Free-Space Laser Communication Using a Partially Coherent Laser Source

Jennifer C. Ricklin,* Frederic M. Davidson** and Thomas Weyrauch***

ABSTRACT

Atmospheric turbulence degrades the performance of laser communication systems in that system bit error rates can be orders of magnitude larger than in the absence of turbulence. Using a partially coherent laser beam may reduce system bit error rates due to irradiance scintillations in the receiver focal plane. In order to better understand the propagation of a partially coherent beam in atmospheric turbulence, we derive an analytic expression for the cross-spectral density of a partially coherent lowest-order Gaussian laser beam (TEM_{00}) in turbulence. From the second moment equation expressions for the average intensity, beam size, radius of curvature and lateral coherence length are derived. These results are valid for any beam type: focused, collimated, divergent, and the limiting cases of the plane and spherical wave. We also present preliminary experimental results that indicate a reduction in bit error rates would occur if a partially coherent beam were used.

1. INTRODUCTION

Historically, wave propagation through atmospheric turbulence has been characterized in terms of the complex mutual coherence function $\Gamma(\mathbf{r}_1,\mathbf{r}_2,\tau)$ which obeys the wave equation. More recent treatments[1,2] of the propagation of partially coherent fields have focused on the cross spectral density function $W(\mathbf{r}_1,\mathbf{r}_2,\nu)$ which is the temporal Fourier transform of $\Gamma(\mathbf{r}_1,\mathbf{r}_2,\tau)$. The cross spectral density function obeys the Helmholtz equation and characterizes the behavior of each frequency component of the partially coherent field's optical power spectral density. If the field is strictly monochromatic or sufficiently narrow band, then both characterizations yield identical results. Strictly speaking, however, the cross-spectral density is the more fundamental quantity since each frequency component of the optical field must obey the Helmholtz equation. If the optical field has a substantial spread in optical frequencies as might well be the case in very high data rate optical communication systems, $\Gamma(\mathbf{r}_1,\mathbf{r}_2,\tau)$ may always be obtained by inverse Fourier transformation (perhaps by numerical computation) of $W(\mathbf{r}_1,\mathbf{r}_2,\nu)$ which is found from solution of the Helmholtz equation.

Direct solution of the wave equation for $\Gamma(\mathbf{r}_1,\mathbf{r}_2,\tau)$ is more difficult if quasi-monochromaticity does not strictly apply. The work described here discusses the behavior of $W(\mathbf{r}_1,\mathbf{r}_2,\nu = \nu_0)$ where ν_0 is the center frequency of a partially spatially coherent lowest-order Gaussian (TEM_{00}) laser beam after propagation through clear air turbulence. A recent study of the influence of a controlled phase diffuser at the input to an atmospheric optical link indicated that turbulence-induced intensity fading is reduced through the use of a partially coherent source input to the channel.[3]

2. FREE-SPACE PROPAGATION OF GAUSSIAN BEAMS

At $z = 0$ the free-space electric field of a lowest-order paraxial Gaussian beam (TEM_{00}) propagating predominantly along the z-axis can be represented in the form

$$U_d(r, 0) = A_o \exp\left[-\left(\frac{1}{W_o^2} + \frac{ik}{2R_o}\right)r^2\right], \tag{1}$$

where W_o is the beam radius (beam size), R_o is the radius of curvature at the plane $z = 0$, and $k = 2\pi/\lambda$ is the optical wave number. At a propagation distance z from the transmitter the optical field becomes

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$$U_d(\mathbf{r}, z) = \frac{\exp(jkz)}{\Omega_o + j\Omega} exp\left[-\frac{1}{\Omega_o + j\Omega}\left(\frac{1}{W_o^2} + \frac{ik}{2R_o}\right) r^2 \right]. \tag{2}$$

In Eq. (2) we have made use of the transmitter beam parameters[4-6]

$$\Omega_o = 1 - \frac{L}{R_o}, \quad \Omega = \frac{2L}{kW_o^2} \tag{3}$$

where the parameter Ω_o is refractive in nature and the diffractive parameter Ω is related to the Fresnel parameter $\sqrt{\lambda L}$ through $\Omega = \frac{2L}{kW_o^2} = \frac{1}{\pi}\left(\frac{\sqrt{\lambda L}}{W_o}\right)^2$. The beam radius $W(z)$ and radius of curvature $R(z)$ in the receiver plane in terms of the transmitter beam parameters are given by

$$W(z) = W_o(\Omega_o^2 + \Omega^2)^{\frac{1}{2}}, \quad R(z) = \frac{L(\Omega_o^2 + \Omega^2)}{\Omega_o(1 - \Omega_o) + \Omega^2} \quad . \tag{4}$$

For a collimated beam with the waist at $z = 0$, $\Omega_o = 1$ and we obtain the traditional expressions describing beam radius and radius of curvature as a function of z:

$$W(z) = W_o[1 + (\lambda z/\pi W_o^2)]^{\frac{1}{2}}, \quad R(z) = z[1 + (\pi W_o^2/\lambda z)]^{\frac{1}{2}} \quad . \tag{5}$$

In terms of the beam radius $W(z)$ the average intensity at the receiver is expressed as

$$I(\rho, z) = \frac{W_o^2}{W^2(z)} exp\left(\frac{-2\rho^2}{W^2(z)}\right) \quad . \tag{6}$$

Other relations involving these parameters are discussed in Ref. 5.

