Research on wavefront-sensing for improving receiver efficiency in turbulence atmosphere

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Abstract. In the air-to-ground optical communication system, not only must we consider the impact of beam pointing, but also the wavefront turbulence the atmosphere brings to the beam cannot be ignored. This paper simply analyses the influence of the atmosphere turbulence on air-to-ground optical communication, and reforms the traditional adaptive optics (AO) system using the famous Zernike phase contrast method, which can make it be applied to the air-to-ground optical communication system to correct the turbulence of the wavefront and improve the receiving efficiency and the system performance. In the end of this paper, the simulation of this method described above to detect phase is presented.

1. Introduction
In air-to-ground optical communication system, the refractive index of the air fluctuates randomly because of some factors such as temperature gradient, which results in the fluctuations of the intensity and phase¹, and increase of the BER (bit error rate). This paper reforms the traditional adaptive optics system, and applies it to FSOC (free space optics communication) to compensate the effect of atmosphere.

2. The application of adaptive optics² in FSOC
For a long time, adaptive optics has been applied to astronomy to overcome the impact of the atmosphere on the wavefront of the star light. Since the impact stays only in the near-field of telescope, the optical amplitude outside the receiver is approximately constant. So what we have to do is to compensate the phase distortion. But in FSOC, the atmospheric effect on optical signal stays in the far field, which will distort not only the phase but the optical amplitude.

The traditional AO system consists 3 main parts: wavefront sensor, wavefront controller, wavefront adjuster, which are corresponding to 3 stages of AO adjustment: wavefront sensing, wavefront reconstructing, and wavefront adjustment.

This AO system can compensate the distortion of the wavefront, but contains some components like wavefront sensor, which makes the system extremely complicated, so it cannot be applied on the satellite whose constructor and weight is strictly limited. On the other hand, this type of AO system cannot respond quickly, and will fail in the circumstance with strong scintillation.

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In order to overcome these disadvantages of traditional AO system, the novel AO system without wavefront sensor comes to existence. This AO system adopts single estimation factor such as Strehl ratio, coupling efficiency, optical intensity etc., as the foundation for optical wave adjustment. It uses complex algorithm to control the wavefront adjuster in the close-loop recursively until the convergence point is reached. The algorithm adopted earlier are mountain-climbing method, multiple high-frequency vibration method, recently some heuristic algorithm like stochastic parallel gradient descent algorithm and simulated annealing is often used.

This type of AO system has lots of advantages such as the simplicity of system construction, the low cost. But the algorithm is complex and the convergence process is long.

This paper integrates both of the systems described above, and brings up a novel idea. First of all, the complex wavefront sensor must be abandoned, but the constitution cannot be as simple as the AO system without wavefront which has so few estimation factors that the algorithm cannot converge as soon as possible. Second a CCD can be used to detect the intensity after the optical transformation to derive the phase distortion information. The specific system block diagram is shown in Fig.3.

In FSOC, of the optical distortion produced by the atmospheric turbulence, the tilt is the most serious aberration, but the deformable mirror deformation is not enough to compensate it, so it is necessary to add the steering mirror tilt to the system to deal with the tilt aberration, while the deformable mirror is to compensate for the higher-order aberrations.

This system has simple structure, and high optical efficiency because of the only one spectral. And we can also use the CCD of air-to-ground optical communication system designed for rough tracking to detect the optical intensity, which utilizes the existing resource and makes the structure simpler.

The key point of this method is to obtain phase information from the CCD, then generate the compensation signal through the algorithm to re-adjust the phase.
3. Improved Zernike phase contrast method

In the theory of physical optics, there is a Zernike phase contrast method that can derive phase information from the light intensity distribution.

The theory of Zernike phase contrast method[7] is shown below.

![Diagram of Zernike phase contrast system](image)

**Figure 4.** the diagram of Zernike phase contrast system

This figure actually shows a so-called 4f system. According to the theory of physical optics[2], the process that light waves spreads from the front focal plane of the lens to the rear focal plane can be seen as a two-dimensional spatial Fourier transform. So the FT(Fourier transform) plane(Zernike phase film) field shows the spatial frequency distribution of the incident wave. The structure of phase filter of the Zernike phase contrast method is very simple. What is needed is just a glass substrate with its central location coated with a membrane of certain thickness which makes the phase of zero-frequency light shift $\pi/2$ or $3\pi/2$ relative to other frequency light.

