Speckle formation through an optically thick diffuser: A wave propagation-based model

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Abstract

Speckle effect arises from coherent light interacting with rough surfaces or randomly scattered media, offering useful parameters for metrology. Inspired by the phase-screen method used to simulate atmospheric turbulence effects on optical systems, this study investigates speckle generated from a numerical model that simulates wave propagation through multiple apertured phase screens imposed with diffuse illumination as a thick diffuser. It is observed that as the number of phase screens increases, the diffraction intensity increases as well, yet its width scan eventually gets narrower until it matches the dimensions of the aperture. Additionally, when the wave propagates through a single phase screen, the speckle size is relatively larger compared to the propagation involving multiple screens. Speckle size is quantified by obtaining the full width at half maximum (FWHM) of the autocorrelation profiles of the speckle frames.

Keywords: speckle pattern, wave propagation, diffraction, Fourier optics

1 Introduction

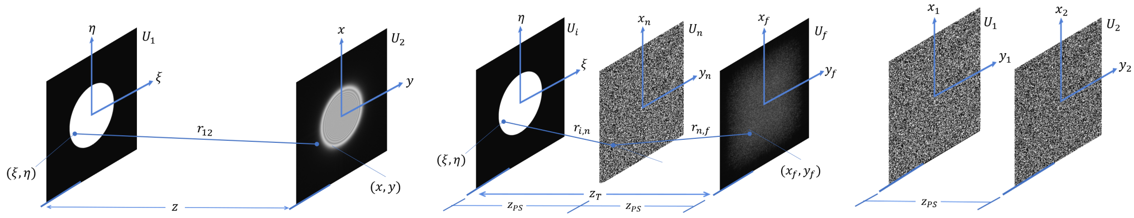
The interaction of coherent light with a rough or turbid media leads to the production of speckle [1]. In most cases, these patterns are considered as an undesirable noise that must be removed. However, the analysis of speckle patterns finds practical applications as it extracts valuable information about surface roughness, deformations, and topography [2].

Optical diffusers play a crucial role in the production of speckles since they have fixed and defined parameters tailored to specific applications [3]. In phase retrieval, they are employed to generate speckle illumination, effectively introducing sufficient intensity variations essential for the reconstruction process, thereby preventing stagnation [4]. However, modeling them numerically can be challenging due to material properties and microscopic structures. In addition, particular types of scatterers exist that do not scatter light in a controlled manner but induce significant distortions. These random variations, known as optical turbulence, lead to fluctuations in the refractive index along the path of propagation [5]. With the phase-screen method, two-dimensional grids or screens act as an element that introduces variations in phase across the passing wavefront. These variations can either be random or predetermined using statistical models designed to emulate specific characteristics of the simulated medium [6]. Recent studies commonly employ phase screens to simulate light propagation through optical turbulence.

In this study, a proposed numerical model based on wave propagation through multiple phase screens was simulated that will act as a thick diffuser. The optically thick diffuser is represented as a cascade of arbitrary number of phase screens, where the output of each screen serves as the input for the subsequent screen. Instead of simulating random variations of turbulence, each phase screen is imposed with a scattering medium by applying a phase factor with a controlled roughness through depth of randomization. The primary investigation will focus on assessing speckle formations by comparing diffraction scans and analyzing speckle sizes using autocorrelation profiles caused by varying different parameters of the model.

2 Framework of the Algorithm

Wavefront propagation is done using the Rayleigh-Sommerfeld scalar diffraction equation. Figure 1 shows the propagation geometry for the input and output planes with and without phase screen in path of propagation. By comparison, propagation through phase screens differs from a typical scenario as shown in Figure 1a, as the phase screens are treated as an additional plane along the propagation path. Figure 1b illustrates the fundamental propagation geometry of the proposed model, with the inclusion of a single phase screen. Here, the wavefront propagation through the phase screen is divided into multiple steps, with each step representing a partial propagation that accounts for the effect of the diffusive component in the screen on the wavefront. Thus, when multiple phase screens are generated in the propagation path, the full propagation is divided into several partial propagations (as shown in Figure 1c).



