of the lens $L1$, λ is the wavelength, and D is the aperture size. Using a plane-wave input the visibility of the interference pattern was maximized by attenuating the object beam with an amplitude filter. The interference patterns were captured on a 128×128, 8-bit CCD camera.

Open-loop systems based on static PDIs are sensitive to wavefront tilts that result in decreased visibility in the interference pattern [9]. This PDI was designed to work in a closed-loop system that is assumed to have partially, or fully, corrected the incoming beam so should not suffer from this problem once closed-loop operation is achieved. However, for static aberrations the system may not be able to achieve closed-loop operation for all cases.

2.1. Wavefront reconstruction

For the preliminary investigation reported in this paper a Fourier reconstructor, described by Takeda [15], was chosen as it allowed the phase to be recovered from a single interferogram. The interference observed between two waves, $A_1(r) = a_1(r)e^{i\phi_1(r)}$ and $A_2(r) = a_2(r)e^{i\phi_2(r)}$, in the x, y plane is given by

$$I(r) = \alpha(r) + \gamma(r) + \gamma^*(r), \quad (1)$$

where $\alpha(r) = a_1^2(r) + a_2^2(r)$, $\gamma(r) = a_1(r)a_2(r)e^{i\delta\phi(r)}$, and $\delta\phi(r) = \phi_1(r) - \phi_2(r)$. Taking the Fourier transform of $I(r)$ gives

$$\tilde{I}(k) = \mathscr{F}\{I(r)\} = \tilde{\alpha}(k) + \tilde{\gamma}(k) + (\tilde{\gamma}(-k))^*, \quad (2)$$

where tilde denotes Fourier transform. Adding a spatial carrier frequency, achieved by introducing a wavefront tilt to the object beam, separates the three terms in the Fourier domain. By retaining only the $\tilde{\gamma}(k)$ term the phase $\delta\phi(r)$ can be recovered by

$$\delta\phi(r) = \arg[\mathscr{F}^{-1}\{\tilde{\gamma}(k)\}], \quad (3)$$

where $\mathscr{F}^{-1}\{\cdots\}$ denotes the inverse Fourier transform. This was achieved using discrete Fourier transforms (DFT). A consequence of using the DFT on a non-periodic fringe pattern is the leakage of frequencies in the Fourier domain, and edge effects that result in a high frequency ringing in the reconstructed data [15]. To avoid this the interference patterns were extended to produce periodic fringes using the iterative Gerchberg–Saxton extrapolation algorithm [16,17]. The constraint placed on the Fourier domain was to retain the d.c. and a.c. lobes with everything else set to zero. In the object plane the original values were put back inside the extended interferogram. It was found that 50 iterations were adequate to produce extended, periodic interference patterns.

The relatively large computational requirement of this Fourier transform phase retrieval approach makes it less suitable for a high-speed system: a less computationally intensive technique such as phase stepping would be more appropriate in that case. Nevertheless the FT method of phase retrieval provides a useful simple means of investigating the behaviour of the PDI.

2.2. The experimental AO set-up

The experimental layout of the closed-loop system is shown in Fig. 2. Optical aberrations are generated using a 256×256 pixel spatial light modulator as a first-order diffractive element [18,19]. The technique uses Lee encoded binary holograms that are capable of producing waves with both amplitude and phase fluctuations [20]. A drawback of the Lee encoding is the limited dynamic range of the generated wave's intensity, which is controlled by the hologram's fringe width. Through simulations using a Fourier reconstruction of the generated holograms it was found that encoding errors resulted in an average noise to signal ratio of 0.04, and a RMS phase error of 0.1 for waves with scintillation strengths characterized by the Rytov number $\sigma_R^2 = 3.3$, and an aperture size $D = 4\sqrt{\lambda L}$, where L is the propagation distance, and λ is the wavelength. The noise in this case is the component of the generated wave that is orthogonal to the original wave.

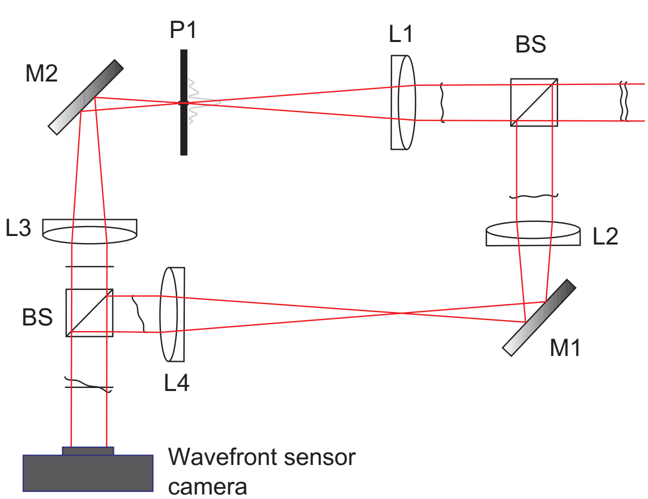

Fig. 1. Diagram of a Mach-Zehnder PDI. Key: BS, non-polarizing beam-splitters; L1–4, lenses; P1, pinhole; and M1–2, mirrors.