3. CROSS-SPECTRAL DENSITY OF A PARTIALLY COHERENT BEAM IN TURBULENCE

The cross-spectral density $W(\rho_1, \rho_2, L)$ at the field point $z = L$ (receiver) can be represented as[1,7]

$$\begin{aligned} W(\rho_1, \rho_2, L) = \left\langle U(\rho_1, L) U^*(\rho_2, L) \right\rangle = \frac{1}{(\lambda L)^2} \iiiint d^2 r_S \, d^2 r_d \left\langle U(r_1) U^*(r_2) \right\rangle \\ \text{x} \left\langle exp\left(\Psi(r_1, \rho_1) + \Psi^*(r_2, \rho_2) \right) \right\rangle exp\left[\frac{ik}{2L}\left[(\rho_1 - r_1)^2 - (\rho_2 - r_2)^2 \right] \right] \end{aligned} \tag{7}$$

where r_1, r_2, ρ_1, ρ_2 are two-dimensional vectors perpendicular to the direction of propagation in the planes $z = 0$ and $z = L$, respectively. The paraxial approximation has been used and quasi-monochromaticity assumed $(\Delta\nu/\nu << 1)$. The fundamental quantity describing propagation of an electromagnetic field is the cross-spectral density, as $W(\rho_1, \rho_2, L)$ is the solution to the Helmholtz equation. However, for purely monochromatic (completely coherent) light the mutual coherence function has historically been used to describe propagation; the mutual coherence function and the cross-spectral density form a Fourier transform pair.

Introduce the sum and difference vector notation $r_S = \frac{1}{2}(r_1 + r_2)$, $r_d = r_1 - r_2$, $\rho_S = \frac{1}{2}(\rho_1 + \rho_2)$, $\rho_d = \rho_1 - \rho_2$. It follows that

$$exp\left[\frac{ik}{2L}\left[(\rho_1 - r_1)^2 - (\rho_2 - r_2)^2\right]\right] = exp\left[\frac{ik}{L}\left[(r_S - \rho_S)\cdot(r_d - \rho_d)\right]\right]. \tag{8}$$

Yura[8] shows that for a spherical wave propagating in homogeneous turbulence

$$\left\langle \exp(\Psi(r_1,\rho_1) + \Psi^*(r_2,\rho_2) \right\rangle \cong exp\left[\frac{-1}{\rho_o^2}\left(r_d^2 + r_d\cdot\rho_d + \rho_d^2\right)\right] \tag{9}$$

where $\rho_o = (0.546 C_n^2 k^2 L)^{-3/5}$ is the coherence length of a spherical wave propagating in turbulence and C_n^2 is the refractive index structure parameter describing the strength of atmospheric turbulence. Following Wang & Plonus,[9] for a partially (spatially) coherent source the field $U(r)$ can be expressed as the product of two factors $U(r) = U_d(r)\, U_r(r)$ where $U_d(r)$ is the deterministic radiation distribution and $U_r(r)$ is the random coherence factor over the source plane. Although spatial coherence of the source is typically attributed to the random characteristics of both amplitude and phase, for simplicity here partial coherence over the source plane is modeled as a statistically random phase having a Gaussian probability distribution with zero mean. The cross-spectral density at the source $W(r_1, r_2, 0)$ can then be expressed as[1]

$$\begin{aligned} W(r_1,r_2,0) &= \left\langle U(r_1)U^*(r_2)\right\rangle = U_d(r_1)U_d^*(r_2)\left\langle U_r(r_1)U_r^*(r_2)\right\rangle \\ &= U_d(r_1)U_d^*(r_2)G(r_1 - r_2) \cong U_d(r_1)U_d^*(r_2)\, exp\left(\frac{-(r_1 - r_2)^2}{2\sigma_g^2}\right). \end{aligned} \tag{10}$$

where σ_g^2 is the variance of the Gaussian random phase describing the partial coherence properties of the source. Recalling the expression for the deterministic field given in Eq. (1) and converting to the sum and difference vector notation, the cross-spectral density at the source becomes

$$W(r_1,r_2,0) = A_o^2\, exp\left[-\frac{1}{W_o^2}\left[\frac{1}{2}(r_d^2 + 4r_S^2)\right] - \frac{ik}{2R_o}\left(2r_d\cdot r_S\right) - \frac{r_d^2}{2\sigma_g^2}\right]. \tag{11}$$

