A Proposal for Astronomical Adaptive Optics by Incoherent Digital Holography

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Abstract: A new type of adaptive optics system is proposed for astronomical imaging. It replaces the wavefront sensing and modulation hardware pieces of conventional adaptive optics with numerical processing capabilities of digital holography of incoherent sources.
OCIS codes: (010.1080) Active or adaptive optics; (090.1000) Aberration compensation; (090.1995) Digital holography; (110.0115) Imaging through turbulent media; (110.1085) Adaptive imaging; (350.1270) Astronomy and astrophysics

1. Introduction

Concepts of sensing the wavefront and adjusting the optical system to compensate for the distortion have been put forward at least several decades ago, in the context of military as well as astronomical applications [1-3]. A common method of wavefront sensing is the Shack-Hartmann sensor that consists of a lenslet array at a conjugate plane of the telescope aperture together with a CCD camera underneath it. Distortions of the wavefront lead to lateral shift of focal spots of the lenslets, representing the local slope of the wavefront, which is used to compute the wavefront profile. For wavefront compensation, various deformable mirrors, micro-mirror arrays, or liquid crystal-based spatial light modulators (SLM) may be used. Diffraction-limited image of a point source has the angular width of the PSF $\sim \lambda/D$, where D is the aperture of the telescope, but the turbulence degrades the resolution to $\sim \lambda/r_0$, where the Fried's parameter r_0 is the coherence length of the atmosphere. When $r_0 \ll D$, the system is said to be seeing-limited. The number of sensor subapertures limits the spatial bandwidth of measurable aberration, while the number and types of actuators in the modulator limit the accuracy and bandwidth of corrections. Accurate registration of the sensor and modulator is also a significant issue, as well as improvements in the speed and accuracy of computation and optomechanical feedback.

We propose to develop a new AO system that dispenses with the wavefront sensor and corrector [4]. The new system, named digital holographic adaptive optics (DHAO), is based on two of important capabilities of digital holography that are not available in conventional analog holography: direct numerical access to and manipulation of wavefront and the availability of efficient techniques for holography of incoherent sources. Digital holography is ideally suited for accurate and efficient determination of the wavefront profile as well as direct numerical manipulation of the wavefront profile [5, 6]. The wavefront sensing is achieved by analyzing the phase profile of the complex field amplitude of the holographic image of a guide star. The measured phase distortion can then be numerically subtracted from the holographic image of the wide-field exposure, thus removing the effect of aberration. The principle of aberration compensation is a well-known characteristics of holography, as clearly demonstrated by Leith and Upatnieks in 1966 [7]. Numerical processing of the complex wavefronts measured by digital holography offers a new level of flexibility and versatility in sensing and control of aberration [8, 9].

Almost all objects of telescopic observations, such as stars and planets, are incoherent sources. A number of techniques have been put forward for holography of incoherent sources since early years of conventional holography [10-12]. But the main difficulty is that although it is possible to generate self-interference of elementary objects, such as point sources, as soon as the number of point sources increase beyond a few, or for objects of extended surfaces, the intensity of interference patterns add incoherently, rapidly washing out the fringes. On the other hand, in DH it is possible to extract the complex amplitude from the interference pattern of each point source. The complex amplitudes then add coherently among all the point sources. A recent example is the Fresnel incoherent correlation holography (FINCH), where two copies of the object wave are superposed with an extra phase curvature introduced on one of them, so that every point source on the object produces Fresnel zone interference pattern [13, 14]. The complex field amplitude can be extracted by quadrature shifting of the relative phase between the two copies. FINCH has been demonstrated to be capable of generating holograms of objects illuminated with arc lamps or holograms of fluorescence with good sensitivity.

2. Principles of DHAO by IDH

Figure 1a) illustrates a self-referenced interferometer used in the experiment. It is a modification of the FINCH interferometer, where the pixel-sharing SLM (spatial light modulator) is replaced with a modified Michelson interferometer. The object field consists of a set of point sources, e.g. LEDs, incoherernt with respect to each other. The collimated light from each point source illuminates the interferometer. The beam-splitter BS generates two copies of the input field. One is reflected to a plane mirror M1 and the other transmitted to a long-focus curved mirror M2. The two parts arrive at the CCD camera. Because a light field is always coherent with respect to a copy of itself, they interfere and form Fresnel zone-like interference. The piezo-mounted mirror M1 is used for phase-shifting digital holography (PSDH) procedure [15], in order to extract the phase and the complex field at the CCD plane, which can be expressed as, referring to Fig.1b) that depicts the essential geometry of the optical system,

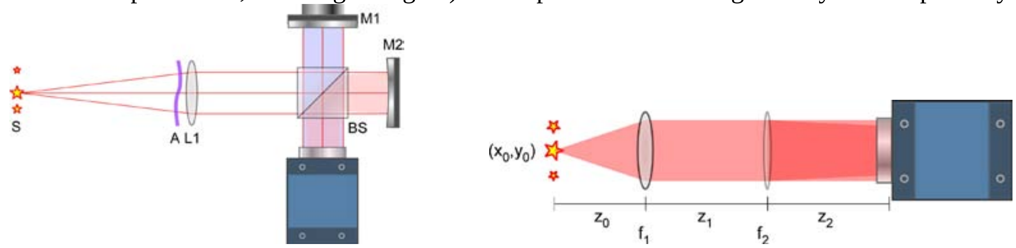

Fig. 1: a) Interferometer for incoherent digital holography; b) geometry of the optical configuration.

