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# Theoretical Analysis of Effects of Atmospheric Turbulence on Bit Error Rate for Satellite Communications in Ka-band

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## 1. Introduction

In electromagnetic wave propagation through the earth's atmosphere like satellite communications, it is known that random fluctuations of the dielectric constant of atmosphere affect propagation characteristics of electromagnetic waves (Fante, 1975; 1980; Ishimaru, 1997; Rytov et al., 1989; Strohbehn, 1977; Tatarskii, 1961; 1971; Tatarskii et al., 1993; Uscinski, 1977; Wheelon, 2003). The random fluctuations, called atmospheric turbulence, cause spot dancing, wave form distortion, scintillations of the received intensity, the decrease in the spatial coherence of wave beams etc. These effects make the received power decrease, and result in the degradation in the performance on satellite communication links. Fig. 1 shows the image of spot dancing and wave form distortion of wave beams. Fig. 2 presents the image of the decrease in the spatial coherence of transmitted waves due to a wave front distortion.

The effects of atmospheric turbulence are not negligible in satellite communications in high carrier frequencies at low elevation angles. For example, tropospheric scintillation, caused by turbulence in the lowest layer of atmosphere, has been observed in satellite communications in Ku-band at low elevation angles (Karasawa, Yamada & Allnutt, 1988; Karasawa, Yasukawa & Yamada, 1988). Therefore, it becomes important to consider the effects of atmospheric turbulence appropriately in the design of such satellite communication systems. Some models to predict tropospheric scintillation have been developed for applications up to around 14 GHz in the carrier frequency on the basis of both theoretical and empirical studies (Ippolito, 2008). However, because a carrier frequency becomes higher according to the increase in the required channel capacity of satellite communication links in the next generation, the analysis of the effects of atmospheric turbulence should be done for applications at the higher carrier frequencies such as Ka-band, a millimeter wave and an optical wave. Some studies are conducted for satellite communications in such frequencies (Marzano et al., 1999; Matricciani et al., 1997; Matricciani & Riva, 2008; Mayer et al., 1997; Otung, 1996; Otung & Savvaris, 2003; Peeters et al., 1997).

We study the effects of atmospheric turbulence on satellite communications in such high frequencies by the theoretical analysis of the moments of wave fields given on the basis of a multiple scattering method (Tateiba, 1974; 1975; 1982). We investigate the method to estimate

