Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
June 2016, 23(3): 94–100
www.sciencedirect.com/science/journal/10058885
The Journal of China Universities of Posts and Telecommunications
http://jcupt.bupt.edu.cn

Performance measurement of adaptive optics system based on Strehl ratio

Wang Liang[1,2], Chen Tao[1], Lin Xudong[1], Wei Peifeng[1,2], Liu Xinyue[1] (✉), Jia Jianlu[1]

1. Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
2. University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

In this article, a method for measuring the performance of adaptive optics (AO) systems is designed and validated by experiments. The Strehl ratio (SR) which is based on the target images is used to evaluate the performance quantitatively because it relates to the effect of AO correction directly. In the calculation of the SR, to avoid energy scaling in the diffraction-limited point spread function, an algorithm based on the integral of the optical transfer function (OTF) is proposed. Then, a 97-element AO system is established to validate this method, and a white-light fiber source is used as a point-like target. To simulate the practical conditions which influence the performance of the AO system, targets of different brightness are simulated in terms of different signal-to-noise ratios (SNRs) of the Shack-Hartmann (SH), and atmospheric turbulence is simulated in terms of the Fried's coherence length and the Greenwood's frequency. Finally, two experiments are conducted in which the SR of different simulated conditions are measured. The results of the experiments show that for a moderate SNR of SH the experimenting AO system is capable of closed-loop wavefront correction when the Fried's coherence length is larger than 5cm and the Greenwood's frequency is lower than 60 Hz. The results also show that the performance of AO is susceptible to the SNR of SH. The experiments validates the effectiveness of this method.

Keywords adaptive optics , performance measurement, Strehl ratio, turbulence simulator

1 Introduction

Recently, AO receives increasing attentions, not only owing to its traditional applications in the fields of astronomy and military equipments [1], but also owing to its fresh applications in laser communication [2], ophthalmology [3] and high-resolution microscopy [4]. Typically, an AO system is composed of a wavefront sensor (WFS), a wavefront corrector (WFC) and a control system [5]. When AO is working, the WFS measures the wavefront distortion in real time and the WFC counteracts this distortion accordingly. And then, the resolution of target images are improved after the AO correction. The most common-used WFS is SH and the common WFC includes deformable mirror (DM) [6] and liquid-crystal corrector [7–8].

Received date: 10-12-2015
Corresponding author: Liu Xinyue, E-mail: sirliuxy@hotmail.com
DOI: 10.1016/S1005-8885(16)60038-9

The motivation of this article is the requirement of developing a method for assessing the performance of an experimental AO system. Through this method, the factors which affect the performance of AO system, such as the control strategies and calibration strategies can be researched. Also using this method, the wavefront processor (WFP) [9], an embedded system which can accelerate the process of wavefront control, can be tested.

The performance measurement of an AO system can be conducted on the telescope in which the AO system is integrated. Then the performance can be measured in terms of the residual wavefront aberrations, when the AO system is correcting the wavefront which originates from a star and is distorted by the real atmospheric turbulence. Similar measurements have been carried out by Liu et al who measure the performance of an AO system for free-space coherent laser communication [10], by Roberts et al who characterize the AO system of the advanced electro-optical system (AEOS) telescope [11], and by Dam et al who characterize the AO system of the W. M. Keck Observatory [12]. However, this configuration is only suitable for a finishing AO system and is not appropriate for a laboratorial AO system which is being optimized. In this paper, the performance measurement will be implemented on an optical bench where an atmospheric turbulence simulator is configured.

For the purpose of performance measurement, an evaluation index is required to measure the system performance quantitatively in different testing environments simulated in the laboratory. SR is a common-used metric for the performance measurement of AO systems [13–14]. In Ref. [11], Robert et al characterized the AEOS AO system using the SR which is calculated from the images of stars. SR outperforms other evaluation indices based on SH such as root of mean square (RMS) of residual aberrations because SR can be measured based on the AO-corrected target images directly. Also, SR may directly relate to certain system parameters for some applications of AO. For example, when AO is applied to compensate aberrations in the free space optical communications, SR can be used to approximate fiber-coupling efficiency [15–17]. Although SR has been used to estimate the correction accuracy of AO system [18–19], essentially, the calculation of SR is based on SH in these papers, because it is calculated by residual aberrations measured by SH. As a result, SR calculated by this method are susceptible to non-common path aberrations between SH and imaging camera [5,20]; also, it can be influenced by truncation error caused by finite Zernike polynomials which is use to fit residual aberrations measured by SH. Therefore, SR is calculated according to the AO-corrected target images. For the calculation of the SR, to avoid energy scaling in the diffraction-limited point spread function, an algorithm based on the integral of the OTF is proposed.

