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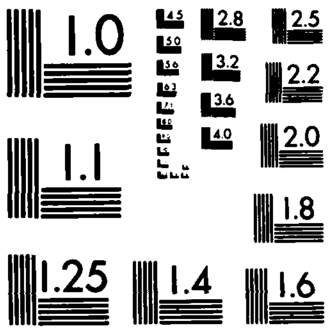
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Aperture Averaging of Scintillation for Space-to-Ground Optical Communication Applications

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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We derive a useful engineering formula for the aperture averaging factor of optical scintillation that exhibits the explicit parametric dependence on wavelength, collector diameter, and path weighted integrals of the index structure constant profile. Numerical results presented here indicate that care should be exercised in the application of available index structure constant profile models to optical communication system performance studies.

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CONTENTS

TABLE

APERTURE AVERAGING OF SCINTILLATION FOR SPACE-TO-GROUND OPTICAL COMMUNICATION APPLICATIONS

Communication from space-to-ground stations which utilize coherent short wavelength radiation (~1μm) as the carrier must contend with atmospherically induced scintillation. The amount of scintillation with which the communication system must deal is a function of the diameter of the collecting entrance pupil in the ground station optical system. As is well known, increasing the size of the aperture diameter reduces the amount of scintillation measured by the detector.[1,2,3]

The aperture averaging factor is defined as the ratio of the variance of irradiance obtained from a finite size collecting aperture to the corresponding quantity obtained from a "point aperture." In this letter the aperture averaging factor is calculated for both spherical and plane waves. The Kolmogorov spectrum with an arbitrary index structure constant C_n^2 profile, as would be encountered in a space-to-ground propagation geometry, is used here. A useful engineering formula for the aperture averaging factor that exhibits the explicit parametric dependence on wavelength, collector diameter and path weighted integrals of C_n^2 is presented below. In Ref. 3 it is shown that the aperture averaging factor, A, can be written as

$$A = \frac{1}{8} \int_0^1 \frac{C_I(Dx)}{C_I(0)} M_L(x)\, x dx \qquad (1)$$

where $C_I(\rho)$ is the covariance of irradiance and

$$M_L(x) = (2/\pi)[\cos^{-1} x - x\,(1-x^2)^{1/2}]$$

is the optical transfer function of an unaberrated circular entrance aperture. Here we consider weak scintillation conditions only where $C_I(0) \ll 1$.

Following the development given in Ref. 3, it can be shown for spherical waves that the aperture averaging factor can be written as

$$A = \frac{B}{C_I(0)} \tag{2}$$

where

$$B = 4\pi^2 \int_0^z dz'(z-z')^2\left(\frac{z'}{z}\right)^2 \int_0^\infty f_s f_R \Phi_n K^5 dK \tag{3}$$

$$C_I(0) = 4\pi^2 \int_0^z dz'(z-z')^2\left(\frac{z'}{z}\right)^2 \int_0^\infty f_s \Phi_n K^5 dK \tag{4}$$

$$f_s = \mathrm{sinc}^2[K^2 z'(z-z')/2kz] \tag{5}$$

$$f_R = \left[\frac{2J_1(KDz'/2z)}{(KDz'/2z)}\right]^2 \tag{6}$$

and, for the Kolmogorov spectrum,

$$\Phi_n(K,z') \simeq 0.033\; C_n^2(z')K^{-11/3}. \tag{7}$$

In Eqs. (3)-(6), $z' = 0$ corresponds to the location of the source, z is the distance between the source and the receiver, k is the optical wavenumber, $\mathrm{sinc}(u) = \sin(u)/u$, D is the diameter of the circular collector, and J_1 is the Bessel function of the first kind of order one. The quantities f_s and f_R can be regarded as the spherical wave turbulent diffraction and receiver filter functions, respectively.[3] To modify Eqs. (3) - (6) for plane wave propagation the factor z'/z is replaced by unity.

We are primarily concerned with downward propagation from an exoatmospheric laser source to a receiver located within the atmosphere or on the ground. For the corresponding case of upward propagation, the transverse irradiance correlation scale length is typically much greater than the diameter of collection apertures of practical concern, and hence no appreciable aperture averaging effects will result (i.e., $A \approx 1$).

For spherical-wave propagation, f_R possesses spatial frequencies $K \lesssim K_R = 2z/Dz' \approx 2/D$. The relative importance of turbulent diffraction effects and aperture averaging can be seen by comparing K_R and K_s, where $K_s = [2kz/z'(z-z')]^{1/2} \approx [2k/z_o]^{1/2}$. For

$$D^2 >> \frac{z_o}{k} , \tag{8}$$

$K_R << K_s$ and all the turbulence lies in the near field of the aperture. In this case the geometrical optics formulation (i.e., $f_s \approx 1$) can be used in Eq. (3) to compute the collected scintillation. On the other hand, for $D^2 << z_o/k$ it follows that $K_R >> K_s$, and one may use the approximation $f_R \approx 1$ in Eq. (3) with the result that the aperture averaging factor approaches unity. The quantity z_o is of the order 10 km and thus, for example, apertures of diameters larger than a few inches will exhibit averaging effects for visible light propagation.