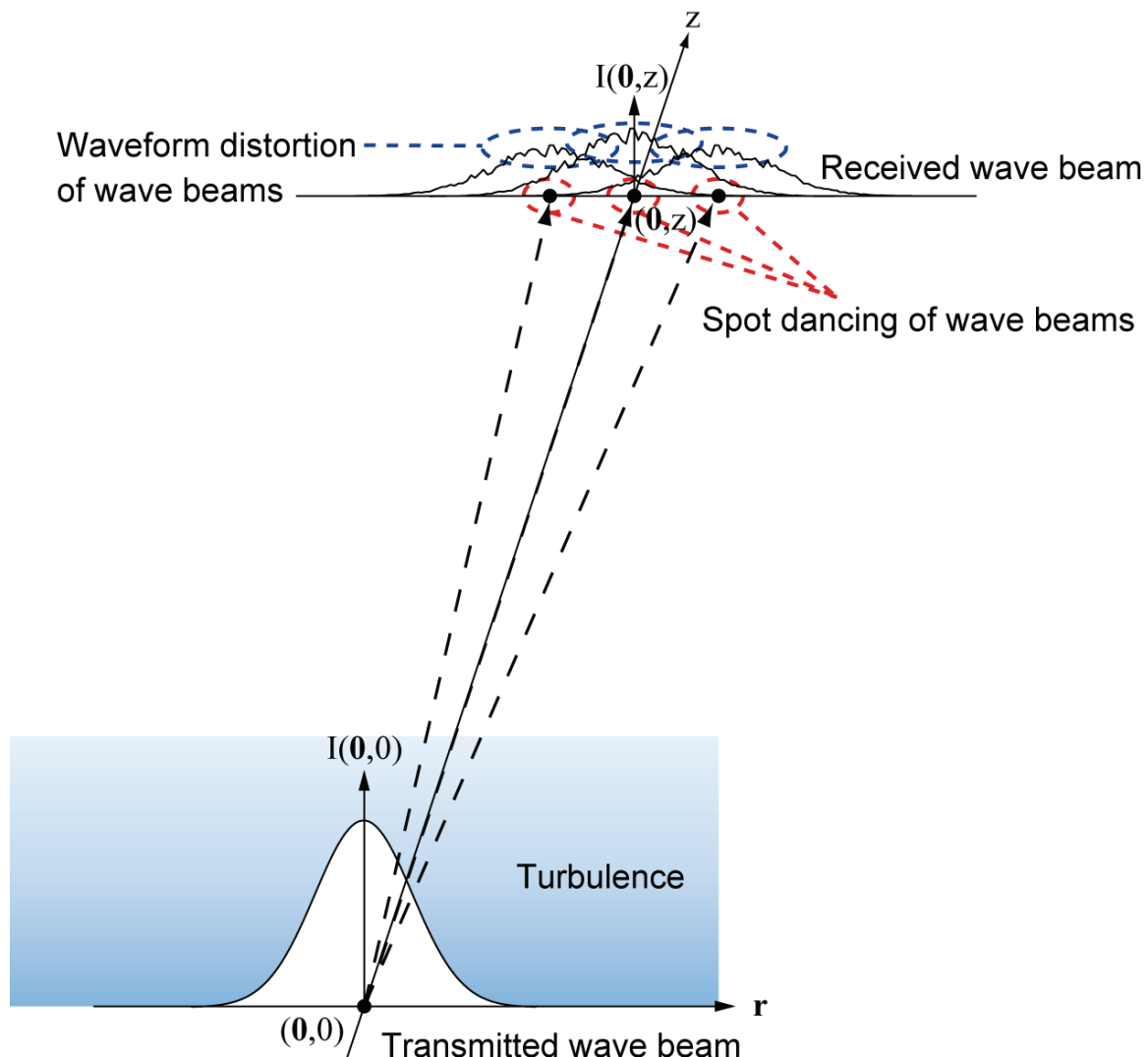


Fig. 1. Spot dancing and wave form distortion of wave beams through atmospheric turbulence where  $I(\mathbf{r},z)$  denotes the intensity of a wave beam at  $(\mathbf{r},z)$ .

the effect on bit error rate (BER) which is one of the most important parameters to determine the system performance (Hanada et al., 2008a;b; 2009a;b;c;d). The probability density function (PDF) of  $E_b/N_0$  (the energy per bit to noise power density ratio) is needed in the analysis of BER for satellite communications. However, it is very difficult to derive the arbitrary order moment and the PDF by the multiple scattering theory, so that the alternative method to estimate effects of atmospheric turbulence on BER has to be considered.

In this chapter, we give attention to the average value of received power which can be obtained by the second moment of a Gaussian wave beam, and then we formulate BER derived from the average received power. We provide the method to estimate effects of atmospheric turbulence on satellite communications by analyzing the degradation in BER performance due to the decrease in the average received power.

Sec. 2 presents formulations which are used in the analysis of BER on satellite communications. We introduce the second moment of a Gaussian wave beam obtained by the moment equation. Using the second moment of a Gaussian wave beam, we prepare the

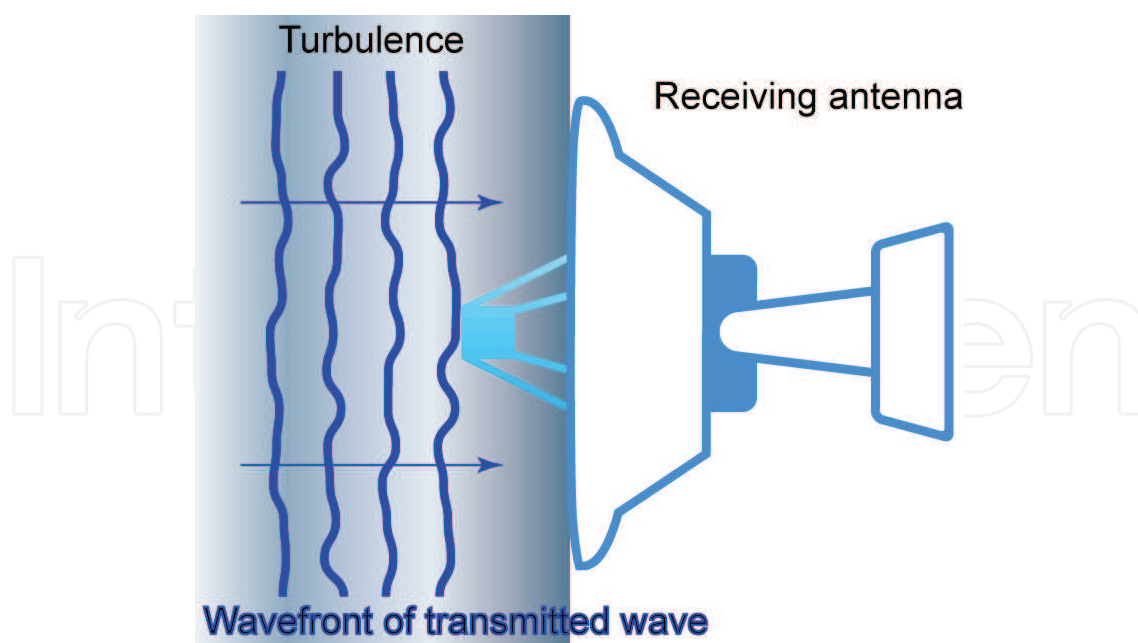


Fig. 2. Decrease in the spatial coherence of transmitted waves due to a wave front distortion.

modulus of the complex degree of coherence (DOC) and the BER derived from the average received power.

Sec. 3 shows the results of analysis of the effect of atmospheric turbulence on satellite communications in Ka-band at low elevation angles. We analyze the DOC and the BER derived from the average received power for the uplink and the downlink, respectively. Furthermore, we analyze the effect of atmospheric turbulence on the BER when we make an aperture radius of the ground station's antenna large in order to increase the antenna gain and improve BER performance.

Sec. 4 provides a summary of this chapter and subjects to resolve in future.