(a) typical wave propagation (without phase screen)

(b) wave propagation through a single phase screen

(c) partial propagation between phase screens

Figure 1: Propagation geometry for input and output planes and phase screens

Figure 2 shows the algorithm of the wave propagation with phase screens. The test object used is a circular aperture with a random phase distribution of real numbers. The algorithm starts by establishing the desired propagation distance z_T and the number of partial propagations N_p (or number of phase screens N_{U_n} - 1).

Like the typical wave propagation model, the wavefront U_i is propagated to the phase screen U_n at a distance z_{ps} using the angular spectrum equation [7].

$$U_n(x_n, y_n) = \tilde{\mathcal{F}}^{-1}\left\{\tilde{\mathcal{F}}\left\{U_1(\xi,\eta)\right\}H\left(f_{x_n}, f_{y_n}\right)\right\} \tag{1}$$

where H is the transfer function given by

$$H\left(f_{x_n}, f_{x_n}\right) = \exp\left[ikz_{PS}\sqrt{1-\left(\lambda f_{x_n}\right)^2-\left(\lambda f_{y_n}\right)^2}\right] \tag{2}$$

Here, λ is the illumination wavelength (set at $633nm$), k is the wavenumber $2\pi/\lambda$, f_{x_n} and f_{y_n} are the coordinates in the Fourier domain, and $z_{ps} = z_T/N_{U_n}$ as the partial propagation distance from a plane or screen to the next, implying equidistant screens. To generate diffuse illumination at each phase screen, a random phase function is imposed after the partial propagation output in each U_n just before the wavefront is propagated onto the succeeding screen. When an arbitrary number of phase screens is set, the output wavefront of the 1st phase screen U_1 modulated by the phase function is the input of the next succeeding screen. The function is given by:

$$\varphi_{DIFFUSER} = \exp(i\cdot\varsigma\cdot\text{rand}([0,1])) \tag{3}$$

where ς is the depth of randomization (DoR) and rand([0,1]) denotes a uniformly distributed random matrix with elements ranging from 0 to 1 with dimensions equal to that of the the object field ($M \times M$). The cycle of propagation from one phase screen to the next is repeated until the final output plane U_f at distance z_T is reached.

The speckle formation and the differences in the respective diffraction intensity scans of the final output wavefront were analyzed by varying the number of phase screens, depth of randomization ς, and propagation distances z_T. The mean speckle size can be deduced by obtaining the FWHM (full width at half the maximum) of the radially-averaged autocorrelation profiles of speckle frames [8].

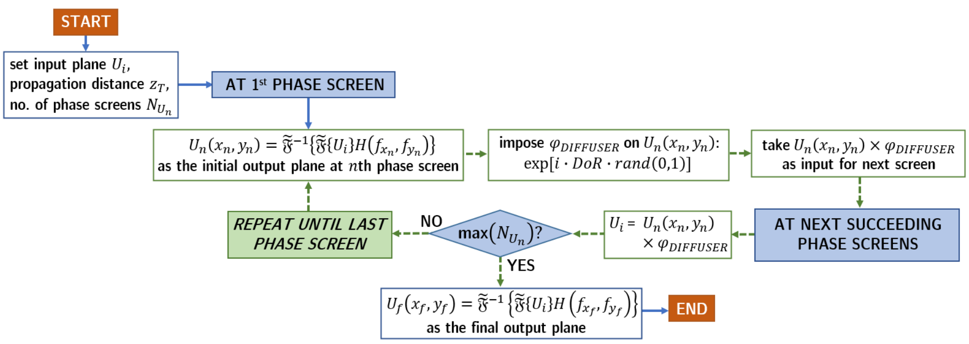
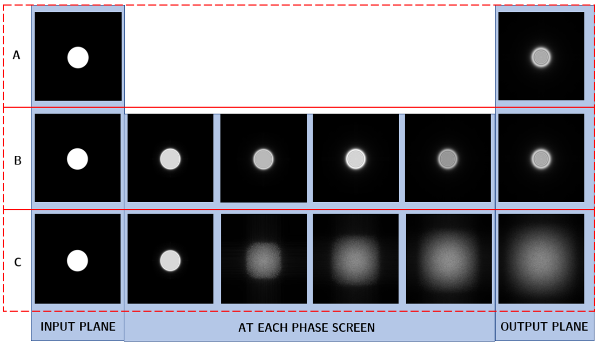
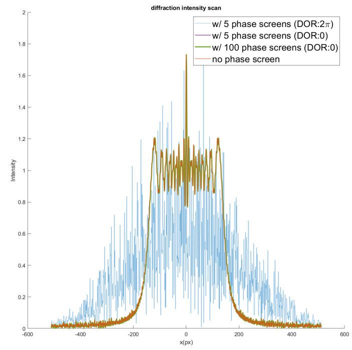