The rest of this article is organized as follows. A method for calculating SR based on target images is developed in Sect. 2. The experiment system for AO performance measurement is established in Sect. 3. The method of simulating practical environments are introduced and how to measure testing parameters are discussed in Sect. 4. The experiment results of performance measurement are shown and discussed in Sect. 5. Sect. 6 summarizes this article.

2 Method for calculating SR

The SR R_{SR} of an optics system is defined as the ratio of the peak intensity of a measured point spread function (PSF) to the peak intensity of a diffraction-limited PSF [13],

$$R_{\mathrm{SR}} = \frac{\max\limits_{\boldsymbol{x}}\left\{I_{\mathrm{m}}\left(\boldsymbol{x}\right)\right\}}{\max\limits_{\boldsymbol{x}}\left\{I_{\mathrm{dl}}\left(\boldsymbol{x}\right)\right\}} \tag{1}$$

where the vector $\boldsymbol{x}$ denotes coordinates in the imaging plane, $I_{\mathrm{m}}\left(\boldsymbol{x}\right)$ denotes the measured PSF and $I_{\mathrm{dl}}\left(\boldsymbol{x}\right)$ denotes the diffraction-limit PSF. The measured PSF can be obtained from the imaging camera when a white-light fiber source is adopted as a point source. The diffraction-limit PSF can be obtained by using an Inverse Fourier transform of an aberration-free generalized pupil function $P\left(\boldsymbol{u}\right)$ [21],

$$I_{\mathrm{dl}}\left(\boldsymbol{x}\right) = \left|\mathcal{F}^{-1}\left\{P\left(\boldsymbol{u}\right)\right\}\right|^2 \tag{2}$$

where the vector $\boldsymbol{u}$ denotes coordinates in the pupil plane, and the functor $\mathcal{F}^{-1}$ refers to the inverse Fourier transform. The function $P\left(\boldsymbol{u}\right)$ is a binary mask which is defined as follows [21],

$$P\left(\boldsymbol{u}\right) = \begin{cases} 1; & \left\|\boldsymbol{u}\right\|_2 \leqslant r_{\mathrm{p}} \\ 0; & \left\|\boldsymbol{u}\right\|_2 > r_{\mathrm{p}} \end{cases} \tag{3}$$

where r_{p} denotes the radius of the pupil. Easy to find from Eqs. (2), (3) that an energy mismatch exists between the measured PSF and the diffraction-limit PSF, therefore, the latter should be scaled to match the former's energy. Lewis et al. proposed an equation for calculating SR in spatial frequency domain in Ref. [13],

$$R_{\mathrm{SR}} = \frac{\int_{\left\|\boldsymbol{f}\right\|_2 \leqslant f_{\mathrm{c}}} \mathcal{H}_{\mathrm{m}}\left(\boldsymbol{f}\right)\mathrm{d}\boldsymbol{f}}{\int_{\left\|\boldsymbol{f}\right\|_2 \leqslant f_{\mathrm{c}}} \mathcal{H}_{\mathrm{dl}}\left(\boldsymbol{f}\right)\mathrm{d}\boldsymbol{f}} \tag{4}$$

where the vector $\boldsymbol{f}$ denotes coordinates in spatial frequency domain, f_{c} denotes the cut-off frequency of the optical system, $\mathcal{H}_{\mathrm{m}}\left(\boldsymbol{f}\right)$ and $\mathcal{H}_{\mathrm{dl}}\left(\boldsymbol{f}\right)$ denote the OTF of AO-corrected system and diffraction- limit system, respectively, which are defined as follows

$$\mathcal{H}_{\mathrm{m}}\left(\boldsymbol{f}\right) = \frac{\mathcal{F}\left\{I_{\mathrm{m}}\left(\boldsymbol{x}\right)\right\}}{\int I_{\mathrm{m}}\left(\boldsymbol{x}\right)\mathrm{d}\boldsymbol{x}} \tag{5}$$

$$\mathcal{H}_{\mathrm{dl}}\left(\boldsymbol{f}\right) = \frac{\mathcal{F}\left\{I_{\mathrm{dl}}\left(\boldsymbol{x}\right)\right\}}{\int I_{\mathrm{dl}}\left(\boldsymbol{x}\right)\mathrm{d}\boldsymbol{x}} \tag{6}$$

where the functor $\mathcal{F}$ refers to the Fourier transform. Seen from Eqs. (5), (6), energy normalization is done when calculating the OTF; therefore, the energy match is