# Comparison between relay propagation and direct propagation of Gaussian–Schell-model beam in turbulent atmosphere along a slant path

Chu Xiu-Xiang(储修祥)[a)b)c)†], Liu Ze-Jin(刘泽金)[b)], and Wu Yi(吴 毅)[c)]

[a)] *School of Sciences, Zhejiang Forestry University, Lin'an* 311300, *China*
[b)] *College of Optoelectronic Science and Engineering, National University of Defence Technology, Changsha* 410073, *China*
[c)] *Anhui Institute of Optics and Fine Mechanics, the Chinese Academy of Sciences, Hefei* 230031, *China*

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The relay propagation of Gaussian–Schell-model in turbulent atmosphere along a slant path is studied in this paper. Based on the extended Huygens–Fresnel principle and a quadratic approximation, an analytical formula of average intensity for Gaussian–Schell-model beams in turbulent atmosphere along a slant path is derived, and some special cases are discussed. From the study and the comparison with the direct propagation, we can see that the relay propagation has an advantage over the direct propagation. When the altitude of the target is low, the peak intensity of relay propagation is much larger than that of direct propagation. However, because of the limitation of the relay system aperture for relay propagation and the variation of coherence length for direct propagation, the difference in peak intensity between the two propagations decreases with the increase of the target altitude.

**Keywords:** relay propagation, Gaussian–Schell-model beam, turbulence
**PACC:** 4225B, 4225K, 9265R

## 1. Introduction

With the increase of laser power and the development of relevant technology, many applications based on the propagation of high power laser in atmosphere will come true, such as optical communications and many military applications.[1] However, there are many factors that will restrict these applications. For example, diffraction, turbulence and thermal blooming will cause beam spreading; scattering and absorption of atmosphere will cause the loss of light. Experiments have proved that it is difficult for a high power laser to propagate a long distance through atmosphere, even with the use of adaptive optics.[2] Relay propagation has been proved to be a method to achieve the longer distance propagation. The relay mirror at high elevation angles has been studied for several decades.[3] In recent years, relay propagation has also been used at lower elevation angles and along a horizontal path, such as in free space optical communications and quantum cryptography.[1,3]

Propagation of laser beams in turbulent atmosphere has been studied in a wide range,[4−17] such as average intensity,[4−8] scintillation of various types coherent laser beams,[9−11] cross-spectral density,[12,13] and degree of polarisation of partially coherent beam.[14] However, relay propagation of laser beam in turbulent atmosphere has received less attention. In our previous paper, the relay propagation of flattened Gaussian beam in turbulence along a horizontal path has been studied.[18] Studies show that the propagation will not be significantly enhanced unless the correction to laser beam in relay system is made. In the present paper, it is investigated that if the propagation of beams in turbulent atmosphere along a slant path without the correction can be enhanced.

## 2. General theory

The propagation of laser beams along a slant path with a relay system can be shown as in Fig. 1. The relay system at high altitude receives the beams, which have been projected from a laser source, and redirects them to a target. $z_1$ and $z_2$ are the propagation distances. $z_3$ is the distance between laser source and target. $\xi_1$, $\xi_2$ and $\xi_3$ denote the zenith angles. $H$

†Corresponding author. E-mail: chuxiuxiang@yahoo.com.cn
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and $h_0$ are the altitudes of relay system and target, respectively.

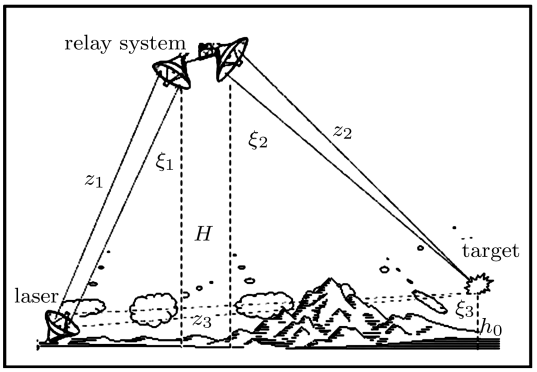



**Fig. 1.** Configuration of relay propagation.

In practice, the performance of relay system will be affected by many factors, such as scatter and absorption, jitter and scintillation, presence or absence of adaptive optics system, correction to the beam in relay system, and so on. In the present paper, the effects of aperture of relay system and weak turbulence are only considered. Therefore, relay system can be regarded as a mirror with a zoom lens optical system.