## 2. Formulation

### 2.1 Moment of received waves

We assume that an inhomogeneous random medium, which represents atmospheric turbulence, is characterized by fluctuations of the dielectric constant. The dielectric constant  $\varepsilon$ , the magnetic permeability  $\mu$  and the conductivity  $\sigma$  are expressed as

$$\varepsilon = \varepsilon_0[1 + \delta\varepsilon(\mathbf{r}, z)] \quad (1)$$

$$\mu = \mu_0 \quad (2)$$

$$\sigma = 0, \quad (3)$$

where  $\mathbf{r} = \mathbf{i}_x x + \mathbf{i}_y y$  ( $\mathbf{i}_x$  and  $\mathbf{i}_y$  denote the unit vectors of  $x$  and  $y$  coordinates, respectively) and  $\varepsilon_0$  and  $\mu_0$  are the dielectric constant and the magnetic permeability for free space, respectively. The function  $\delta\varepsilon(\mathbf{r}, z)$  is a Gaussian random function with the properties:

$$\langle \delta\varepsilon(\mathbf{r}, z) \rangle = 0 \quad (4)$$

$$\langle \delta\varepsilon(\mathbf{r}_1, z_1) \cdot \delta\varepsilon(\mathbf{r}_2, z_2) \rangle = B(\mathbf{r}_-, z_+, z_-), \quad (5)$$

where  $\mathbf{r}_- = \mathbf{r}_1 - \mathbf{r}_2$ ,  $z_+ = (z_1 + z_2)/2$ ,  $z_- = z_1 - z_2$ ,  $B(\mathbf{r}_-, z_+, z_-)$  is the correlation function of random dielectric constant and the bracket notation  $\langle \cdot \rangle$  denotes an ensemble average of the

quantity inside the brackets. Thus the medium fluctuates inhomogeneously in the  $z$  direction and homogeneously in the  $\mathbf{r}$  direction. Moreover, we assume that for any  $z$ ,

$$B(\mathbf{0}, z, 0) \ll 1 \quad (6)$$

$$kl(z) \gg 1, \quad (7)$$

where  $k = 2\pi/\lambda$  is the wave number for free space and  $\lambda$  is the wave length. The wave length can be described by  $\lambda = c/f$ , where  $c$  and  $f$  are velocity of light and the carrier frequency, respectively. The function  $l(z)$  is the local correlation length of  $\delta\epsilon(\mathbf{r}, z)$ . The medium changes little the state of polarization of the wave under the conditions (6) and (7), and the present analysis can be made in the scalar approximation. In addition, the forward scattering and the small angle approximations can be applied.

We represent  $u(\mathbf{r}, z)$  as a successively forward scattered wave with  $\exp(-j\omega t)$  time dependence in the inhomogeneous random medium. Fig. 3 shows a model of wave propagation in the inhomogeneous random medium. An arbitrary order moment of  $u(\mathbf{r}, z)$ , which is defined as

$$M_{\mu\nu}(z) \equiv \left\langle \prod_{m=1}^{\mu} u(\mathbf{s}_m, z) \prod_{n=1}^{\nu} u^*(\mathbf{t}_n, z) \right\rangle, \quad (8)$$

satisfies the following moment equation (Tateiba, 1982):

$$\begin{aligned} & \left[ \frac{\partial}{\partial z} - j \frac{1}{2k} \left( \sum_{m=1}^{\mu} \nabla_{\mathbf{s}_m}^2 - \sum_{n=1}^{\nu} \nabla_{\mathbf{t}_n}^2 \right) - j(\mu - \nu)k \right] M_{\mu\nu}(z) \\ &= - \left\{ \frac{k^2}{4} \int_0^z dz' \left[ (\mu - \nu)^2 B \left( \mathbf{0}, z - \frac{z'}{2}, z' \right) + \sum_{m=1}^{\mu} \sum_{n=1}^{\nu} D \left( \mathbf{s}_m - \mathbf{t}_n, z - \frac{z'}{2}, z' \right) \right. \right. \\ & \quad \left. \left. - \sum_{m=1}^{\mu} \sum_{n>m}^{\mu} D \left( \mathbf{s}_m - \mathbf{s}_n, z - \frac{z'}{2}, z' \right) - \sum_{m=1}^{\nu} \sum_{n>m}^{\nu} D \left( \mathbf{t}_m - \mathbf{t}_n, z - \frac{z'}{2}, z' \right) \right] \right\} M_{\mu\nu}(z) \\ & M_{\mu\nu}(0) = M_{\mu\nu}^{\text{in}}(0), \end{aligned} \quad (9)$$

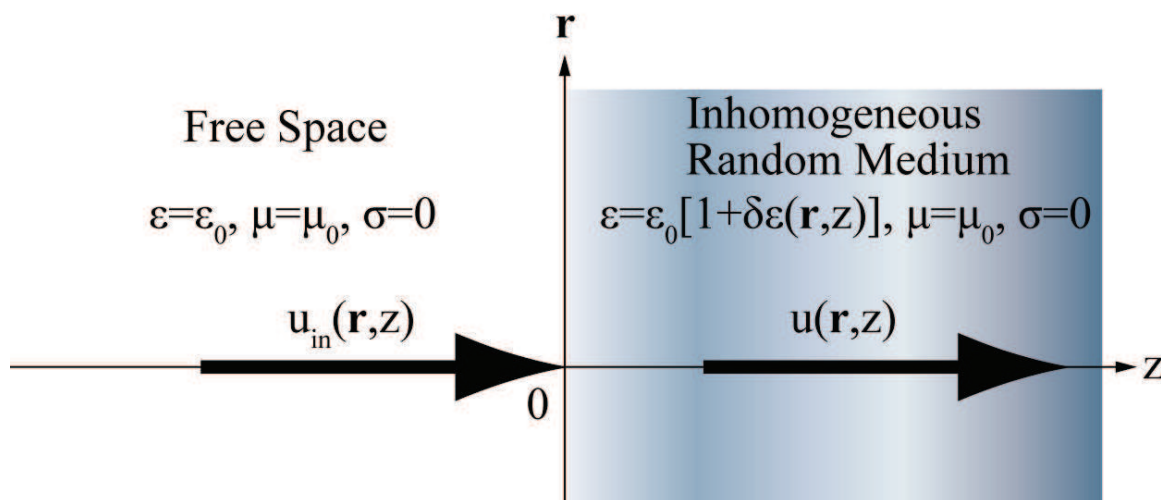


Fig. 3. Model of wave propagation in an inhomogeneous random medium.