We can now express the cross-spectral density at the field point:

$$\begin{aligned} W(\rho_1,\rho_2,L) = \frac{A_o^2}{(\lambda L)^2} \iint d^2 r_d \iint d^2 r_S\, exp\left(\frac{-2r_S^2}{W_o^2}\right) exp\left(\frac{-ikr_S\cdot r_d}{R_o} + \frac{ikr_S\cdot(r_d - \rho_d)}{L}\right) \\ \times exp\left[-\frac{r_d^2}{2W_o^2} - \frac{r_d^2}{2\sigma_g^2} - \frac{\left(r_d^2 + r_d\cdot\rho_d + \rho_d^2\right)}{\rho_o^2} - \frac{ik\rho_S\cdot\left(r_d - \rho_d\right)}{L}\right]. \end{aligned} \tag{12}$$

Define the beam size for a partially coherent beam in turbulence:

$$W_\zeta(z) = W_o(\Omega^2\zeta^2 + \Omega_o^2)^{\frac{1}{2}}, \quad \zeta^2 = 1 + \frac{W_o^2}{\sigma_g^2} + \frac{2W_o^2}{\rho_o^2} \tag{13}$$

where we have also defined the quantity ζ^2 which we refer to as the global coherence parameter. Physically speaking, the global coherence parameter is a measure of the degree of global coherence of the light across the source plane. For a fully coherent beam ($\sigma_g \to \infty$) in the absence of turbulence ($\rho_o \to \infty$) the global coherence parameter reduces to one. Note that ζ^2 operates exclusively on the diffractive beam parameter Ω and does not affect the refractive focusing parameter Ω_o, as one would expect to be the case. For a fully coherent beam in the absence of turbulence the beam size in Eq. (13) reduces to its diffractive form given in Eq. (4).

Evaluating the integral in Eq. (12) we obtain the expression for the cross-spectral density at the field point:

$$W(\rho_1,\rho_2,L)=\frac{A_o^2}{\Omega^2\zeta^2+\Omega_o^2}exp\left\{-\rho_d^2\left(\frac{1}{\rho_o^2}+\frac{1}{2W_o^2\Omega^2}\right)+\frac{2i\rho_S\cdot\rho_d}{W_o^2\Omega}\right\}$$

$$\times exp\left\{\frac{-2\rho_S^2}{W_\zeta^2(z)}\right\} exp\left\{\frac{-2\left[\frac{i\phi}{2}\right]^2\rho_d^2}{W_\zeta^2(z)}\right\} exp\left\{\frac{-2\left[\frac{i\phi}{2}\right]\rho_d\cdot\rho_S}{W_\zeta^2(z)}\right\},\ \phi=\frac{\Omega_o}{\Omega}-\frac{\Omega W_o^2}{\rho_o^2}. \tag{14}$$

A. Beam Size

Compare the beam size for a partially coherent beam in turbulence to the equivalent expression for a partially coherent collimated beam propagating in free-space.[1,2] For a partially coherent beam in the absence of turbulence $\zeta^2 \to 1+W_o^2/\sigma_g^2$. If we assume a collimated beam ($\Omega_o \to 1, \Omega = 2z/kW_b^2$) with the beam waist W_b located at the $z=0$ (transmitter) plane the beam size at the receiver takes the form

$$W_\zeta(z)=W_b(1+\Omega^2\zeta^2)^{\frac{1}{2}} = W_b\left[1+\left(\frac{2z}{k\delta W_b}\right)^2\right]^{\frac{1}{2}}. \tag{15}$$

where $\frac{1}{\delta^2}=\frac{1}{4\sigma_S^2}+\frac{1}{\sigma_g^2}$ is defined in Ref. 1. Equating the square of the beam size in Eq. (13) with four standard deviations of the Gaussian field ($W_b^2=4\sigma_S^2$) it follows that

$$W_\zeta(z)=W_b\Delta(z)=2\sigma_S\Delta(z),\quad \Delta(z)=\left[1+\left(\frac{2z}{k\delta W_b}\right)^2\right]^{\frac{1}{2}}, \tag{16}$$

where $\Delta(z)$ is the expansion coefficient of the beam. These results are identical to those given in Ref. 1. For a fully coherent beam in the absence of turbulence it follows that $\zeta^2 \to 1$ and Eq. (15) reduces to the diffractive expression for a fully coherent Gaussian beam wave in free space.[5,6] An expression for the partially coherent beam in turbulence previously derived by another author has been shown to contain an error.[10]

B. Average Intensity

The average intensity $\langle I(\rho)\rangle$ for a unit amplitude beam is obtained from Eq. (14) when $\rho_1=\rho_2$ so that $\rho_S=\rho$ and $\rho_d=0$:

$$\langle I(\rho)\rangle=\frac{W_o^2}{W_\zeta^2(z)}exp\left(\frac{-2\rho^2}{W_\zeta^2(z)}\right). \tag{17}$$

Again notice that the combined effects of partial coherence and turbulence operate solely on the diffractive parameter Ω and that the refractive parameter Ω_o describing focusing characteristics is unaffected. For a fully coherent beam in the absence of turbulence $\zeta^2 \to 1$ and the expression given above for the average intensity of a partially coherent beam propagating in a turbulent medium exactly reduces to the expression for a fully coherent diffractive Gaussian beam wave in free space given in Eq. (6).