Because turbulent atmosphere decreases the coherence length of laser beams, and the variation of coherence length will influence the propagation of laser beam from relay system to the target, relay propagation of laser beams in turbulent atmosphere can be described with the propagation of cross-spectral density of Gaussian–Schell-model beam. The cross-spectral density of Gaussian–Schell-model in the source plane is expressed as[13−15]

$$\begin{aligned} & W_0\left(\boldsymbol{r}_{01}, \boldsymbol{r}_{02}, 0\right) \\ = & \exp\left(-\frac{\boldsymbol{r}_{01}^2+\boldsymbol{r}_{02}^2}{\omega_0^2}\right) \exp\left[-\frac{\left(\boldsymbol{r}_{01}-\boldsymbol{r}_{02}\right)^2}{2\sigma_0^2}\right] \\ & \times \exp\left[-\mathrm{i}k\frac{\left(\boldsymbol{r}_{01}^2-\boldsymbol{r}_{02}^2\right)}{2R_0}\right], \end{aligned} \tag{1}$$

where $\boldsymbol{r}_{01}$ and $\boldsymbol{r}_{02}$ are the transverse radial vectors of two points in the source plane, $\omega_0$ is the waist width of Gaussian beam, $\sigma_0$ is the spatial correlation length of partially coherent Gaussian–Schell-model beam, $k = 2\pi/\lambda$ with $\lambda$ being the wavelength, and $R_0$ is the phase front radius of curvature: $R_0 > 0$ presents a convergent beam and $R_0 < 0$ presents a divergent beam. Based on the extended Huygens–Fresnel principle, the cross-spectral density in the $z_1$-plane can be expressed as[4−8]

$$\begin{aligned} & W\left(\boldsymbol{r}_1, \boldsymbol{r}_2, z_1\right) \\ = & \left(\frac{k}{2\pi z_1}\right)^2 \\ & \times \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{d}^2\boldsymbol{r}_{01}\mathrm{d}^2\boldsymbol{r}_{02} W_0\left(\boldsymbol{r}_{01}, \boldsymbol{r}_{02}, 0\right) \\ & \times \exp\left\{\mathrm{i}k\left[\left(\boldsymbol{r}_1-\boldsymbol{r}_{01}\right)^2-\left(\boldsymbol{r}_2-\boldsymbol{r}_{02}\right)^2\right] \Big/ \left(2z_1\right)\right\} \\ & \times \left\langle \exp\left[\psi\left(\boldsymbol{r}_{01}, \boldsymbol{r}_1\right)+\psi^*\left(\boldsymbol{r}_{02}, \boldsymbol{r}_2\right)\right]\right\rangle, \end{aligned} \tag{2}$$

where $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the transverse radial vectors of different points in the $z_1$-plane, the asterisk denotes the complex conjugation, and the $\langle\rangle$ indicates the ensemble average over the medium covering the log-amplitude and phase fluctuations due to turbulent atmosphere. The last term on the right-hand side of Eq. (2) is the mutual coherence function of a point source located at the observation points $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$, evaluated at $\boldsymbol{r}_{01}$ and $\boldsymbol{r}_{02}$ in the input plane. It can be expressed as

