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Signal to noise ratio of free space homodyne coherent optical communication after adaptive optics compensation

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ABSTRACT

Designing and evaluating the adaptive optics system for coherent optical communication link through atmosphere requires to distinguish the effects of the residual wavefront and disturbed amplitude to the signal to noise ratio. Based on the new definition of coherent efficiency, a formula of signal to noise ratio for describing the performance of coherent optical communication link after wavefront compensation is derived in the form of amplitude non-uniformity and wavefront error separated. A beam quality metric is deduced mathematically to evaluate the effect of disturbed amplitude to the signal to noise ratio. Experimental results show that the amplitude fluctuation on the receiver aperture may reduce the signal to noise ratio about 24% on average when Fried coherent length $r_0 = 16$ cm.

1. Introduction

Free space coherent optical communication is nowadays one of the most attractive ways to transfer high speed data signals from long range for its advantages of high sensitivity, low energy consuming and even sunlight immunity, but challenges still exist in the coherent optical communication link when the information-bearing laser signal needs to transmit through the turbulent atmosphere. The effects of laser beam propagation through turbulent atmosphere such as wave-front distortion, scintillation, beam wandering and spreading will not only degrade the entrance efficiency of telescopes but also cause the mismatch of the field of signal beam and local oscillator. For an optical communication system, the signal to noise ratio (SNR) is an important measure of its performance, which relates to the energy budget, the capacity and the bit error rate etc. It has been pointed out that the SNR of a coherent detecting system is sensitive to the turbulence induced wave-front distortions especially when the aperture of receiving terminal is larger than the Fried parameter r_0. Then, an adaptive optics (AO) system will be required to compensate the wave-front aberrations, and eventually to maintain the SNR of the coherent receiver, and the validity and improvement of an AO system on the coherent receiver has been demonstrated numerically and experimentally by many researchers [1–4].

In this article, the theory of combined effects of signal beam's amplitude fluctuation and residual wave-front error on the SNR of coherent receiver is developed with the assumption that an AO setup is used to compensate the wave-front distortions. The mechanism of AO system determines that though most of the wave-front distortions can be compensated, the amplitude field of the signal laser beam is relatively independent and can hardly be improved, so the effects of AO compensation to SNR should be distinguished clearly from the effect of disturbed amplitude for designing and evaluation the AO system specified for coherent optical communication link. The research attempts to derive an analytical expression for the estimation of to how extent an AO system can satisfy the SNR requirement of a homodyne coherent optical communication link. The derivation is based on the previous work of Fried and Winick [5,6] and the mismatches of signal beam's amplitude and residual wavefront error to local oscillator are emphasized simultaneously to estimate the SNR.

2. The expression of SNR

Based on the theory of coherent optical communication, the mean optical power of information-bearing signal for one bit in a homodyne coherent communication link received by the

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demodulator after AO compensation can be written as

$$P_r = \left(\frac{eQ_e}{h\nu}\right)^2 G^2 R \left| \iint A_s(\mathbf{r}) A_l(\mathbf{r}) \cos[\varphi(\mathbf{r})] d\mathbf{r} \right|^2 \tag{1}$$

where e is the electron charge, Q_e is the quantum efficiency of photodetector, h is Planck constant, ν is the frequency of signal beam, G is the gain of current amplifier, R is the load resistance, $\mathbf{r}$ is coordinate, $A_s(\mathbf{r})$ is the amplitude of received signal beam, $A_l(\mathbf{r})$ is the amplitude of LO beam and $\varphi(\mathbf{r})$ is the phase difference between signal beam and LO beam, which also represents the residual wavefront error of AO after wavefront compensation. Here the signal beam and LO beam are supposed to be collimated at the same size before mixing, and the integral is calculated at the entrance pupil of the focal lens before photodetector for optical heterodyne mixing efficiency invariance [7].

Generally, for a given communication system, the parameters outside the integrator and the amplitude of LO beam in Eq. (1) are constants. That means the variation of signal power is dominated by the randomness of signal beam's amplitude distribution and the residual wavefront errors after AO compensation. To distinguish the effects of amplitude and wavefront error on the information-bearing signal power, we define a new variable named coherent efficiency η differentiated from mixing efficiency and heterodyne efficiency

$$\eta = \frac{\left| \iint A_s(\mathbf{r}) A_l(\mathbf{r}) \cos[\varphi(\mathbf{r})] ds \right|^2}{\left| \iint A_s(\mathbf{r}) A_l(\mathbf{r}) ds \right|^2} \tag{2}$$

Eq. (2) means the ratio of signal power with residual wavefront error $\varphi(\mathbf{r})$ over that of the wavefront aberration been completely compensated. Comparing to the previous literatures, where the mixing efficiency is usually defined as [4,8]

$$\eta_{mix} = \frac{\left| \iint A_s(\mathbf{r}) A_l(\mathbf{r}) \cos[\varphi(\mathbf{r})] ds \right|^2}{\iint |A_s(\mathbf{r})|^2 ds \bullet \iint |A_l(\mathbf{r})|^2 ds} \tag{3}$$

In the definition of coherent efficiency, the denominator represents the information-bearing signal power when the wavefront aberration is completely compensated while the amplitude may be still disturbed. However, the definition of mixing efficiency can represent the SNR loss due to atmosphere turbulence when only small aperture telescope is applied to collect the signal beam, in which the amplitude of signal beam and LO beam are generally assumed as constants, therefore, the effect of non-uniform amplitude has been ignored in previous works [4,6]. Therefore, Eq. (3) is not precise for calculating the SNR loss of coherent optical communication under AO compensation especially when the non-uniformity of amplitude distribution is considered. The reason is that the denominator in Eq. (3) is not equal to the information-bearing signal power when amplitude distribution on aperture is disturbed.