Using the notation of Ref. 1 define the 1/e fall-off in intensity as $\bar{\rho}_S(z)$. Recalling Eq. (16) write

$$\bar{\rho}_S(z) = \frac{W_\zeta(z)}{\sqrt{2}} = \frac{2\sigma_S\Delta(z)}{\sqrt{2}} = \sqrt{2}\,\sigma_S\Delta(z) \tag{18}$$

which exactly corresponds to the result in Ref. 1 for a partially coherent collimated beam propagating in free-space.

C. Radius of Curvature

We can derive the expression for wave-front radius of curvature for a partially coherent beam propagating in turbulence from the imaginary portion of Eq. (14):

$$W(\rho_1,\rho_2,L)_{imag} = \frac{A_o^2}{\Omega^2\zeta^2+\Omega_o^2}\, exp\left\{\frac{-ik\,\rho_S\cdot\rho_d}{2R_\zeta(z)}\right\}, \tag{19}$$

where the radius of curvature $R_\zeta(z)$ is defined as

$$R_\zeta(z) = \frac{z(\Omega_o+\zeta^2\Omega^2)}{\Omega\phi-\Omega_o^2-\zeta^2\Omega^2}, \quad \phi = \frac{\Omega_o}{\Omega} - \frac{\Omega W_o^2}{\rho_o^2}. \tag{20}$$

For a fully coherent beam in the absence of turbulence the radius of curvature reduces to its diffractive form given in Eq. (4). Eq. (20) also reduces to the expression for a partially coherent collimated beam propagating in free-space given in Ref. 2.

D. Coherence Length

To consider propagation of the degree of coherence of the optical wave, consider the normalized quantity

$$\mu(L,\rho_d) = \frac{W(0,\rho_d,L)}{W(0,0,L)} = exp\left\{-\rho_d^2\left(\frac{1}{\rho_o^2}+\frac{1}{2W_o^2\Omega^2}\right)\right\} exp\left\{\frac{-2\left[\frac{i\phi}{2}\right]^2\rho_d^2}{W_\zeta^2(z)}\right\}, \tag{21}$$

which simplifies to

$$\mu(L,\rho_d) = exp\left\{-\frac{\rho_d^2}{\rho_o^2}\left(1+\frac{\rho_o^2}{2W_o^2\Omega^2}-\frac{\phi^2\rho_o^2}{2W_\zeta^2(z)}\right)\right\} = exp\left\{-\frac{\rho_d^2}{\rho_c^2}\right\}, \tag{22}$$

where ρ_c is the lateral coherence length of the field at the (receiver) plane $z = L$ given by

$$\rho_c = \rho_o\left(1+\frac{\rho_o^2}{2W_o^2\Omega^2}-\frac{\phi^2\rho_o^2}{2W_\zeta^2(z)}\right)^{-\frac{1}{2}}. \tag{23}$$

A similar expression derived from the mutual coherence function by another author was shown to contain an error.[10] Note that Eq. (23) approaches ρ_o in the spherical wave limit ($\Omega_o \to 1$, $\Omega \to \infty$), while in the plane wave limit ($\Omega_o \to 1$, $\Omega \to 0$) $\rho_c \to \rho_o/\sqrt{3}$ as expected.

We can compare the results derived here to those given in Ref. 1 for a partially coherent collimated beam in the absence of turbulence. Again using the notation of Ref. 1, define the 1/e falloff in coherence as $\bar{\rho}_\mu(z)$. Eq. (23) for a collimated beam ($\Omega_o \to 1, \Omega = 2z/kW_b^2$) in the absence of turbulence ($\phi = 1/\Omega$) can be expressed as:

$$\frac{1}{\bar{\rho}_\mu^2(z)} = \frac{1}{2W_b^2\Omega^2} - \frac{1}{2W_\zeta^2(z)\Omega^2} \quad . \tag{24}$$

Recalling that $W_\zeta = W_b\Delta(z)$ and using the relationship $W_b^2 = 4\sigma_S^2$ we obtain

$$\bar{\rho}_\mu(z) = \sqrt{2}\,\delta\,\Delta(z) \tag{25}$$

which is identical to the result obtained in Ref. 1 for a partially coherent collimated beam propagating in free space.