Figure 2: Flowchart for the wave propagation model with multiple phase screens



(a) Amplitude profiles at the input and output planes in propagation without phase screens (A), and amplitudes at each plane through four phase screens with $\varsigma = 0$ (B) and $\varsigma = 2\pi$ (C)



(b) Diffraction scans of the final output amplitude over a 50mm distance through varied number of phase screens and DoR

Figure 3: Comparison of amplitude profiles and diffraction intensity scans without phase screens and through varying number of phase screens and depth of randomization

3 Results and Discussion

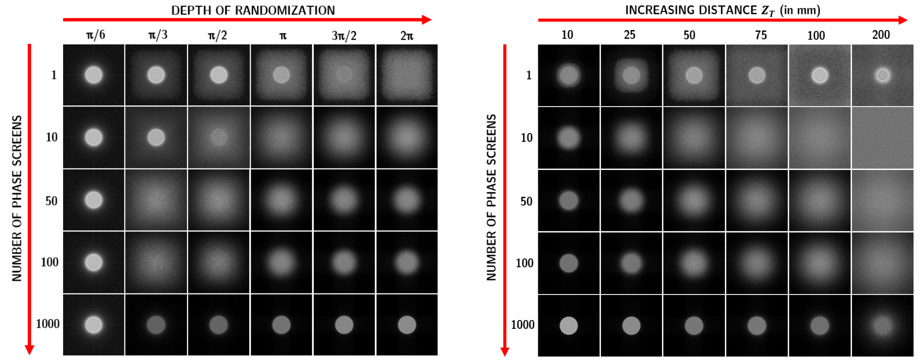
Figure 3 shows the comparison of the two wave propagation models by their respective amplitude profiles and diffraction scans. It can be observed in Figure 3a that the profiles at the output plane of the propagation without phase screen (Section A) and with four phase screens with $\varsigma = 0$ (Section B) are of similar structure. The phenomenon is also evident by evaluating the diffraction intensity scans as shown Figure 3b wherein the propagation through 5 and 100 phase screens with $\varsigma = 0$ perfectly or closely overlaps to the line plot of that with no phase screen. However, when $\varsigma \neq 0$ (2π, in this case), speckle patterns are produced and diffraction is evident as observed in Figure 3a Section C and in the blue diffraction line scan in Figure 3b.

To further investigate the diffraction patterns and speckle formations that arise from the proposed model, Figure 4 shows two tabular arrangements of the intensity profile trends evident in the final output intensity images when the wave propagates through 1, 10, 50, 100, and 1000 phase screens with varying ς and propagation distances z_T. Figure 4a shows the trend when the propagation distance z_T is set at 50mm with varying depth of randomization from $\pi/6$ to 2π, while Figure 4b shows the trend when the model is set to propagate at distances z_t 10, 25, 50, 75, 100, and 200mm with DoR set at $\varsigma = \pi$. For both of these visualizations, it can be observed that as the number of phase screen increases, the diffraction pattern at the output plane is continually minimized and will eventually be restricted to the actual dimensions of the initial object aperture. Thus, the speckle patterns that arise from the diffraction phenomena will also decrease until it no longer disperses.

