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Atmospheric turbulence phase screen modeling method based on sub-bands division and multirate sampling

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ABSTRACT

The phase screen method is a well-established approach to analyze the effects of atmospheric turbulence in free space optical (FSO) communication and astronomical imaging system. Owning to the variation of atmospheric turbulence, low complexity modeling is required. Meanwhile, low frequency power should be compensated to overcome shortcomings of classical methods. The method based on sub-bands division and multirate sampling is proposed to solve these problems, and analytic formulas of the model is derived correspondingly. Simulation results are provided to show that our method overperforms the existing methods when both computational complexity and power compensation are taken into account. Furthermore, the proposed method is flexibly in operating which could be used to simulate the base phase screen of time-varying atmospheric turbulence.

1. Introduction

When the light beam is propagating through atmosphere, its properties of intensity and phase would be easily affected by atmospheric turbulence, thus introducing noises in practical applications, such as FSO communication system and optical imaging system [1,2]. To overcome influences from atmosphere, numbers of experiments have been conducted to analyze light beam's changing process of intensity and phase, based on which several technologies are developed to deal with the problems of intensity attenuation and phase fluctuation [3,4]. Considered the difficulties to carry out a long-distance FSO communication experiment, the most frequently used method is to take experiments in laboratory by simulating atmosphere environment though a gas pool [5]. The newly invented gas polls generally have functions such as temperature control, wind speed control, etc. However, it still has shortages in usage. For example, composition and temperature of a gas pool are not completely in accordance with the real atmosphere environment, and divergences between atmospheric turbulence of different altitudes are difficult to simulate accurately.

Along with the rapid development of digital signal processing technology, numerical simulation techniques are widely used in analysis of light beam's propagation in atmospheric turbulence environment [6]. To simulate phase's changing process in propagation, an accurate phase screen model is crucial [7–9]. There is a series of methods to model a phase screen, mainly including the power spectrum method and Zernike polynomials method. The power spectrum method [10,11] could model phase screens with large size, and it is fast in generation when operated based on iFFT calculation [12]. However, it

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has low accuracy in modeling low frequency part of the atmospheric phase spectrum. The method based on solving Zernike polynomials [13] has good performance in modeling the low frequency part of atmospheric spectrum when computation is enough. However, it could only model the Kolmogorov spectrum, meanwhile, its accuracy degrades when simulating the high frequency part of the phase spectrum. Except for the above two methods, several techniques are put forward to improve practicability of phase screen modeling, such as interpolation method and stochastic realization method. Interpolation method [14,15] could enhance the resolution of simulated atmospheric turbulence phases by interpolating grids to a base phase screen. However, for computing reasons, errors of the phase screen would be accumulated in the interpolation procedure if the base screen is with low accuracy. Stochastic realization method [16,17] is presented based on the stochastic realization theory, which is a kind of fast update mechanism to extend phase screens from a base phase screen in time. To sum up, both the performance of the two modeling techniques depend on the property of base screen, hence phase screen modeling method with high accuracy is indispensable. Besides, low operation complexity is needed when phase screens are modeled to simulate non-stationary turbulence environment, thus it could update phase screens along with the variation of turbulent strengths.

From the analysis above, the power spectrum method is most suitable to model a base phase screen for its wide scope in application and low complexity in calculation. To further improve its accuracy in simulating low spatial-frequency spectrum, a great deal of improvement is made, including the method of subharmonics, large-scale phase screen simulation and the method based on multi-order frequency grids. The method based on subharmonics [18] is operated by directly incorporating low-frequency subharmonics into the modeled phase screen, thus compensating the low-frequency power. However, it may cause discontinuities of phase at the edges of the phase screen. A quite large phase screen [19] could avoid the discontinuity problem, but its computational complexity would be greatly increased. The method based on multi-order frequency grids [20] is a newly proposed method to compensate low-frequency power, which is implemented by multi-order dividing frequency grids in low-frequency domain. However, a large size simulation is still required to solve the discontinuity problem because of its non-uniform property. Additionally, its computational complexity is high due to the great deal of inverse discrete Fourier transform (iDFT) calculations.

So, based on the above analysis, how to achieve a tradeoff between power compensation and computational complexity is still an urgent problem to be solved. Our study will focus on solving the above problem based on several signal processing technologies.

2. Power spectrum method based on iFFT calculation

When the light beam is propagating through atmosphere, its phase's changing process $\varphi(x, y)$ can be regarded as a two-dimensional wide sense stationary stochastic process with zero mean and continuous mean square. The process could be achieved by a 2-Dimensional inverse Fourier transformation (2-D iFT) as [10]

$$\varphi(x, y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Z(f_x, f_y) e^{j2\pi(xf_x+yf_y)} \mathrm{d}f_x \mathrm{d}f_y, \tag{1}$$

where $j = \sqrt{-1}$, (f_x, f_y) are the two rectangular components of the spatial frequency. $Z(f_x, f_y)$ is a random spectrum and calculated as

$$Z(f_x, f_y) = \sqrt{\Phi_\varphi(f_x, f_y)}, \tag{2}$$

where $\Phi_\varphi(f_x, f_y)$ denotes the power spectral density of $\varphi(x, y)$.

The power spectrum method is then operated on basis of Eq. (1). Its basic operating principle is that using power spectrum of atmospheric turbulence to filter a complex Gauss random matrix and then obtaining atmospheric turbulence phases through iDFT calculation. A two-dimensional phase screen is to be designed, with L length and $N \times N$ grids, thus it could depict the spectrum with a spatial frequency range of $[1/L, N/L]$. We choose $N_\mathrm{f} \times N_\mathrm{f}$ frequency points to model a square phase screen. The calculation process is as follows [12]:

$$\varphi(x, y) = \sum_{m=1}^{N_\mathrm{f}}\sum_{n=1}^{N_\mathrm{f}} R_{m,n} Z(f_{xm}, f_{yn}) e^{j2\pi(xf_{xm}+yf_{yn})} \cdot \Delta f_{xm} \Delta f_{yn}, \tag{3}$$

where $R_{m,n}$ are Gauss random numbers with zero mean and unit variance, f_{xm} and f_{yn} are discrete components of the spatial frequency. Aimed at reducing complex calculations in Eq. (3), iFFT calculation is adopted. According to the existing research, iFFT could only be used when frequency points of the modeled phase screen are uniformly sampled as phase grids, namely $N_\mathrm{f} = N$ [21]. Then, the calculation process based on iFFT is as follows:

$$\varphi(x, y) = \sum_{m=1}^{N}\sum_{n=1}^{N} R_{m,n} Z(m\Delta f_0, n\Delta f_0) e^{j2\pi(xm\Delta f+yn\Delta f)} \cdot (\Delta f_0)^2, \tag{4}$$

where $\Delta f_0 = 1/L$. iFFT calculation greatly reduces the computational complexity, while at the same time, it limits the choices of spatial frequency points as it could only uniformly sampling. The deficiency above would directly influence