where  $\nabla = \mathbf{i}_x \partial / (\partial x) + \mathbf{i}_y \partial / (\partial y)$ ,

$$D(\mathbf{r}_-, z_+, z_-) = 2[B(\mathbf{0}, z_+, z_-) - B(\mathbf{r}_-, z_+, z_-)] \quad (10)$$

$$M_{\mu\nu}^{\text{in}}(z) = \prod_{\mu}^{\mu} u_{\text{in}}(\mathbf{s}_m, z) \prod_{\nu}^{\nu} u_{\text{in}}^*(\mathbf{t}_n, z), \quad (11)$$

and  $u_{\text{in}}(\mathbf{r}, z)$  represents a transmitted waves which is a wave function in free space where  $\delta\epsilon(\mathbf{r}, z) = 0$ . The function  $D(\mathbf{r}_-, z_+, z_-)$  is the structure function of random dielectric constant. The exact solutions to (9), however, have not been obtained except for the second moment, which is one of the most important unsolved problems. The second moment of  $u(\mathbf{r}, z)$  can be derived as follows (Tateiba, 1985):

$$\begin{aligned} M_{11}(\mathbf{r}_+, \mathbf{r}_-, z) &= \langle u(\mathbf{r}_1, z) u^*(\mathbf{r}_2, z) \rangle \\ &= \frac{1}{(2\pi)^2} \iint_{-\infty}^{\infty} d\boldsymbol{\kappa}_+ \hat{M}_{11}^{\text{in}}(\boldsymbol{\kappa}_+, \mathbf{r}_-, z) \\ &\quad \cdot \exp \left[ j\boldsymbol{\kappa}_+ \cdot \mathbf{r}_- - \frac{k^2}{4} \int_0^z dz_1 \int_0^{z_1} dz_2 D \left( \mathbf{r}_- - \frac{z - z_1}{k} \boldsymbol{\kappa}_+, z_1 - \frac{z_2}{2}, z_2 \right) \right], \end{aligned} \quad (12)$$

where  $\mathbf{r}_+ = (\mathbf{r}_1 + \mathbf{r}_2)/2$ ,

$$\hat{M}_{11}^{\text{in}}(\boldsymbol{\kappa}_+, \mathbf{r}_-, z) = \iint_{-\infty}^{\infty} d\mathbf{r}_+ M_{11}^{\text{in}}(\mathbf{r}_+, \mathbf{r}_-, z) \exp(-j\boldsymbol{\kappa}_+ \cdot \mathbf{r}_+) \quad (13)$$

$$M_{11}^{\text{in}}(\mathbf{r}_+, \mathbf{r}_-, z) = u_{\text{in}}(\mathbf{r}_1, z) u_{\text{in}}^*(\mathbf{r}_2, z). \quad (14)$$

## 2.2 Second moment for Gaussian wave beam

A transmitted wave is assumed to be a Gaussian wave beam, where the transmitting antenna is located in the plane  $z = 0$  and the amplitude distribution is Gaussian with the minimum spot size  $w_0$  at  $z = -z_0$  and  $w_0$  denotes the radius at which the field amplitude falls to  $1/e$  of that on the beam axis (see Fig. 4). Then, the wave field in free space (Tateiba, 1985) is given by

$$u_{\text{in}}(\mathbf{r}, z) = \sqrt{\frac{2A}{\pi}} \frac{1}{w} \exp \left[ -(1 - jp) \frac{r^2}{w^2} + j(kz - \beta) \right], \quad (15)$$

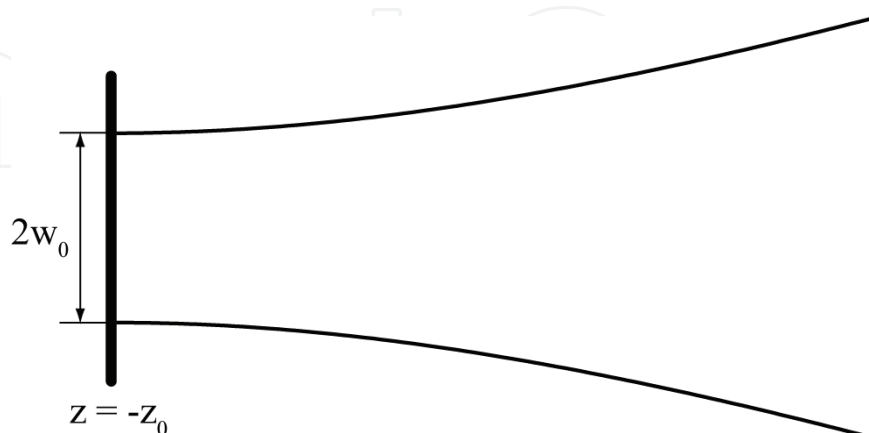


Fig. 4. Gaussian wave beam.

