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Phase diversity for calibrating noncommon path aberrations of adaptive optics system under nonideal measurement environment

Xinxue Ma[a], Jianli Wang[a], Bin Wang[a,*], Hongzhuang Li[a]

[a] Laboratory of Optoelectronic Detection, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

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ABSTRACT

When the defocus cannot be measured and the wavefront solution set is restricted by a multi-channel, some practical problems exist in the calibration of the noncommon path aberrations of the adaptive optics system. To solve these problems, an evaluation function of phase diversity algorithm is constructed in this paper. We use the method that the estimated aberration and the modulated deformable mirror iterate each other to make up the nonideal measurement environment. Then the ill-pose problem of the solution by phase diversity, produced as relaxing constraints of the diversity defocus on the wavefront solution set, is solved. We have adopted the proposed method to measure the noncommon path aberrations of the adaptive optics system on a 1.23 m telescope. Experimental results demonstrate that wavefront solution is more accurate and the whole imaging quality is improved effectively by using the deformable mirror to compensate the aberration measured.

1. Introduction

In the optical system, one optical path is divided into two beams: one estimates the system wavefront phase, the other gets into the terminal imaging camera. To ensure the exact match between the wavefront correction effects and the camera imaging results, the wavefront phase difference between the two beams from the optical path should be minimized. For the optical path adjustment (components, processing, etc.), there are noncommon path aberrations between the two beams, which affects the correction effect. If the noncommon path aberrations are measured accurately and the deformation mirror as the initial surface shape is added, it will improve the correction effect and system imaging quality significantly. However, the measurement of the noncommon path aberrations is under the precondition of the maintenance of the optical system path, and the traditional testing equipment cannot be used.

The phase diversity (PD) technique, proposed by Gonsalves, extracts phase information from focused and defocused images and recovers the object with known defocus [1]. The PD technique not only simplifies the optical path of wavefront and complexity, but also estimates the extended object and gets rid of the dependence on the point object for the majority of wavefront sensors [2]. The PD theory had been further perfected by Paxman et al. [3–5], and the mathematical model of the multi-frame PD under Gaussian noise and Poisson noise was given, where the estimated precision of PD with noise is improved greatly. Vogel et al. proposed the fast numerical solution using the theories of inverse problem [6,7]. Löfdahl et al. had applied the phase-diverse speckle (PDS) theory to the field of solar observation successfully, and high imaging resolution is obtained for the solar surface structure [8,9].

In the field of optical estimation, PD is used to estimate the aberration, alignment errors, mirror flatness etc. Bolcar introduced PD theory into the estimation of synthetic aperture and segmented mirror [10,11]. Löfdahl et al. applied phase-diverse phase retrieval (PDPR) to calibrate the noncommon path aberrations of the AO system on KECK telescope. Mugnier and Blanc et al. proposed the edge of estimation PD theory, applied PD technology to the imaging restoration of French NAOS-CONICA astronomical telescope and calibrated the static aberration of AO system [12–14].

In this paper, we designed a system to calibrate the noncommon path aberrations of a 137 unit AO system on a 1.23 m telescope when the defocus cannot be measured. We constructed an evaluation function of phase diversity (PD), restricted the wavefront

* Corresponding author.
E-mail address: eatingbeen@hotmail.com (B. Wang).

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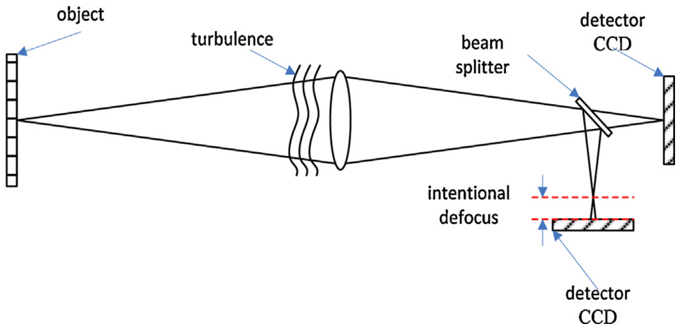

Fig. 1. Scheme of data-collection image by PD.

solution set by a multi-channel, and used the method to iterate the estimated aberration and the modulated deformable mirror with each other to make up the nonideal measurement conditions, we got more accurate wavefront solution by PD where the constraints of diversity defocus on the wavefront solution set relaxed. We enhanced the telescope imaging quality effectively by using the initial bias of the deformable mirror to compensate the aberration measured.

The remainder of this paper is organized as follows: Section 2 describes the basic theory of PD and the definition of variable; Section 3 describes the overall experiment; Section 4 gives the experimental results and discussion; the conclusion is given in Section 5.

2. Theory

As the point-spread function (PSF) can be mapped to multiple wavefronts, the wavefront solution from a single image are ill-posed.