Note that the ratio of the coherence width in any transverse cross-section of the beam to the beam width in that cross section is constant on propagation:

$$\frac{\bar{\rho}_\mu(z)}{\bar{\rho}_S(z)} = \frac{\delta}{\sigma_S} = 2\zeta^{-1}\,; \tag{26}$$

that is, the degree of global coherence of light in any transverse cross-section of a Gaussian Schell-model beam is invariant on propagation. This key result is given in Ref. 1 for the special case of a collimated beam:

$$\frac{\bar{\rho}_\mu(z)}{\bar{\rho}_S(z)} = \frac{\sigma_g}{\sigma_S}. \tag{27}$$

The result derived here in Eq. (26) extends this relationship to the more general case of the Gaussian beam wave propagating either in turbulence or in free-space.

4. ANALYSIS

Here we examine behavior of the beam size $W_\zeta(z)$ given by Eq. (13), and the radius of curvature $R_\zeta(z)$ given in Eq. (20). Fig. 1 shows the normalized beam size W_ζ^2/W_o^2 as a function of the diffractive beam parameter Ω for values of ζ^2 representing beams from the fully coherent (global coherence parameter $\zeta^2 = 1$) to the strongly partially coherent ($\zeta^2 = 26$). As the global coherence parameter increases past unity the spatial coherence of the beam decreases. The effect this has on a propagating beam is clearly seen in Fig. 1. As the beam becomes less coherent the beam size begins to increase beyond its diffractive size. Fig. 2 compares behavior of the coherent beam to the partially coherent beam for nearly focused ($\Omega_o = .001$) and collimated ($\Omega_o = 1$) beams. The partially coherent beam behaves exactly like the coherent beam, except that the expected increase in normalized beam size occurs at smaller values of the diffractive beam parameter Ω. The curve for the normalized beam size is shifted towards smaller values of Ω with the magnitude of this shift being a function of the size of the global coherence parameter ζ^2.

The normalized radius of curvature for a collimated beam is shown as a function of normalized distance Ω for different values of the global coherence parameter ζ^2 in Fig. 3. As ζ^2 increases indicating increased partial coherence of the source beam, observe the pronounced dip in $R_\zeta(z)$ occurring for small values of Ω. For values of $\Omega > 2$ there is an increasingly diminished effect on the radius of curvature due to partial coherence. While in Fig. 3 we have assumed that any increase in global coherence is due to increased partial coherence of the source, in Fig. 4 we have considered the role of turbulence as well. From Fig. 4 we see that when turbulence is present the radius of curvature is impacted for all values of ζ^2, not just for values of $\Omega < 2$ as occurs for a partially coherent beam propagating in free space. Compare the curve for $\zeta^2 = 26$ in Fig. 3 with the curve for $\zeta^2 = 5$, $W_o/\rho_o = 4$ in Fig. 4, both of which have an equivalently sharp minimum in the radius of curvature occurring at about $\Omega = 0.3$. In Fig 3, $\zeta^2 = 26$ while in Fig. 4 where a portion of the global degree of coherence can be attributed to the effects of turbulence $\zeta^2 = 5$. However, both curves are very similar except at higher values of Ω where the influence of turbulence prevents the radius of curvature from eventually approaching its diffractive value, as occurs in Fig. 3. Due to the influence of the turbulence coherence length ρ_0 on the beam parameter ϕ, the radius of curvature is more strongly affected by turbulence than is the beam size.

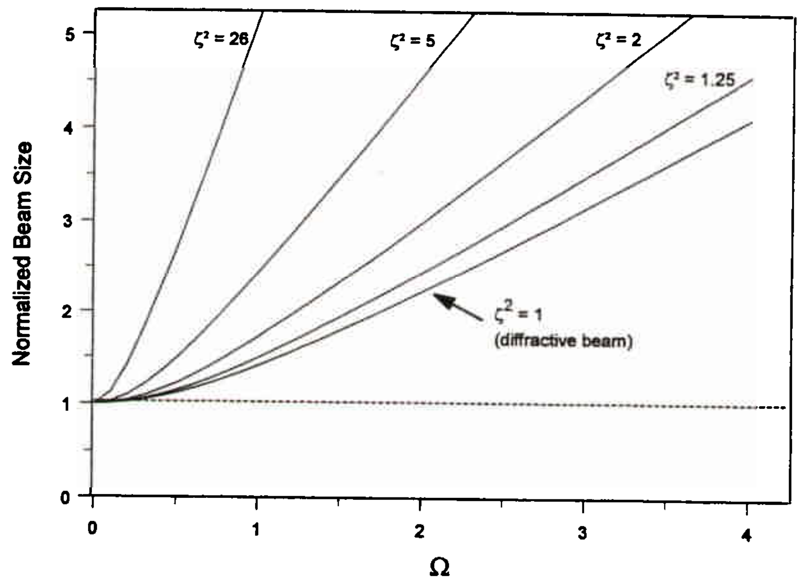

Fig. 1. Normalized beam size W_ζ^2 / W_o^2 as a function of normalized distance Ω for different values of ζ^2.