where  $A$  is constant,  $r = |\mathbf{r}|$  and

$$w = w_0(1 + p^2)^{1/2} \quad (16)$$

$$p = 2(z + z_0)/(kw_0^2) \quad (17)$$

$$\beta = \tan^{-1} p. \quad (18)$$

Therefore,

$$M_{11}^{\text{in}}(\mathbf{r}_+, \mathbf{r}_-, z) = \frac{2A}{\pi w^2} \exp \left[ -\frac{2}{w^2} r_+^2 + j \frac{2p}{w^2} (\mathbf{r}_+ \cdot \mathbf{r}_-) - \frac{r_-^2}{2w^2} \right] \quad (19)$$

$$\hat{M}_{11}^{\text{in}}(\boldsymbol{\kappa}_+, \mathbf{r}_-, z) = A \exp \left[ -\frac{w^2}{8} \kappa_+^2 + \frac{p}{2} (\mathbf{r}_- \cdot \boldsymbol{\kappa}_+) - \frac{r_-^2}{2w_0^2} \right]. \quad (20)$$

Substituting (20) into (12), the second moment for a Gaussian wave beam is given by

$$M_{11}(\mathbf{r}_+, \mathbf{r}_-, z) = \frac{A}{(2\pi)^2} \iint_{-\infty}^{\infty} d\boldsymbol{\kappa}_+ \exp \left[ -\frac{w^2}{8} \kappa_+^2 + \left( j\mathbf{r}_+ + \frac{p}{2} \mathbf{r}_- \right) \cdot \boldsymbol{\kappa}_+ - \frac{r_-^2}{2w_0^2} \right. \\ \left. - \frac{k^2}{4} \int_0^z dz_1 \int_0^{z_1} dz_2 D \left( \mathbf{r}_- - \frac{z - z_1}{k} \boldsymbol{\kappa}_+, z_1 - \frac{z_2}{2}, z_2 \right) \right]. \quad (21)$$

### 2.3 Structure function of random dielectric constant

We assume that the correlation function of random dielectric constant defined by (5) satisfies the Kolmogorov model. We use the von Karman spectrum (Ishimaru, 1997) which is the modified model of the Kolmogorov spectrum to be applicable over all wave numbers  $\kappa$  for  $|\mathbf{r}_- + \mathbf{i}_z z_-|$ :

$$\Phi_n(\kappa, z_+) = 0.033 C_n^2(z_+) \frac{\exp(-\kappa^2/\kappa_m^2)}{(\kappa^2 + 1/L_0^2)^{11/6}}, \quad 0 \leq \kappa < \infty \quad (22)$$

where  $\kappa_m = 5.92/l_0$ . Parameters  $C_n^2(z_+)$ ,  $L_0$  and  $l_0$  denote the refractive index structure constant, the outer scale and the inner scale of turbulence, respectively.

Here, we assume that the dielectric constant is delta correlated in the direction of propagation, which is the Markov approximation (Tatarskii, 1971). On this assumption,  $B(\mathbf{r}_-, z_+, z_-)$  can be expressed by using the Dirac delta function  $\delta(z)$  as follows:

$$B(\mathbf{r}_-, z_+, z_-) = 16\pi^2 \delta(z_-) \int_0^\infty d\kappa \kappa \Phi_n(\kappa, z_+) J_0(\kappa r_-), \quad (23)$$

where  $J_0(z)$  is the Bessel function of the first kind and order zero. Therefore, we obtain the structure function defined by (10) as follows:

$$D(\mathbf{r}_-, z_+, z_-) = 32\pi^2 \delta(z_-) \int_0^\infty d\kappa \kappa \Phi_n(\kappa, z_+) [1 - J_0(\kappa r_-)] \\ = \delta(z_-) \cdot \frac{96\pi^2}{5} \cdot 0.033 C_n^2(z_+) L_0^{5/3} \left[ 1 - \Gamma\left(\frac{1}{6}\right) \left(\frac{r_-}{2L_0}\right)^{5/6} I_{-5/6}\left(\frac{r_-}{L_0}\right) \right. \\ \left. + \Gamma\left(\frac{1}{6}\right) \left(\frac{1}{\kappa_m L_0}\right)^{5/3} \sum_{n=0}^{\infty} \frac{1}{n!} \left(\frac{1}{\kappa_m L_0}\right)^{2n} {}_1F_1\left(-n - \frac{5}{6}; 1; -\frac{\kappa_m^2 r_-^2}{4}\right) \right], \quad (24)$$



where  $\Gamma(z)$ ,  ${}_1F_1(a; b; z)$  and  $I_\nu(z)$  are the gamma function, the confluent hypergeometric function of the first kind and the modified Bessel function of the first kind, respectively. Note that we use the solution including an infinite series (Wang & Strohbehn, 1974) in order to ease the numerical analysis of the integral with respect to  $\kappa$ .

## 2.4 Model of analysis

We analyze effects of atmospheric turbulence on the GEO satellite communications for Ka-band at low elevation angles. Fig. 5 shows the propagation model between the earth and the GEO satellite. The earth radius, the altitude of satellite and the elevation angle are expressed by  $R$ ,  $L$  and  $\theta$ , respectively. A height of the top of atmospheric turbulence is shown by  $h_t$ . The  $z_L$  is the distance from a transmitting antenna to a receiving antenna:

$$z_L = \sqrt{(R + L)^2 - (R \cos \theta)^2} - R \sin \theta, \quad (25)$$

and  $z_{ht}$  is the distance of propagation through atmospheric turbulence:

$$z_{ht} = \sqrt{(R + h_t)^2 - (R \cos \theta)^2} - R \sin \theta. \quad (26)$$

Note that  $z_L \gg z_{ht}$  is satisfied for the GEO satellite communications. Therefore, for the uplink, we can approximate  $z - z_1 \simeq z$  in the integral with respect to  $z_1$  in (21), and then express the second moment of received waves at the GEO satellite:

$$M_{11}(\mathbf{r}_+, \mathbf{r}_-, z_{UL}) \simeq \frac{A}{(2\pi)^2} \iint_{-\infty}^{\infty} d\kappa_+ \exp \left[ -\frac{w^2}{8} \kappa_+^2 + \left( j\mathbf{r}_+ + \frac{p}{2}\mathbf{r}_- \right) \cdot \kappa_+ - \frac{r_-^2}{2w_0^2} \right. \\ \left. - \frac{k^2}{4} \int_0^{z_{UL}} dz_1 \int_0^{z_1} dz_2 D \left( \mathbf{r}_- - \frac{z_{UL}}{k} \kappa_+, z_1 - \frac{z_2}{2}, z_2 \right) \right], \quad (27)$$