$$\begin{aligned} & \left\langle \exp\left[\psi\left(\boldsymbol{r}_{01}, \boldsymbol{r}_1\right)+\psi^*\left(\boldsymbol{r}_{02}, \boldsymbol{r}_2\right)\right]\right\rangle \\ = & \exp\left[-0.5 D_\psi\left(\boldsymbol{r}_{01}-\boldsymbol{r}_{02}, \boldsymbol{r}_1-\boldsymbol{r}_2\right)\right], \end{aligned} \tag{3}$$

where $\psi\left(\boldsymbol{r}_0, \boldsymbol{r}\right)$ denotes the random part of the complex phase of a spherical wave that propagates from the source point $\boldsymbol{r}_0$ to the receiver point $\boldsymbol{r}$, and $D_\psi\left(\boldsymbol{r}_{01}-\boldsymbol{r}_{02}, \boldsymbol{r}_1-\boldsymbol{r}_2\right)$ is the wave structure function. Under the assumption of Gaussian field statistics and employing a quadratic approximation, the structure function can be expressed as[19]

$$\begin{aligned} & D_\psi\left(\boldsymbol{r}_{01}-\boldsymbol{r}_{02}, \boldsymbol{r}_1-\boldsymbol{r}_2\right) \\ \approx & \frac{2}{\rho_0}\left[\left(\boldsymbol{r}_{01}-\boldsymbol{r}_{02}\right)^2+\left(\boldsymbol{r}_{01}-\boldsymbol{r}_{02}\right)\left(\boldsymbol{r}_1-\boldsymbol{r}_2\right)\right. \\ & \left.+\left(\boldsymbol{r}_1-\boldsymbol{r}_2\right)^2\right], \end{aligned} \tag{4}$$

where $\rho_0$ is the coherence length. For different beams, such as plane wave, spherical wave and focused beam, their corresponding formulas for $\rho_0$ are different. For simplicity, the formula corresponding to the focused beam is adopted in this paper. Thus, for the uplink propagation, $\rho_0$ can be expressed as[20]

$$\begin{aligned} & \rho_0 \\ = & \left[1.46k^2\sec\left(\xi_1\right)\int_0^H C_n^2\left(h\right)\left(1-\frac{h}{H}\right)^{5/3}\mathrm{d}h\right]^{-3/5}, \end{aligned} \tag{5}$$

where $h$ is the variable of altitude, $H = z_1\cos(\xi_1)$ is the altitude of relay system, and $C_n^2\left(h\right)$ is $h$ dependent structure constant and selected as[7]

$$C_n^2\left(h\right)$$

$$= 8.148\times10^{-56}V^2h^{10}\exp\left(-h/1000\right) + 2.7\times10^{-16}\exp\left(-h/1500\right)+C_0\exp\left(-h/100\right), \tag{6}$$

where $V=\left(v_{\rm g}^2+30.69v_{\rm g}+348.91\right)^{1/2}$ is the wind speed along the vertical path, $v_{\rm g}$ is the ground wind speed, and $C_0$ is the nominal value at ground level (typically, the value is $1.7\times10^{-14}$ $\rm m^{-2/3}$). For convenience, we set $v_{\rm g}=5$ m/s.

If the dimensionless quantities $\tau_1=1-z_1/R_0$, $\tau_2=2z_1/\left(k\omega_0^2\right)$, $\tau_3=2z_1/\left(k\omega_0\sigma_0\right)$, $\tau_4=2\sqrt{2}z_1/\left(k\omega_0\rho_0\right)$ and $\tau^2=\tau_1^2+\tau_2^2+\tau_3^2+\tau_4^2$ are introduced, from Eqs. (1)–(4), the cross-spectral density in the $z_1$-plane can be expressed as

$$W\left(\boldsymbol{r}_1,\boldsymbol{r}_2,z_1\right) = \frac{\omega_0^2}{\omega^2}\exp\left(-\frac{\boldsymbol{r}_1^2+\boldsymbol{r}_2^2}{\omega^2}\right)\exp\left[-\frac{\left(\boldsymbol{r}_1-\boldsymbol{r}_2\right)^2}{2\sigma^2}\right] \exp\left[-{\rm i}k\frac{\left(\boldsymbol{r}_1^2-\boldsymbol{r}_2^2\right)}{2R}\right], \tag{7}$$