On the other way, if only the LO beam is assumed to be a plane wave with uniform amplitude distribution, Eq. (2) can be written as

$$\eta = \left| \frac{1}{S} \iint \frac{A_s(\mathbf{r})}{\langle A_s(\mathbf{r}) \rangle} \cos[\varphi(\mathbf{r})] ds \right|^2 \tag{4}$$

where the bracket $<.>$ denotes spatial average, $A_s(\mathbf{r})/<A_s(\mathbf{r})>$ represents the signal beam's amplitude normalized by its mean value on the cross section, S is the area of beam profile. It is inferred from Eq. (4) mathematically that the instantaneous coherent efficiency equals to the square of mean value of the product of normalized amplitude and the cosine residual wavefront error.

According to the principle of an AO system, the signal beam's amplitude is not involved in the close loop to realize the process of wavefront detection and construction, therefore the residual wavefront error of AO system is mostly unrelated with the amplitude distribution on beam profile, and approximately we could have

$$\langle A_s(\mathbf{r}) \cos[\varphi(\mathbf{r})] / \langle A_s(\mathbf{r}) \rangle \rangle = \langle A_s(\mathbf{r}) / \langle A_s(\mathbf{r}) \rangle \rangle \langle \cos[\varphi(\mathbf{r})] \rangle \tag{5}$$

A simulating experiment has been conducted to examine the independence between the amplitude and the residual wavefront error. Here the amplitude of a coherent laser disturbed by atmospheric turbulence was measured on a 4.8 km slope optical path from the height of 50 m to that of 12 m. A solid laser works at the wavelength of 671 nm was used as the light source, whose root mean square (RMS) power is less than 1% in four hours. The divergence of laser beam is about 1.5 mrad. Through long distance propagation, part of the far-field intensity illuminates on a 1 m square diffuse white board, and the intensity picture was taken by a camera runs at 16 bits on the frame frequency of 1107 Hz. The data was measured at peaceful night, when the Fried coherent length monitored by the scintillometer is about 16 cm. A typical intensity profile of the laser beam disturbed by atmospheric turbulence on the board is shown in Fig. 1a. It looks more seriously than what can be seen by eyes for the reason of high frequency. The amplitude of laser beam can be obtained by the

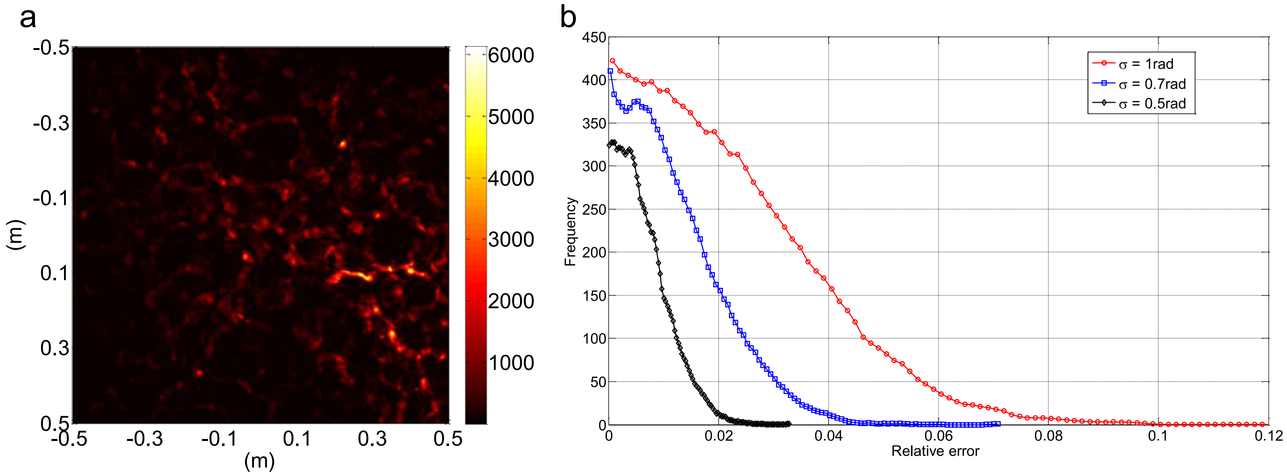

Fig. 1. Comparison of $<A_s(\mathbf{r})\cos[\varphi(\mathbf{r})]>/<A_s(\mathbf{r})>$ and $<\cos[\varphi(\mathbf{r})]>$ after AO wavefront compensation. (a)Typical amplitude profile disturbed by turbulence; (b) histograms of the relative error between $<A_s(\mathbf{r})\cos[\varphi(\mathbf{r})]>/<A_s(\mathbf{r})>$ and $<\cos[\varphi(\mathbf{r})]>$.