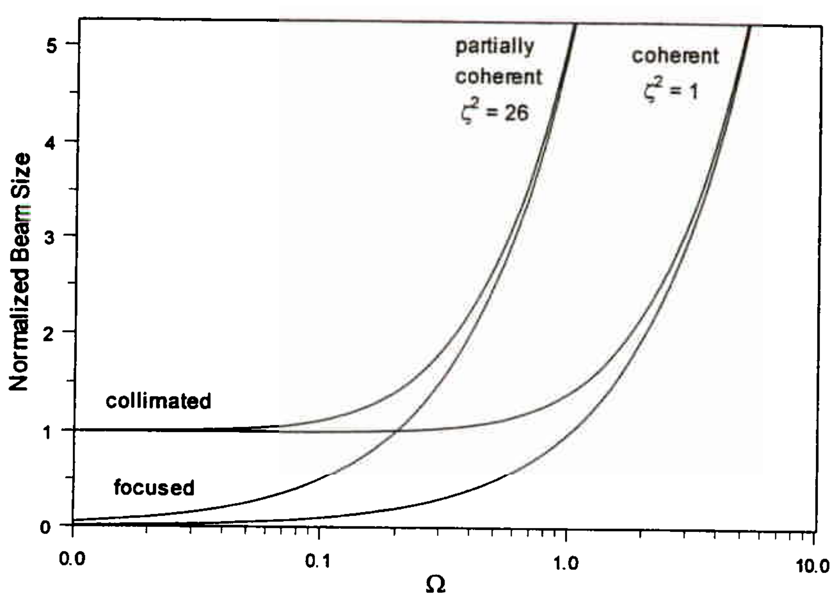

Fig. 2. Normalized beam size W_ζ^2 / W_o^2 as a function of normalized distance Ω for a coherent ($\zeta^2 = 1$) and partially coherent ($\zeta^2 = 26$) collimated beam ($\Omega_o = 1$), and for a coherent ($\zeta^2 = 1$) and partially coherent ($\zeta^2 = 26$) focused beam ($\Omega_O = .001$).

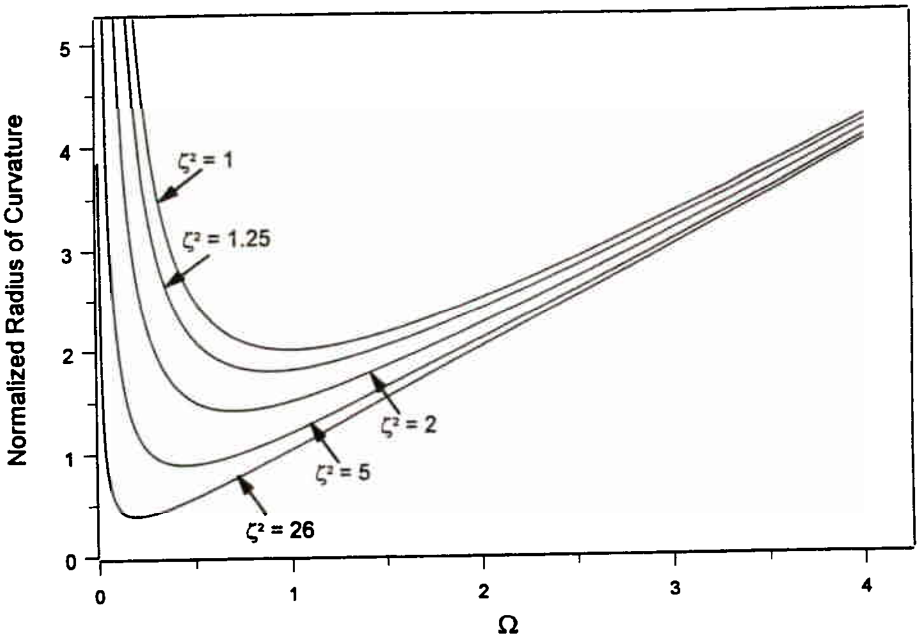

Fig. 3. Normalized radius of curvature $R_\zeta(z)/(\frac{1}{2}W_o^2k)$ as a function of normalized distance Ω for different values of ζ^2.