In the downward propagation direction, the atmospheric turbulence is limited to the latter portion of the propagation path where $z' \approx z$. The function $C_n^2(z')$ is nonzero only in the range $z - z_o \leq z' \leq z$, where for an exoatmospheric source $z_o \ll z$. A change of variables from z' to $\eta = z - z'$ is indicated with $C_n^2(z')$ replaced by $C_n^2(\eta)$, where $\eta = 0$ corresponds to the location of the receiver. If inequality (8) is satisfied, then $f_s \approx 1$ in Eq. (3) and the aperture averaging factor is given by

$$A \simeq A_o(\lambda h_o/D^2)^{7/6} \tag{9}$$

where

$$A_o = 4\,\frac{\int_o^\infty x^{-2/3}\; J_1{}^2(x)\, dx}{\int_o^\infty x^{-11/16}\; \sin^2 x\, dx} = \frac{\Gamma^5(1/3)}{\pi^{14/3}[3^{1/2}-1]} \simeq 0.90, \tag{10}$$

$$h_o = \left[\frac{\int_{path} d\eta C_n^2(\eta)\eta^2(1-\eta z^{-1})^{-1/3}}{\int_{path} d\eta C_n^2(\eta)[\eta(1-\eta z^{-1})]^{5/6}}\right]^{6/7}, \tag{11}$$

λ is the optical wavelength, and Γ is the gamma function. The quantity h_o can be regarded as an atmospheric turbulence aperture averaging scale height. For plane waves or for spherical waves where $z \gg z_o$ (i.e., $\eta/z \ll 1$) we have that

$$h_o \simeq \left[\frac{\int_{path} d\eta\; C_n^2(\eta)\eta^2}{\int_{path} d\eta\; C_n^2(\eta)\eta^{5/6}}\right]^{6/7} \tag{12}$$

An important attribute of Eq. (9) is that it reveals the explicit parametric dependence of the aperture averaging factor on optical wavelength, collector diameter, and path weighted integrals of C_n^2. For propagation at zenith angle θ it is easy to show that h_o in Eq. (9) is replaced by $h_o \sec\theta$, and $C_n^2(\eta)$ in Eqs. (11) and (12) is now given by the index structure constant profile for the situation of interest.

An engineering formula can be constructed from Eq. (9) which can be useful even when inequality (8) is violated (i.e., for small apertures). Indeed, for $D^2 \ll z_o/k$, $A \approx 1$, and thus without requiring detailed knowledge of $C_I(\rho)$, the aperture averaging factor can be approximated by the engineering formula:

$$A \simeq \frac{1}{1 + A_o^{-1}[D^2/\lambda h_o \sec\theta]^{7/6}} \tag{13}$$

where $A_o^{-1} \simeq 1.1$. This expression gives the aperture averaging factor for space-to-ground propagation conditions in closed form and is thus suitable for system studies of a broad class of atmospheric turbulence models.

For illustrative purposes we present, in Table 1, numerical values of h_o and A for zenith propagation, $\lambda = 1$ μm, $D = 1$ m, and various C_n^2 profiles quoted in the literature. In addition, we give the corresponding weak scintillation values for the "point aperture" variance of irradiance: $C_I(0) \simeq 2.24\, k^{7/6}\int C_n^2(\eta)\eta^{5/6}d\eta$.

Examination of Table 1 reveals for the turbulence models considered here that both h_o and A based on the NAVY/DARPA model are about a factor of two to four less than the corresponding quantities based on Barleti's and Hufnagel's models. For example, the NAVY/DARPA daytime model and the Hufnagel model (for V = 27 m/sec) both indicate that the variance of irradiance at a "point" is about 0.1. On the other hand, the ratio of the corresponding aperture averaging factors is about 3.6. Hence, for $\lambda = 1$ μm and a 1 m entrance aperture diameter, the variance of irradiance based on the Hufnagel model is 3.6 times larger than that obtained from the NAVY/DARPA daytime model. As this example illustrates, care should be exercised in the application of available C_n^2 models to optical communication system performance studies.

Table 1. Aperture averaging scale height and reduction factor for various C_n^2 profiles. The quantity V is the rms wind speed between 5 and 20 km altitude above mean sea level.[6]

Turbulence Model	Scale Height h_o (km)	Aperture Averaging Factor: Zenith Propagation, $\lambda = 1\mu m$, D = 1m	Point Irradiance Variance
NAVY/DARPA[(4)] (DAYTIME)	3.4	1.2×10^{-3}	0.095
NAVY/DARPA (NIGHTIME)	5.3	2.0×10^{-3}	0.053
Barleti et al.[(5)]	9.8	4.1×10^{-3}	0.18
HUFNAGEL[(6)] (V = 18 m/sec)	9.1	3.7×10^{-3}	0.063
HUFNAGEL (V = 27 m/sec)	10.3	4.3×10^{-3}	0.11
HUFNAGEL (V = 36 m/sec)	10.8	4.6×10^{-3}	0.19

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