$$I_H(x)=\int dx_0 I_H(x;x_0)=\left[I_0\left(\frac{z_0}{z_2}x_0'\right)\odot I_H(x_0';0)\right](x), \tag{1}$$

with the intensity contribution from a single point source

$$I_H(x;x_0)=I_0(x_0)\left\{\left[\Psi P_{\frac{x_0}{z_0}}\right]\odot Q_{z_2}(x)\right\}\cdot\left\{\left[\Psi P_{\frac{x_0}{z_0}}Q_{-f_2}\right]\odot Q_{z_2}(x)\right\}^{*}. \tag{2}$$

Here $I_0(x_0)$ is the source intensity distribution, $Q_z(x)\equiv\exp\left[\frac{ik}{2z}x^2\right]$ is quadratic phase factor, $P_\alpha(x)\equiv\exp[ik\alpha x]$ is a plane wave, and the phase aberration is represented with Ψ. The symbol $\odot$ represents convolution. For simplicity, we abbreviate all (x,y) expressions with (x), as well as setting $z_1=0$. In the absence of aberration, $\Psi=1$, and the (1) becomes

$$I_H^{(0)}(x)=\int dx_0 I_H^{(0)}\left(x-\frac{z_2}{z_0}x_0;0\right)=\left[I_0\left(\frac{z_0}{z_2}x_0'\right)\odot Q_{-(z_2-f_2)}\right](x) \tag{3}$$

with the effective PSF of

$$I_H^{(0)}(x;0)=I_0\exp\left[-\frac{ik}{2}\frac{x^2}{z_2-f_2}\right]. \tag{4}$$

The intensity distribution can be reconstructed in a manner identical to electric field reconstruction in ‘conventional’ digital holography using coherent source. This is experimentally demonstrated in Fig. 2. Two incoherent point sources reconstruct at correct distances and the phase of the complex hologram shows coherent superposition of the two point sources.

a) b) c) d) e)

Fig. 2: Digital holography experiment using two LEDs: a) phase of complex hologram extracted by PSDH; b) and c) numerical reconstruction of the two LEDs separated by 12 cm of z-distance; d) raw intensity profile from the interferometer at CCD plane; e) phase of corresponding complex hologram.

In the presence of the aberration, the effective PDF is

$$I_H(x;0)=I_0\left[\left\{\Psi\odot Q_{z_2}\right\}\cdot\left\{\left[\Psi Q_{-f_2}\right]\odot Q_{z_2}\right\}^{*}\right](x) \tag{5}$$

The hologram represented by (1) can be deconvolved if the inverse of (5) is its complex conjugate, which we assume to be approximately true.

$$I_H\left(x;0\right)\odot I_H^*\left(x;0\right)\approx\delta\left(x\right) \tag{6}$$

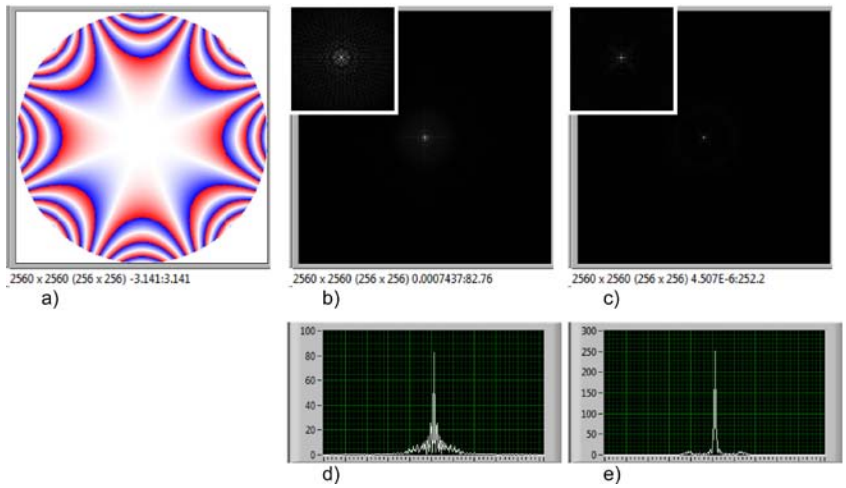

Fig. 3: Numerical simulation of aberration compensation: a) aberration profile of a Zernike polynomial Z_4^4; b) numerical direct focusing of the aberrated field; c) aberration compensation by deconvolution with Eq. (5). Insets show 2x magnified views of the central spot. Graphs d) and e) show cross-sections through the central spot.

The ability to compensate phase aberration by deconvolution is verified by numerical simulation in Fig. 3. Experimental demonstration, including multiple point sources, will be presented.

3. Conclusions

The digital holographic adaptive optics (DHAO) substantially reduces complexity, and very likely the cost, of the optomechanical system. Wavefront sensing and correction by DHAO have almost the full resolution of the CCD camera. It does not involve electronic-numerical-mechanical feedback. Numerical computation of holographic images is faster than the conventional AO feedback loop. Dynamic range of deformation measurement is essentially unlimited – large deformations only result in the wrapping of the phase profile.

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