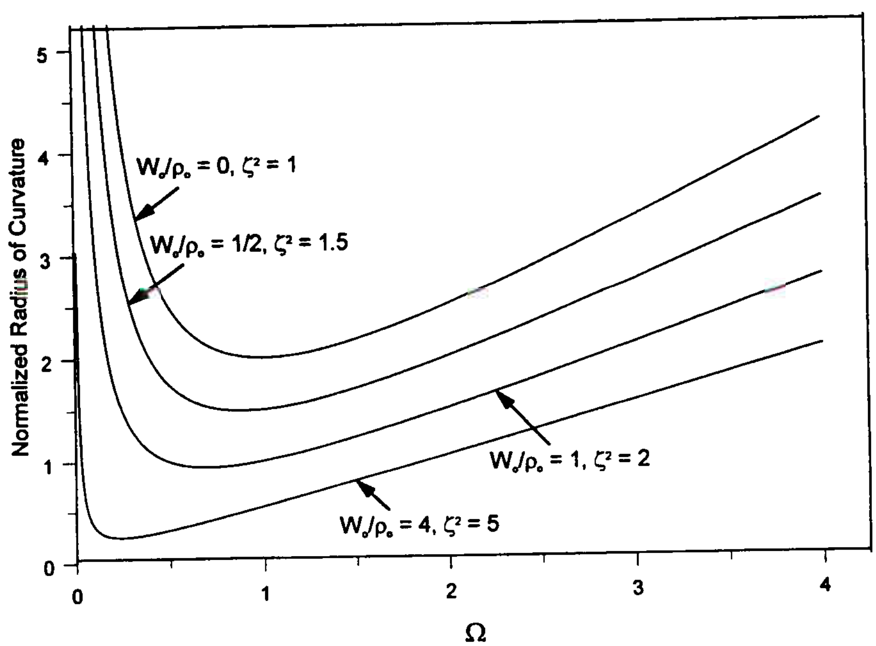

Fig. 4. Normalized radius of curvature $R_\zeta(z)/(\frac{1}{2}W_o^2k)$ as a function of normalized distance Ω for different turbulence strengths W_o/ρ_o and values of ζ^2.

5. EXPERIMENTAL RESULTS

We performed an experiment to examine the behavior of a partially coherent beam propagated through laboratory-created turbulence. The setup used for this experiment is shown below in Fig. 5. A laser beam (diameter ≈ 12 mm) was reflected from a deformable membrane mirror and expanded using lens L1 and the Maksutov-Cassegrain telescope to a diameter of 80 mm. After reflection from the cat's eye consisting of lens L2 and mirror M1 the beam was redirected by beamsplitter BS and focused onto the pinhole PH. The optical power in the pinhole PH was measured using a photo-multiplier and then passed through a lowpass filter. The signal was then acquired by a personal computer (PC) equipped with an A/D converter. A heater was placed about 0.5 m in front of the telescope to artificially induce turbulence. The distance between the telescope and the cat's eye was 2.7 m.

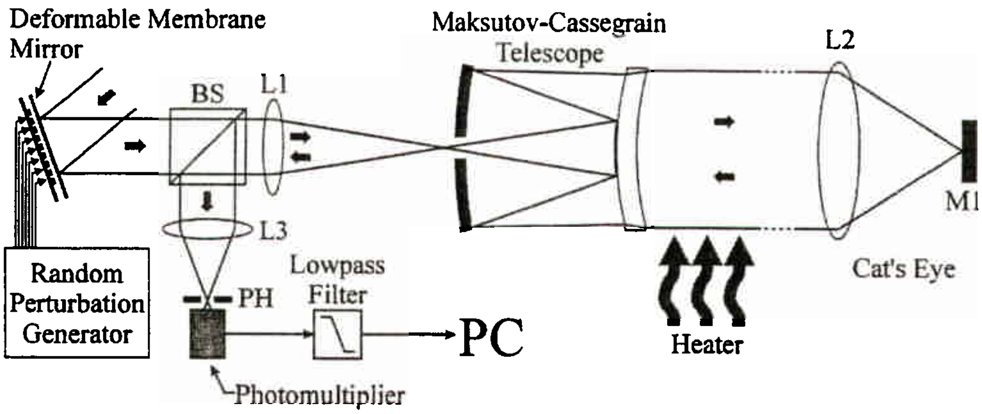

Fig. 5. Experimental set-up.

The deformable membrane mirror from Flexible Optical B.V. (OKO mirror) has 37 independently addressable electrodes in a hexagonal configuration on a 12 mm diameter area.[11,12] At the beginning of the experiments and in the absence of turbulence the control voltages u_i^0 (i = 1,...,37) were set to maximize the power in the pinhole. Then the heater was switched on to create turbulence and the power in the pinhole was measured at an acquisition rate of about 700 Hz. Since the signal fluctuations induced by the turbulence were slower than 50 Hz the signal was not affected by the 50 Hz low-pass filter. Because of the cat's eye reflector the system is virtually insensitive to turbulence-induced tilts and all power fluctuations in the pinhole are due to higher-order aberrations.

To model partial coherence, phase distortions were applied to the laser beam by adding random perturbation voltages δu_i to the control voltages u_i^0. The perturbation voltages $\delta u_i = \pm\sigma$ followed a Bernoulli distribution, with a constant value σ having equal probability for positive and negative perturbation voltages, i.e. $p(+\sigma) = p(-\sigma) = 0.5$. The perturbation voltages were updated with a frequency of about 1400 Hz. Data sets of 8 × 10^5 values were acquired for both application of perturbed and unperturbed control voltages. Because of the 50 Hz low-pass filter, each measured value represents the average of several random phase perturbation realizations and in this way models partial coherence. The data sets were used to compute the probability distributions ρ for the measured power values P normalized by their mean value $<P>$, as shown in Fig. 6. To virtually exclude effects caused by long-term turbulence fluctuations, the data sets were measured in alternating intervals of about 6 seconds each.