The transformation function is shown below:

$$H(f_x, f_y) = \begin{cases} \pm j & f_x = f_y = 0 \\ 1 & \text{other} \end{cases}$$

(1)

When this 4f system is illuminated by the coherent plane wave with unit amplitude, the incident wavefront distribution can be described as

$$f(x_1, y_1) = \exp[j\varphi(x_1, y_1)]$$

(2)
Assume the phase-shift is small, that is to say $\phi(x, y) \ll 1 \text{rad}$, and then the equation can be simplified as

$$f(x, y) \approx 1 + j\phi(x, y)$$  \hspace{1cm} (3)

That’s the spatial frequency distribution

$$F(f_x, f_y) = \delta(f_x, f_y) + j\Phi(f_x, f_y)$$  \hspace{1cm} (4)

after the transformation of Zernike phase film, it becomes

$$F(f_x, f_y)H(f_x, f_y) = \pm j\delta(f_x, f_y) + j\Phi(f_x, f_y)$$  \hspace{1cm} (5)

Then the complex amplitude distribution of output plane is

$$g(x_3, y_3) = \pm j + j\phi(x_3, y_3)$$  \hspace{1cm} (6)

and the intensity distribution

$$I(x_3, y_3) \approx 1 \pm 2\phi(x_3, y_3)$$  \hspace{1cm} (7)

The fluctuation appears in the uniform background generated by $\phi$, and their relationship is linear, so it is easy to derive the incident wave distribution form the intensity.

However, there is still a problem remained. The conclusions of Zernike phase contrast method are derived under the assumption that the amplitude of the incident wave is constant. But as described above, in FSOC, the atmospheric effect on optical signal stays in the far field, which will distort not only the phase but also the optical amplitude, so the light intensity of the receiving plane cannot be regarded as a constant parameter.

Supposing the phase and amplitude meet the requirement of weak fluctuation, the incident optical wave can be written as

$$u(x_1, y_1) = [1 + A(x_1, y_1)] \exp[i\phi(x_1, y_1)]$$

In Eq.(8), $A(x_1, y_1)$ denotes the fluctuation of amplitude and $\phi(x_1, y_1)$ the phase.

$$u(x_1, y_1) = 1 + A(x_1, y_1) + j\phi(x_1, y_1) + jA(x_1, y_1)\phi(x_1, y_1)$$

$$\approx 1 + A(x_1, y_1) + j\phi(x_1, y_1)$$  \hspace{1cm} (9)

The spatial frequency is

$$F = \delta(f_x, f_y) + a(f_x, f_y) + j\Phi(f_x, f_y)$$  \hspace{1cm} (10)

The system transforms the zero-frequency light with $\frac{\pi}{2}$ phase-shift. After the Fourier transformation of the second lens, the complex wave becomes

$$u(x_3, y_3) = j + A(x_3, y_3) + j\phi(x_3, y_3)$$  \hspace{1cm} (11)

And the intensity distribution is

$$I(x_3, y_3) = |u(x_3, y_3)|^2 = [1 + \phi(x_3, y_3)]^2 + A^2(x_3, y_3)$$

$$= 1 + 2\phi(x_3, y_3) + \phi^2(x_3, y_3) + A^2(x_3, y_3)$$

$$\approx 1 + 2\phi(x_3, y_3)$$  \hspace{1cm} (12)
the Zernike phase contrast method is still suitable for this case.

4. Numerical simulation

Based on the theory described above, this chapter presents the simulation result of Zernike phase contrast method with weak perturbation.

Fig.(5) and Fig.(6) show the perturbations of phase and amplitude of the incident light field, respectively. The coordinates of all figures are relative values.

And Fig.(7) shows the intensity distribution after the transformation of the Zernike phase contrast method.

As shown in the figures, the output intensity information can accurately reflect the distribution of the incident light field phase, which can be used to adjust the wavefront phase.

![Figure 5](image1.png)

**Figure 5.** the amplitude perturbation of input optical field

![Figure 6](image2.png)

**Figure 6.** the phase perturbation of input optical field
5. Conclusion
This paper combines the characteristics of air-to-ground optical communication to improve the traditional adaptive optics system. In this paper, a phase adjustment device with simple structure is presented which has several advantages. First of all, it gets rid of the complex wave-front sensor, simplifying the system structure, which makes the system easy to install; second, the system utilizes the existing CCD in the ATP system of air-to-ground optical communication to derive the phase information through some algorithm. These features make it easier to be used in the air-to-ground optical communication systems.

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References
[1] Wizen Ke, Xiaoli Xi, The introduction of wireless laser communication, Beijing University of Posts and Telecommunications Press. 2004
[2] Renzhong Zhou, The theory of adaptive optics, Beijing Institute of Technology Press.1996.1~3.
[3] HuiZhen Yang, Xinyang Li, Wenhan Jiang, Applications of Adaptive Optics Technology in Atmospheric Laser Communications System.2007, Vol44, No. 10: 61~68.
[4] Chunyi Chen, Huamin Yang, Huilin Jiang, Xin Feng, Hui Wang, Research Progress of Mitigation Technologies of Turbulence Effects in Atmospheric Optical Communication, Vol.30, No.6, 2009.6.
[5] Huizhen Yang, Xinyang Li, Wenhan Jiang, Comparison of several stochastic parallel optimization control algorithms for adaptive optics system, 2008,Vol.20, No.1: 11~16.
[6] R. El-Agmy, H. Bulte, A. H. Greenaway et al. Adaptive beam profile control using a simulated annealing algorithm.OPTICS EXPRESS, 2005, Vol. 13 Issue 16:6085~6091.
[7] Naiguang Lv, Fourier optics,2006.