where $\omega$, $\sigma$ and $R$ are the waist width, the spatial correlation length and the phase front radius of curvature of the Gaussian beam in the $z_1$-plane, respectively. In Eq. (7)

$$\omega^2=\tau^2\omega_0^2=\left(\tau_1^2+\tau_2^2+\tau_3^2+\tau_4^2\right)\omega_0^2, \tag{8}$$

$$\sigma^2=\left\{\frac{2}{\rho_0^2}\left[1+\frac{1}{\tau^2}\left(1+\tau_1-\frac{\tau_2^2\omega_0^2}{2\rho_0^2}\right)\right]+\frac{1}{\tau^2\sigma_0^2}\right\}^{-1}, \tag{9}$$

and

$$R=\frac{\tau^2z_1}{\tau_1-\tau^2-\tau_2^2\omega_0^2/\rho_0^2}, \tag{10}$$

where $\tau_1$, $\tau_2$, $\tau_3$ and $\tau_4$ can be interpreted as the factors that describe the beam spreading due to geometrical magnification, diffraction, coherence of initial beams and turbulence, respectively. If we set $\boldsymbol{r}_1=\boldsymbol{r}_2$, Eq. (6) is the average intensity at in the $z_1$-plane. In practice, a Cassegrain telescope with central obscuration is often used as a receiver, and the maximum receiving efficiency can be obtained by changing $R_0$ or selecting the parameters of beams. The receiving efficiency can be expressed as

$$\eta=\exp\left(-\frac{2\varepsilon^2a^2}{\omega^2}\right)-\exp\left(-\frac{2a^2}{\omega^2}\right), \tag{11}$$

where $a$ is the radius of aperture, $\varepsilon$ is the obscuration ratio. From Eq. (11) we can see that when

$$\omega=a\sqrt{\frac{\varepsilon^2-1}{\ln\varepsilon}}, \tag{12}$$

the receiving efficiency is maximum. For example, with $a=1.5\omega_0$ and $\varepsilon=0.2$, we can see that when $\omega=1.16\omega_0$ the receiving efficiency is maximum.

For simplicity, we assume that $\varepsilon=0$ and the receiver of relay system is the same as the transmitter. Therefore, the cross-spectral density of the beams projected from relay system can be expressed as

$$W'\left(\boldsymbol{r}_1,\boldsymbol{r}_2,z_1\right) = t\left(\boldsymbol{r}_1,\boldsymbol{r}_2,z_1\right)W\left(\boldsymbol{r}_1,\boldsymbol{r}_2,z_1\right) \times\exp\left[-{\rm i}k\frac{\left(\boldsymbol{r}_1^2-\boldsymbol{r}_2^2\right)}{2f}\right], \tag{13}$$

where $f$ is the focal length of relay system, $t(\boldsymbol{r}_1,\ \boldsymbol{r}_2,\ z_1)$ is the aperture function and can be expressed as

$$t\left(\boldsymbol{r}_1,\boldsymbol{r}_2,z_1\right)=\begin{cases}1 & \boldsymbol{r}_1\ \text{ or }\ \boldsymbol{r}_2\le a,\\ 0 & \text{otherwise.}\end{cases} \tag{14}$$