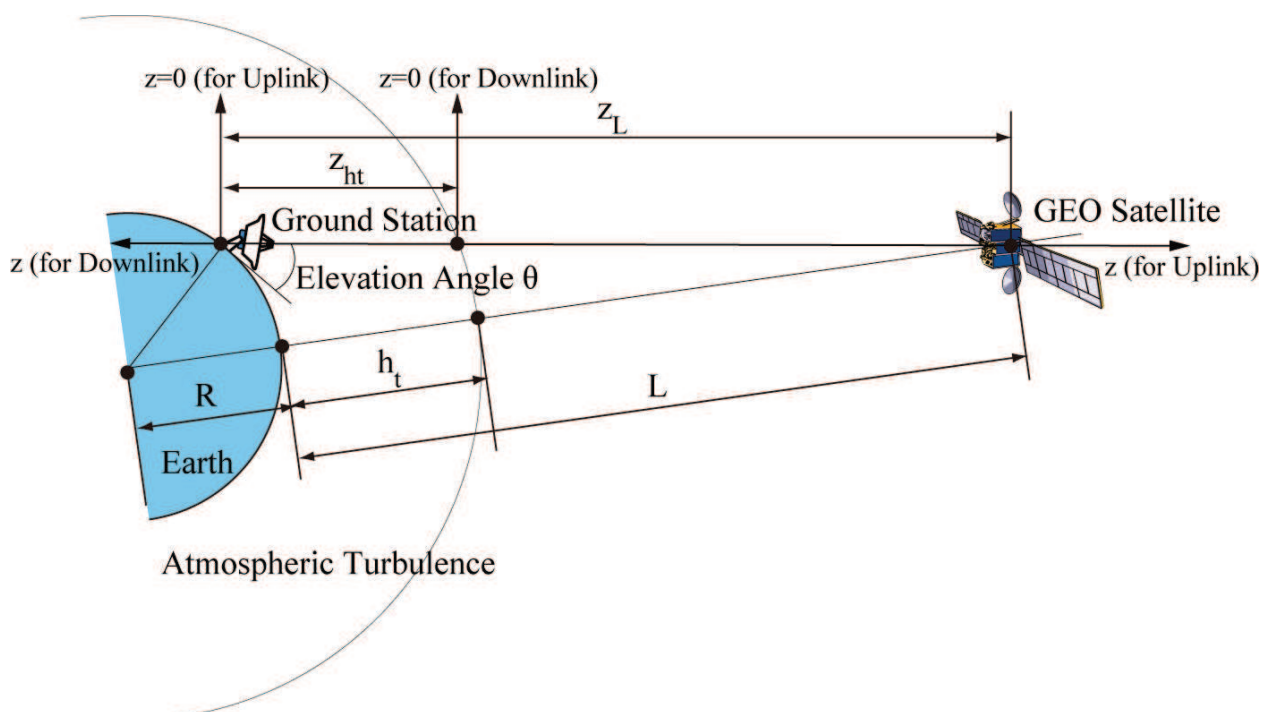


Fig. 5. Earth – GEO satellite propagation model.



where  $z_{UL} = z_L$ ,  $w = w_0 \sqrt{1 + p^2}$ ,  $p = 2z_L / (kw_0^2)$  and the subscript of  $z_{UL}$  denotes the uplink. On the other hand, for the downlink, the statistical characteristics of a wave beam's incidence into atmospheric turbulence can be approximately treated as those of a plane wave's incidence. Thus the second moment of received waves at the ground station can be approximately expressed by

$$M_{11}(\mathbf{r}_+, \mathbf{r}_-, z_{DL}) \simeq \frac{2A}{\pi w^2} \exp \left[ -\frac{k^2}{4} \int_0^{z_{DL}} dz_1 \int_0^{z_1} dz_2 D \left( \mathbf{r}_-, z_1 - \frac{z_2}{2}, z_2 \right) \right], \quad (28)$$

where  $z_{DL} = z_{ht}$ ,  $w = w_0 \sqrt{1 + p^2}$ ,  $p = 2(z_L - z_{h1}) / (kw_0^2)$  and the subscript of  $z_{DL}$  denotes the downlink.