Comparing to a single channel which takes the wavefront as unknown to resolve the blind deconvolution, PD uses PSFs of images collected by two channels to restrict the wavefront, where a fixed amount of defocus are known. Therefore, the ill-pose problem [15–20] is reduced in the wavefront solution.

The optical path of the PD system, with focus and defocus collection channels, is illustrated in Fig. 1. Based on the engineering necessity, the numbers of collection channels can be increased. The problem of PD imaging restoration can be regarded as the inverse problem of seeking the original signal phase [21,22] through the known analog of the interference signal or an adaptive filter.

2.1. Imaging system model

The atmosphere and telescope can be approximately regarded as a linear space-invariant system. In the non-coherent light illumination, the imaging function with Gaussian noise is defined as [1]

$$d(x) = f(x) * s(x) + n(x), \tag{1}$$

where d is the real estimated image; f is the ideal object image; s is the PSF; n is the Gaussian noise; x is the coordinates of image plane; and* denotes a convolution. The intensity PSF is defined as [1]

$$s(x) = \left| \mathscr{F}^{-1}\left\{ P(\upsilon) e^{i\phi(\upsilon)} \right\} \right|^2, \tag{2}$$

where $\mathscr{F}^{-1}$ is the inverse Fourier transform operator; υ is the complex plane coordinate; P is the pupil function; and φ is the wavefront phase, which can be decomposed into a set of Zernike polynomials:

$$\phi(\upsilon) = \theta(\upsilon) + \sum_{m=1}^{M} \alpha_m Z_m(\upsilon), \tag{3}$$

where α_m is the mth coefficient of polynomials; Z_m is the mth basis Zernike polynomial; and θ is the known fixed-defocus phase.

2.2. Evaluation function

The mathematical model of PD can be understood as an adaptive filter. In the Gaussian noise model, the mean square deviation of the object and multi-channel images can be used as likelihood function. In frequency domain, the evaluation function of the multi-channel PD mentioned is defined as

$$L(f, \alpha) = \frac{1}{2N} \sum_{u} \left(\sum_{c=1}^{C} \sigma_c^{-2} \left| D_c(u) - FS_c(u) \right|^2 + \gamma \left| F(u) \right|^2 \right), \tag{4}$$

where u is spatial-frequency domain coordinate; C is the number of channels; N is the total number of pixels of a single image; α and f are the unknown phase and object parameters, respectively; D_c, F, and S_c are the Fourier transformation of d_c, f and s_c, respectively; The second term in the right pair of brackets is the Tikhonov regularization term, used to improve the numerical stability and speedup the convergence of the algorithm [6,7]; γ is the regular coefficient, which is non-negative; and σ_c^{-2} (σ is non-negative) is the reciprocal of the noise variance in channel c.

The stationary point F expressed in Eq. (5) can be obtained by setting the derivative Eq. (4) to F to be 0. Eq. (6) is obtained by substituting Eq. (5) into Eq. (4). Thus, we can use the target state estimator as an independent intermediate process separated from the phase estimator, and then get an evaluation function which is independent of the object [4]. The expression of the target state estimator is the intermediate process of deriving the evaluation function. It has the same form as the wiener filter and reduces the influence of noise effectively.

$$F = \frac{\sum_{c=1}^{C} \sigma_c^{-2} D_c S_c^*}{\gamma + \sum_{c=1}^{C} \sigma_c^{-2} \left| S_c \right|^2}, \tag{5}$$

$$L(\alpha) = \frac{1}{2N} \sum_{u} \left(\sum_{c=1}^{C} \sigma_c^{-2} \left| D_c \right|^2 - \frac{\left| \sum_{c=1}^{C} \sigma_c^{-2} D_c S_c^* \right|^2}{\gamma + \sum_{c=1}^{C} \sigma_c^{-2} \left| S_c \right|^2} \right). \tag{6}$$

Eq. (6) is the evaluation function, when the readout noise is inconsistent among the multi-channel. The multi-channel is realized by collecting images at focus plane; and some defocus is known through changing the position of imaging camera by the focusing motor. So σ_c^{-2} has the same value in all channels. The value of σ_c^{-2} can be obtained from collecting the background noise of the camera when the photon noise is ignored.

After the determination of the evaluation function, the process of the wavefront estimation and image restoration can be described as a mathematical optimization problem, which is, a large scale optimization problem. In this paper, we solve the optimization problem by using the quasi-Newtonian method, where the inverse Hessian approximation is used to mimic the property of the true inverse Hessian matrix. And the inverse Hessian approximation is updated using the L-BFGS-B formula [23–28].

3. Experiment

In this section we discuss the relevant details of the experiment. Section 3.1 describes the system components; Section 3.2 describes the experimental procedure; Section 3.3 gives the analysis and solution of the main problems.