To obtain analytical expression for average intensity at target, we use the sum of complex Gaussian functions with finite numbers to express the hard-edge aperture function[21,22]

$$t\left(\boldsymbol{r}_1,\boldsymbol{r}_2,z_1\right) = \sum_{i=1}^{m}\sum_{j=1}^{m}B_iB_j\exp\left(-\frac{C_i}{a^2}r_1^2-\frac{C_j}{a^2}r_2^2\right), \tag{15}$$

where the complex constants $B_j$ and $C_j$ are the expansion coefficients which can be obtained by optimizing the computations directly. If the focal length of relay system is adopted as

$$\frac{1}{f}=\frac{1}{R}+\frac{1}{z_2}, \tag{16}$$

the laser beam can be focused on the target. Therefore, Eq. (13) can be expressed as

$$W'\left(\boldsymbol{r}_1,\boldsymbol{r}_2,z_1\right) = \frac{\omega_0^2}{\omega^2}\sum_{m=1}^{M}\sum_{n=1}^{M}B_mB_n^* \times\exp\left[-\left(\frac{1}{\omega^2}+\frac{C_m}{a^2}\right)\boldsymbol{r}_1^2-\left(\frac{1}{\omega^2}+\frac{C_n*}{a^2}\right)\boldsymbol{r}_2^2\right] \times\exp\left[-\frac{\left(\boldsymbol{r}_1-\boldsymbol{r}_2\right)^2}{2\sigma^2}\right]\exp\left[-{\rm i}k\frac{\left(\boldsymbol{r}_1^2-\boldsymbol{r}_2^2\right)}{2z_2}\right]. \tag{17}$$

With the same steps as those in obtaining the cross-spectral density in the $z_1$-plane, the average intensity at target can be expressed as

$$\left\langle I\left(\boldsymbol{p},z_2\right)\right\rangle = \sum_{m=1}^{M}\sum_{n=1}^{M}B_mB_n^*\frac{\omega_0^2}{\omega'^2}\exp\left(-\frac{2\boldsymbol{p}^2}{\omega''^2}\right), \tag{18}$$

where $\boldsymbol{p}$ is the transverse radial vector at target, $\omega'$ and $\omega''$ can be expressed respectively as

$$\omega' = \left[\tau'^2_2 + \tau'^2_3 + \tau'^2_4 + \tau'^2_2 C_m C_n^* \frac{\omega^4}{a^4} + \frac{(C_m + C_n^*)\,\omega^2}{2a^2}\left(2\tau'^2_2 + \tau'^2_3 + \tau'^2_4\right)\right]^{0.5} \omega, \tag{19}$$

$$\omega'' = \left[\tau'^2_2 + \tau'^2_3 + \tau'^2_4 + \tau'^2_2 \left(\frac{2C_m C_n^* \omega^2/a^2 + C_m + C_n^*}{2a^2/\omega^2 + C_m + C_n^*}\right)\right]^{0.5} \omega. \tag{20}$$

In Eqs. (19) and (20) $\tau'_2 = 2z_2/k\omega^2$, $\tau'_3 = 2z_2/k\sigma\omega$, and $\tau'_4 = 2\sqrt{2}z_2/k\rho'_0\omega$, where $\rho'_0$ is the coherence length from the relay system to the target. For downlink path, $\rho'_0$ can be obtained from Eq. (5) by substituting $C_n^2(h)$ and $h$ by $C_n^2(H-h')$ and $h'$, respectively.

$$\rho'_0 = \left[1.46k^2 \sec(\xi_2) \int_{h_0}^{H} C_n^2(h) \left(\frac{h-h_0}{H-h_0}\right)^{5/3} \mathrm{d}h\right]^{-3/5}, \tag{21}$$

where $h_0$ is the altitude of target. From Eqs. (5), (6) and (21), the coherence lengths ($H = 10$ km, $h_0 = 0$ and $\lambda = 1.06$ $\mu$m) are obtained to be 0.06 m and 0.45 m for uplink and downlink propagations, respectively, which are in agreement with the existing results.

For the loss of light due to the aperture of relay system, $\omega'$ is unequal to $\omega''$. If we set $a \to \infty$, we can see that $\omega'$ is equal to $\omega''$. Studies have shown that in far field, the method of using the sum of complex Gaussian functions to express the hard-edge aperture function can provide satisfactory results.[21−23] Therefore, Eq. (18) can express the intensity distribution in the focal plane accurately.

