The Simulating Turbulence Method of Laser Propagation in the Inner Field

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Abstract. The paper describes the simulating turbulence method of laser propagation in the inner field. The atmosphere turbulence is simulated by using one kind of static phase plate. By the phase plate, the various parameters of atmospheric turbulence and the corresponding propagation effects of the laser in the atmosphere turbulence are simulated in certain range. The design principle of the simulating system is proposed in this paper. The expressions of various propagation effects are given in the form of parameters of the system hardware. In the simulating results the turbulence effects can be produced by the device.

1. Introduction
The laser propagation process can be influenced by atmospheric turbulence. The turbulence could bring on the degradation of the laser beam correlation, induce beam shifting and spreading, finally would affect the capability of the laser detector. In order to research the effects of turbulence on laser propagation more effectively, in practice the familiar methods are to adopt a set of simulating setup in the inner field, which can implement a repeatable and controllable test. That could save much research outlay. At present there are many methods to simulate turbulence, such as the forced motion methods of heated air or water [1], spatial light modulators (SLMs), deformable mirrors (DMs), diffractive optical elements (DOEs), computer generated holograms (CGHs) [2-4], and static phase plates [5]. The method using static phase plates to simulate atmospheric turbulence is with independently controllable spatial and temporal characteristics, and compact for the optical setup.

2. Basis of principle [6]
The turbulence model referenced in this thesis is Kolmogorov spectrum [7]. The Kolmogorov theory indicates that, in the case of homogeneous isotropic turbulence field, the index variability can be expressed with a structure function $D_n(r)$

$$D_n(r) = C_n^2(h)r^{2/3} \quad (l \ll r \ll L)$$

Where $C_n^2(h)$ is the average turbulence intensity at an altitude of h. The density function of Kolmogorov turbulence spectrum is

$$\Phi_n(k) = 0.033C_n^2k^{-11/3}$$

Where $k=2\pi/\lambda$. Fried coherence length is the integral effect that atmospheric influences on the laser beam propagation, expressed as
where $\Omega$ is the zenith angular for the observe direction.

Greenwood time constant $\tau_0$ represents the temporal characteristic of atmosphere turbulence. Its meaning is that the turbulence is considered unchangeable in the Greenwood time. Then it could be described with a freeze turbulence model. $\tau_0$ is related to the transverse wind $v(h)$

$$
\tau_0 = \left\{0.423k^2 \sec \Omega \left[\frac{dC_n^2}{dh}\right]\right\}^{-3/5}
$$

For the detector with a diameter $D$, the coherent time is

$$
\tau \approx 0.53(\tau_0 / v)(D/\tau_0)^{1/6}
$$

3. Simulation system

The static phase plate [8] is the main optic component for simulating turbulence in the inner field. A generic plate is manufactured by two optic quality materials (Figure 1) together with some arbitrary surface profile at their interface. The optical path difference (OPD) for laser beam passing through the area of phase aberrations is given by

$$
OPD(x, \lambda) = h(x)[n_1(\lambda) - n_2(\lambda)] = h(x)\Delta n(\lambda)
$$

where $h(x)$ is the surface profile at the interface, $x$ is a 2-dimensional position vector which origin is the axis of incidence, $n_1(\lambda)$ and $n_2(\lambda)$ are the refractive indices of the materials, and $\lambda$ is the laser wavelength. The parameters of the phase plate are: the coherent length $\tau_0$, sample phase points $N$, sampling space $\Delta r$.

![Figure 1. Schematic diagram of a Near-Index-Match phase plate consisting of a sandwich of 2 materials.](image)

![Figure 2. Conceptual diagram of the optical design for the atmospheric turbulence simulator](image)
by adjusting displace of the plate in the optical axle, which results in different beam footprint diameter \(D_p\).

4. Simulating turbulence effect of laser propagation

Some main simulating parameters are listed as following:

(1) For laser wavelength \(\lambda\), the intensity of the simulated turbulence be given by

\[
C_n^2 = 2.36 \left( \frac{\lambda}{2\pi} \right)^2 \left[ \frac{D \cdot r_{op}}{D_p} \right]^{(-5/3)}
\]

(7)

Where \(D\) is the diameter of the telescope, \(r_{op}\) is the coherent length of the phase plate, \(D_p\) is the beam of the plate can be decided by formula (8)

\[
r_{op} = \frac{1}{2.36} \left( \frac{2\pi}{\lambda} \right)^2 \frac{D_p \cdot C_n^{6/5}}{D}
\]

(8)

According to the relation of the sampling space \(\Delta r\), sample phase points \(N\), and the coherent length \(r_{op}\)

\[
r_{op} = N\Delta r
\]

(9)

The main parameters \(\Delta r\) and \(N\) corresponding to the simulated turbulence strength can be properly selected. Figure 3 shows, for a phase plate which parameters are fixed, different turbulence intensity can be simulated when \(D/D_p\) is adjusted.

Figure 3. \(D/D_p\) Vs \(C_n\) (\(\lambda=0.532\)nm, \(N=512, \Delta r =20\)μm).

(2) The coherent length \(r_0\) simulated on the receiving system be given by

\[
r_0 = \left[ 0.423 \left( \frac{2\pi}{\lambda} \right)^2 C_n^2 \right]^{(-3/5)}
\]

(10)

Accordingly \(r_{op}\) can be expressed as

\[
r_{op} = \frac{D_o}{D} r_0
\]

(11)

(3) Turbulence brings random change to atmosphere refractive index, which can directly lead to the beam shifting. The shifting angular is expressed as

\[
\sigma_o = 1.75 C_n^2 L d_0^{1/3}
\]

(12)

(4) The diffuse angular due to turbulence is

\[
\theta = 4.03 C_n^{6/5} \lambda^{-1/5} L^{3/5}
\]

(13)

(5) The simulated Log amplitude variance which represents the scintillation \(\sigma_n^2\) be given by
\[ \sigma^2 = 0.307 \left( \frac{2\pi}{\lambda} \right)^{7/6} L^{11/6} C^2 \]  

(14)  

(6) The simulated Greenwood time constant \( \tau \) be given by  
\[ \tau \approx 0.53 \left[ \frac{\sigma_v}{V_e(h)} \right] (D/r_0)^{1/6} \]  

(15)  

Where \( V_e(h) \) is the effect wind velocity decided by rotate speed of the phase plate.

5. Conclusion
The turbulence simulating system for laser propagation presented in this paper use a static phase plate as the optical simulating component for generating turbulence. By adjusting the displacement of the phase plate in the optical path, different turbulence intensify can be simulated in a certain range. So the effect of laser propagation in the atmosphere turbulence could be predicted by this method. The whole setup should be compact and easily operated. Synthetically the simulating method can satisfy the need for testing the laser turbulence propagation in inner field.

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