Figure 5a shows the diffraction intensity scans of the final output plane through 1, 10, and 100 phase screens with a set propagation distance $z_T = 50mm$ and $\varsigma = 2\pi$. It can be observed that as the number of phase screen increases, the intensity also increases as the scan width gets narrower. On the other hand, Figures 5b-5d presents various radially averaged profiles of the autocorrelation of speckle frames selected in the final output amplitude profiles. The FWHM of the autocorrelation profiles is visually represented by the black line positioned at 0.5 on the y-axis. Figures 5c and 5d compares the autocorrelation profiles of the speckle produced from the propagations through 1 and 10 screens of various z_T distances and depth of randomization ς. Across all three autocorrelation plots, it is evident that a single phase screen produces relatively larger speckle size than adding extra amount of phase screens regardless of the propagation distance and depth of randomzation. As more phase screens are added, the line plots demonstrate a narrower peak shape, resulting in a smaller FWHM and, consequently, smaller mean speckle sizes.

4 Conclusions

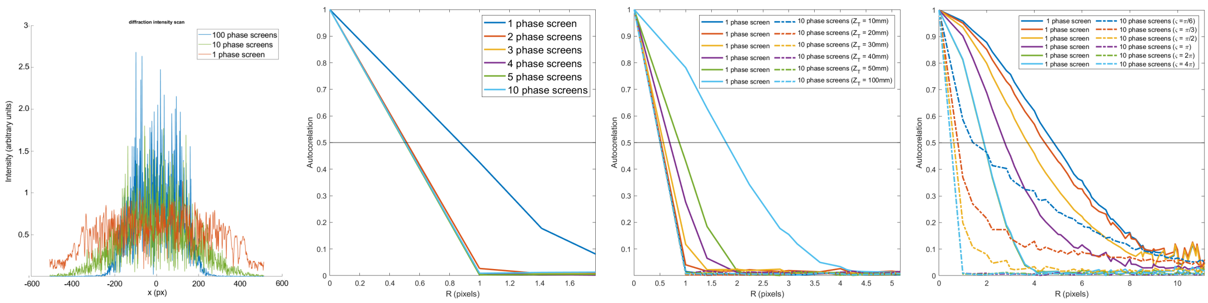
The numerical model based on wave propagation through cascaded multiple apertured phase screens as a thick diffuser was presented and the resulting diffraction scans and speckle formations were investigated. It is observed that as the number of phase screens increases, the diffraction intensity increases as well, yet its width scan eventually gets narrower until it matches the dimensions of the aperture despite an increasing depth of randomization in each phase screen diffuser. Each subsequent phase screen in the model contributes to further scattering, reducing the size of speckles. This is evident when comparing the mean speckle size resulting from a single phase screen, which tends to be relatively larger.



(a) increasing depth of randomization with a propagation distance set at z_t=50mm

(b) increasing propagation distance z_T with depth of randomization set at $\varsigma = \pi$

Figure 4: Trends of intensity profiles at increasing number of phase screens



(a) Diffraction scans of the final output amplitude over 1, 10 and 100 phase screens

(b) Increasing number of phase screens with $\varsigma = \pi$ at propagation distance z_T = 100mm

(c) 1 vs. 10 phase screens with increasing propagation distance (10, 25, 50, 75, 100, 125mm)

(d) 1 vs. 10 phase screens with increasing ς ($\pi/6$, $\pi/3$, $\pi/2$, π, 2π, 4π)

Figure 5: (a) Diffraction intensity scan of the output plane of propagation with $z_T = 50mm$ and $\varsigma = 2\pi$ through varied number of phase screens and (b-c) Profile plots of the autocorrelation of the speckle frames

Based on the study's findings, it is highly recommended to pursue further exploration and development of the phase screen method. It is important to acknowledge that the phase screen method is primarily designed as a numerical tool, which restricts its practical applicability and feasibility in experimental scenarios. The study demonstrates its potential beyond atmospheric turbulence simulations and in effectively modeling wave propagation through thick scattering media. Future studies can focus on investigating the model's effectiveness in generating specific speckle patterns, and utilize these results in the development of metrology, imaging systems, and wavefront reconstruction techniques.

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