## 3. Numerical calculation

If $\xi_1$, $\xi_2$, $H$ and $h_0$ are fixed, from Fig. 1 we can obtain

$$z_1 = H \sec(\xi_1), \tag{22}$$

$$z_2 = (H - h_0)\sec(\xi_2), \tag{23}$$

$$z_3 = \left\{\left[H\tan(\xi_1) + (H-h_0)\tan(\xi_2)\right]^2 + h_0^2\right\}^{1/2}, \tag{24}$$

$$\xi_3 = \arctan\left\{\left[H\tan(\xi_1) + (H-h_0)\tan(\xi_2)\right]/h_0\right\}. \tag{25}$$

To see the properties of average intensity at the target, we assume that $R_0 \to \infty$ (for collimated laser beam $\tau_1 = 1$), $\sigma_0 \to \infty$ (for completely coherent beam $\tau_3 = 0$), $H = 10$ km, $\xi_1 = \pi/6$, $\lambda = 1.06 \times 10^{-6}$ m and $\omega_0 = 0.5$ m. From Eqs. (5), (6) and (9) we can obtain $\tau_4 = 0.15$, $\tau_2 = 0.016$ and $\sigma = 0.03$ m. Because the initial beam is a completely coherent beam, the decrease of spatial correlation length is only due to the turbulence. The normalized intensity distribution is defined as

$$\langle I(\boldsymbol{p}, z_2)\rangle_{\mathrm{N}} = \langle I(\boldsymbol{p}, z_2)\rangle / p_0, \tag{26}$$

where $p_0 = \pi\omega_0^2/2$ can be regard as the incident power. For a comparison with relay propagation, the direct propagation is also studied. It is assumed for the direct propagation that the initial beam is focused on the target directly, so the average intensity can also be expressed as Eq. (7). The normalised average intensity profiles of the relay propagation at the target without any aperture are shown in Fig. 2.

As a comparison, the normalised average intensity profiles for the direct propagation under the same conditions as those in Fig. 2 are shown in Fig. 3.

From Figs. 2 and 3 we can see that the peak intensities increase with $\xi_2$. Compared with the spreading of relay propagation, the spreading of direct propagation at the target is much large when the altitude of target is low. With the increase of the altitude, the difference in peak intensity between the two propagations becomes smaller and smaller. The results can be explained as follows:

On the downlink, since the majority of the atmosphere is near the ground at the end of the propagation path, atmospheric distortion has a limited effect due to insufficient distance in dense atmosphere, namely, the coherence length for downlink path is much longer than that for uplink. The coherence length for the whole path (including uplink and downlink path) approximates to that for the uplink path. For direct propagation (in present paper, $z_3 \geq z_1$), the coherence length is much shorter than that for the uplink propagation when the altitude of target is low (the zenith angle ($\xi_3$) is large). With the increase of altitude, the coherence length for direct propagation increases and trends to that of relay propagation.