Here, the refractive index structure constant is assumed to be a function of altitude. Referring to some researches for the dependence of the refractive index structure constant in boundary layer (Tatarskii, 1971) and in free atmosphere (Martini et al., 2006; Vasseur, 1999) on altitude, we assume the following vertical profile as a function of altitude:  $h = \sqrt{(z + R \sin \theta)^2 + (R \cos \theta)^2} - R$ .

$$\begin{aligned} C_n^2(h) &= C_{n0}^2 \left( 1 + \frac{h}{h_{s1}} \right)^{-2/3}, & \text{for } 0 \leq h < h_1 \\ &= C_{n0}^2 \left( 1 + \frac{h_1}{h_{s1}} \right)^{-2/3} \left( \frac{h}{h_1} \right)^{-4/3}, & \text{for } h_1 \leq h < h_2 \\ &= C_{n0}^2 \left( 1 + \frac{h_1}{h_{s1}} \right)^{-2/3} \left( \frac{h_2}{h_1} \right)^{-4/3} \exp \left( -\frac{h - h_2}{h_{s2}} \right), & \text{for } h_2 \leq h \leq h_t \end{aligned} \quad (29)$$

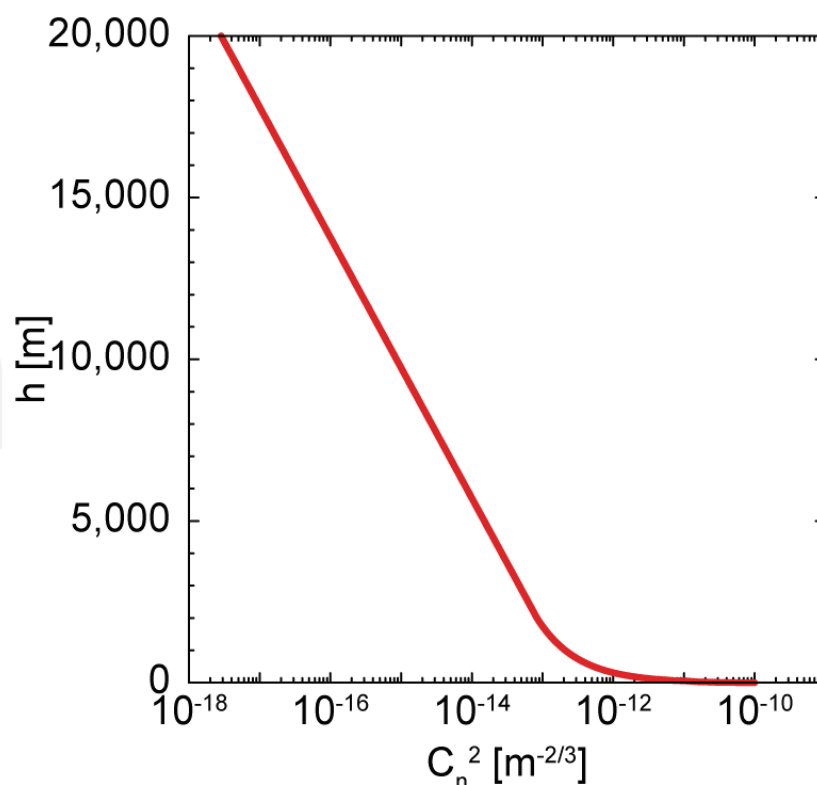


Fig. 6. Vertical profile of refractive index structure constant as a function of altitude.

| ITEM                                                                | VALUE                                  |
|---------------------------------------------------------------------|----------------------------------------|
| Carrier frequency (uplink / downlink): $f$                          | 30.0/20.0 GHz                          |
| Velocity of light: $c$                                              | $3.0 \times 10^8$ m/s                  |
| Elevation angle: $\theta$                                           | 5.0 deg                                |
| Aperture radius of an antenna in the GEO satellite                  | 1.2 m                                  |
| Aperture radius of an antenna in the ground station                 | 1.2 to 7.5 m                           |
| Earth radius: $R$                                                   | 6,378 km                               |
| Height of GEO satellite: $L$                                        | 35,786 km                              |
| Height of the top of atmospheric turbulence: $h_t$                  | 20 km                                  |
| Refractive index structure constant at the ground level: $C_{n0}^2$ | $1.0 \times 10^{-10} \text{ m}^{-2/3}$ |
| Outer scale of turbulence: $L_0$                                    | 100 m                                  |
| Inner scale of turbulence: $l_0$                                    | 1 mm                                   |

Table 1. Parameters used in analysis.

where  $h_1 = 50$  m,  $h_2 = 2,000$  m,  $h_t = 20,000$  m,  $h_{s1} = 2$  m and  $h_{s2} = 1,750$  m. Fig. 6 shows a vertical profile of the refractive index structure constant. We assume  $C_{n0}^2 = 1.0 \times 10^{-10} \text{ m}^{-2/3}$  by referring to the profile of the standard deviation value obtained by Reference (Vasseur, 1999). We set  $L_0 = 100$  m and  $l_0 = 1$  mm.  
Table 1 shows parameters used in analysis.

2.5 Modulus of complex degree of coherence

Using the second moment of received waves, we examine the loss of spatial coherence of received waves on the aperture of a receiving antenna by the modulus of the complex degree of coherence (DOC) (Andrews & Phillips, 2005) defined by

$$\text{DOC}(\boldsymbol{\rho}, z) = \frac{M_{11}(\mathbf{0}, \boldsymbol{\rho}, z)}{[M_{11}(\boldsymbol{\rho}/2, \mathbf{0}, z)M_{11}(-\boldsymbol{\rho}/2, \mathbf{0}, z)]^{1/2}}, \tag{30}$$

where  $\rho = |\boldsymbol{\rho}|$  is the separation distance between received wave fields at two points on the aperture as shown in Fig. 7.