We noticed a decrease in intensity fluctuations when using the partially coherent beam model, representing an expected reduction in bit error rates. When applying random phase distortions to the beam the normalized standard deviation $\sigma_P = [N^{-1}\sum_i (P_i - <P>)^2]^{1/2} / <P>$ was 0.35. In contrast, without random phase distortions the random phase distortion σ_P increased to 0.41.

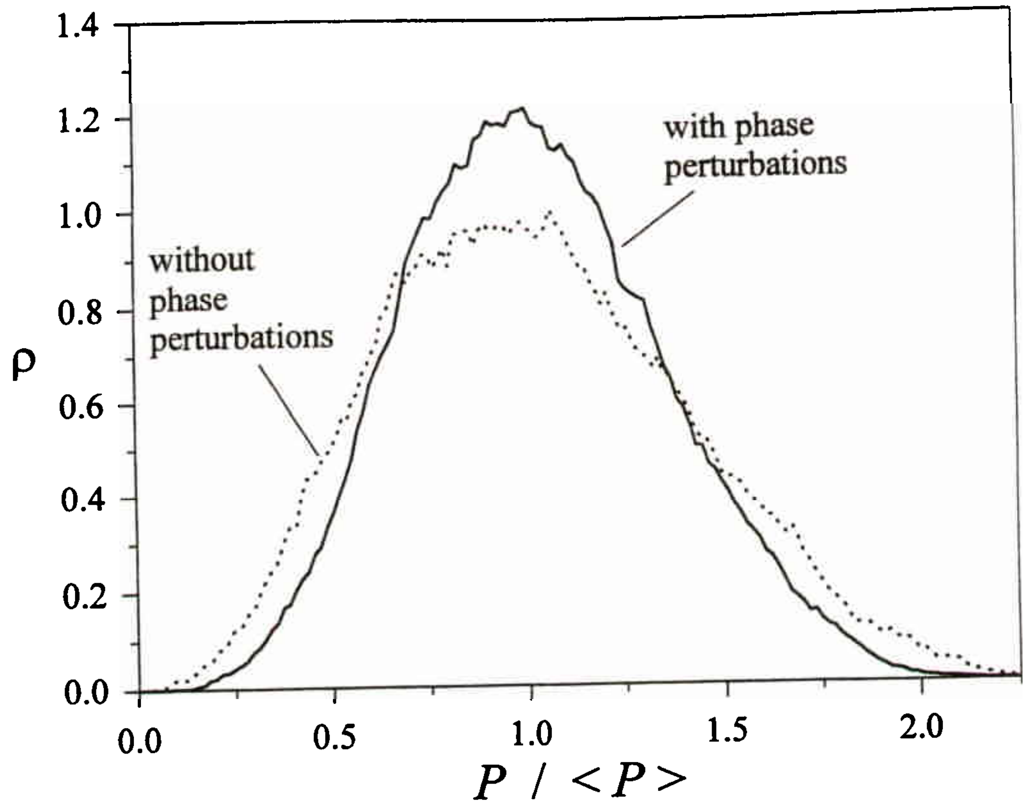

Fig. 6. Probability of occurrence ρ vs. normalized measured power $P/\langle P\rangle$.

6. CONCLUSIONS

We have derived an expression for the cross-spectral density of a partially (spatially) coherent Gaussian TEM_{00} beam propagating through an atmospheric channel containing clear-air turbulence. For a strictly monochromatic or sufficiently narrow band field the cross-spectral density reduces to the complex mutual coherence function. However, if the optical field has a substantial spread in optical frequencies as might well be the case in very high data rate optical communication systems, the mutual coherence function may always be obtained by inverse Fourier transformation of the more fundamental quantity, the cross-spectral density.

From the cross-spectral density we have derived expressions for the average intensity, beam size, radius of curvature and lateral coherence length of a partially coherent beam propagating through clear-air turbulence. These expressions are valid for any beam type – focused, collimated, divergent, and the limiting case of the plane and spherical wave – and reduce to earlier expressions for the diffractive beam and partially coherently collimated beam in free-space. We have also defined a more general expression for the global degree of coherence. Previously it was shown for the special case of a collimated beam that the degree of global coherence of light in any transverse cross-section of a Gaussian Schell-model beam is invariant on propagation. Here we have extended this result to the more general case of the Gaussian beam wave propagating either in turbulence or in free space. Our preliminary experimental results indicate that a reduction in bit error rates should be expected when a partially coherent beam is used in a free-space laser communication system.

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