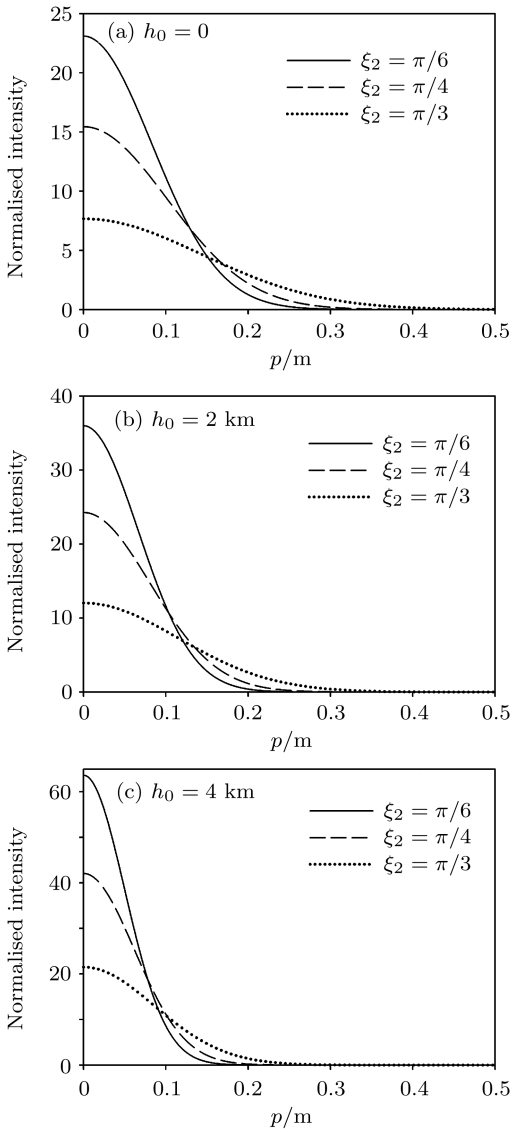



**Fig. 2.** Intensity profiles of relay propagation at target without any aperture.

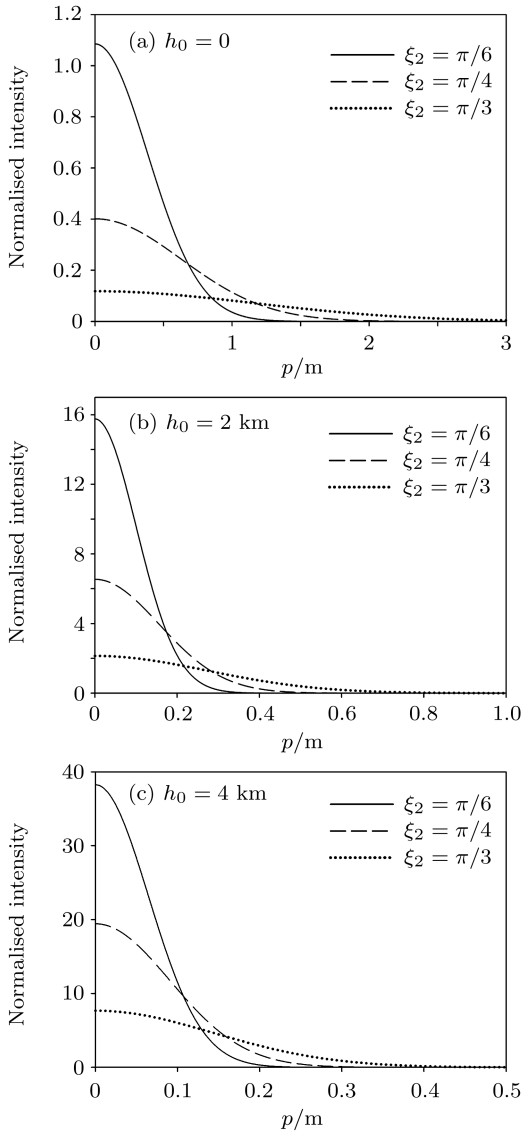



**Fig. 3.** Intensity profiles of direct propagation at target.

However, in practice the aperture effect of the relay system exists more or less. The normalised average intensity profiles of relay propagation with an aperture are shown in Fig. 4. From Fig. 4 we can see that the effects of aperture are small when the radius of aperture is large, for example $a = 1.5\omega_0$. With the decrease of the aperture size the effects become larger and larger.

To see the validity of using the sum of complex Gaussian functions to express the hard-edge aperture function, the analytical expression for on-axis intensity can be derived as[24]

$$\langle I(0, z_2)\rangle = \frac{k^2}{4z_2^2}\sum_{m=0}^{\infty}\frac{1}{m!}\left(\frac{1}{2\sigma^2}+\frac{1}{\rho_0'^2}\right)^{2m}\left(\frac{1}{\omega^2}+\frac{1}{2\sigma^2}+\frac{1}{\rho_0'^2}\right)^{-2m-2} \times\left\{m!-\Gamma\left[m+1, a^2\left(\frac{1}{\omega^2}+\frac{1}{2\sigma^2}+\frac{1}{\rho_0'^2}\right)\right]\right\}^2, \tag{27}$$

where $\Gamma(m, x)$ is the incomplete gamma function. Numerical calculation shows that the infinite sum in Eq. (27) converges rapidly. From Eq. (27), we can obtain that the relative error of on-axis intensity in Fig. 4 due to the expansion of hard-edge aperture function is smaller than 4%.

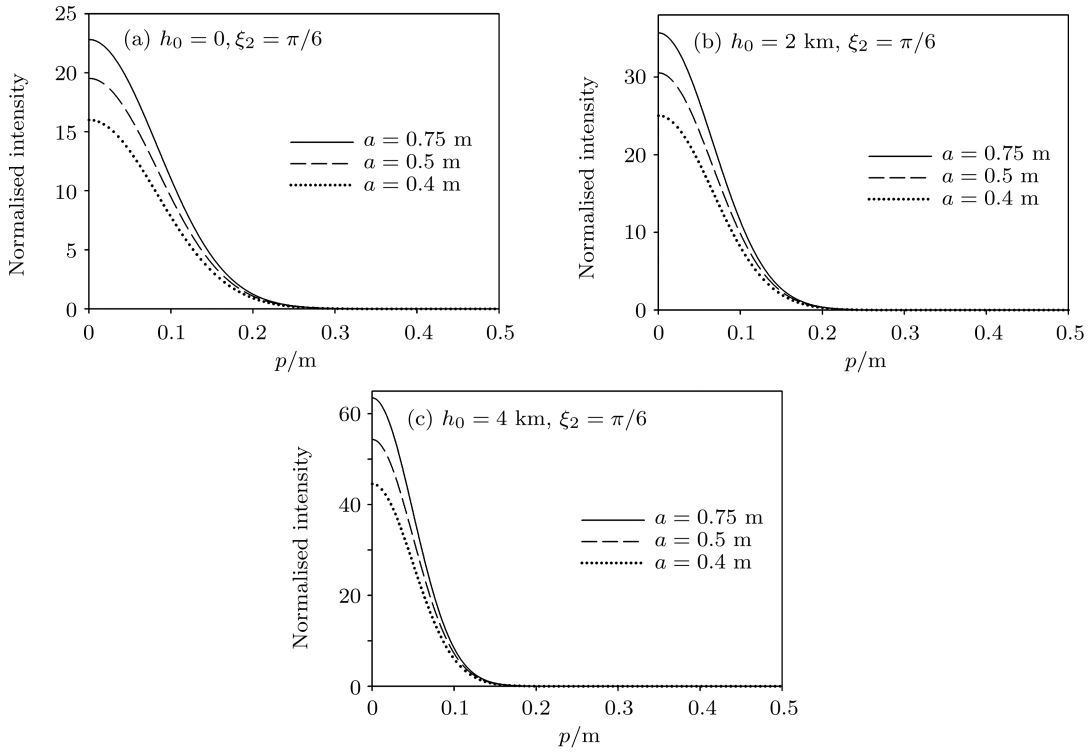



**Fig. 4.** Normalised average intensity profiles of relay propagation with any aperture.

# 4. Conclusion

In this paper we study the relay propagation of Gaussian–Schell-model beam in turbulent atmosphere along a slant path. The effects of different parameters on relay propagation are analysed and discussed. Studies show that the effects of turbulent atmosphere on relay propagation are much smaller than those of direct propagation when the altitude of target is low. With the increase of altitude the advantage of relay propagation becomes less and less.

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