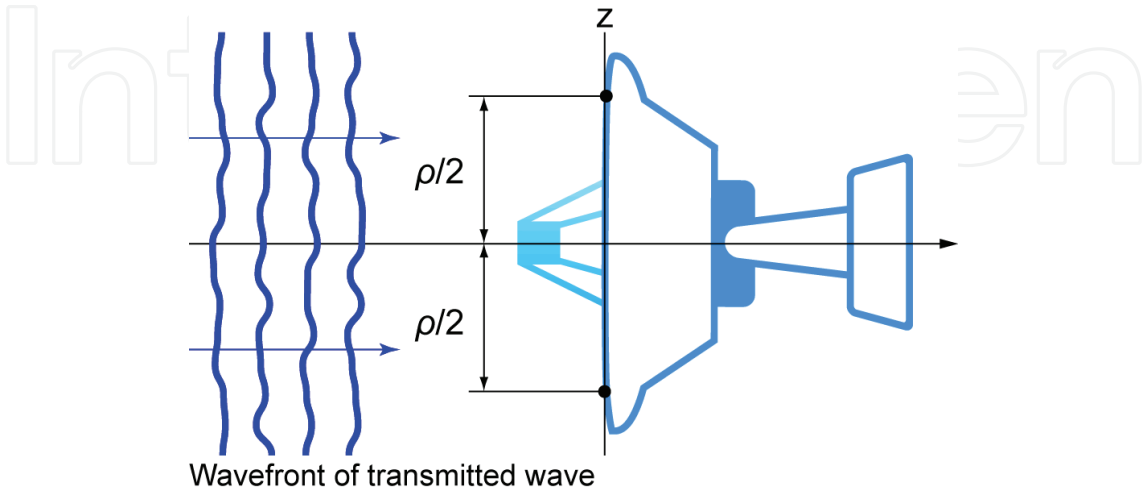


Fig. 7. Modulus of complex degree of coherence.

## 2.6 BER derived from average received power

We define BER derived from the average received power obtained by the second moment of received waves. Here we assume a parabolic antenna as a receiving antenna. When a point detector is placed at the focus of a parabolic concentrator, the instantaneous response in the receiving antenna is proportional to the electric field strength averaged over the area of the reflector. When the aperture size is large relative to the electromagnetic wavelength, the electric field strength averaged over the area of the reflector in free space can be described (Wheelon, 2003) by

$$\overline{u_{\text{in}}(z)} = \frac{1}{S_e} \iint_{-\infty}^{\infty} d\mathbf{r} u_{\text{in}}(\mathbf{r}, z) g(\mathbf{r}), \quad (31)$$

where  $S_e$  is the effective area of a reflector. The field distribution  $g(\mathbf{r})$  is defined by a Gaussian distribution of attenuation across the aperture with an effective radius  $a_e$ :

$$g(\mathbf{r}) = \exp\left(-\frac{r^2}{a_e^2}\right). \quad (32)$$

Then the power received by the antenna in free space is given by

$$\begin{aligned} P_{\text{in}}(z) &= S_e \cdot \frac{\text{Re}[\overline{u_{\text{in}}(z)} \cdot \overline{u_{\text{in}}^*(z)}]}{Z_0} \\ &= \frac{1}{S_e Z_0} \cdot \text{Re} \left[ \iint_{-\infty}^{\infty} \iint_{-\infty}^{\infty} d\mathbf{r}_+ d\mathbf{r}_- M_{11}^{\text{in}}(\mathbf{r}_+, \mathbf{r}_-, z) \exp\left(-\frac{2}{a_e^2} r_+^2 - \frac{1}{2a_e^2} r_-^2\right) \right], \end{aligned} \quad (33)$$

where  $\text{Re}[x]$  denotes the real part of  $x$  and  $Z_0$  is the characteristic impedance. The energy per bit  $E_b$  can be obtained by the product of the received power  $P_{\text{in}}(z)$  and the bit time  $T_b$ :

$$\begin{aligned} E_b &= P_{\text{in}}(z) \cdot T_b \\ &= \frac{T_b}{S_e Z_0} \cdot \text{Re} \left[ \iint_{-\infty}^{\infty} \iint_{-\infty}^{\infty} d\mathbf{r}_+ d\mathbf{r}_- M_{11}^{\text{in}}(\mathbf{r}_+, \mathbf{r}_-, z) \exp\left(-\frac{2}{a_e^2} r_+^2 - \frac{1}{2a_e^2} r_-^2\right) \right]. \end{aligned} \quad (34)$$

We define the average energy per bit  $\langle E_b \rangle$  affected by atmospheric turbulence as the product of the average received power and  $T_b$ . The average received power is given by the second moment of received waves:

$$\langle P(z) \rangle = \frac{1}{S_e Z_0} \cdot \text{Re} \left[ \iint_{-\infty}^{\infty} \iint_{-\infty}^{\infty} d\mathbf{r}_+ d\mathbf{r}_- M_{11}(\mathbf{r}_+, \mathbf{r}_-, z) \exp\left(-\frac{2}{a_e^2} r_+^2 - \frac{1}{2a_e^2} r_-^2\right) \right]. \quad (35)$$

Therefore,

$$\begin{aligned} \langle E_b \rangle &= \langle P(z) \rangle \cdot T_b \\ &= \frac{T_b}{S_e Z_0} \cdot \text{Re} \left[ \iint_{-\infty}^{\infty} \iint_{-\infty}^{\infty} d\mathbf{r}_+ d\mathbf{r}_- M_{11}(\mathbf{r}_+, \mathbf{r}_-, z) \exp\left(-\frac{2}{a_e^2} r_+^2 - \frac{1}{2a_e^2} r_-^2\right) \right]. \end{aligned} \quad (36)$$

We consider QPSK modulation which is very popular among satellite communications. It is known that BER in QPSK modulation is defined by

$$\text{PE} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{E_b}{N_0}} \right), \quad (37)$$

where  $\text{erfc}(x)$  is the complementary error function. We define BER derived from the average received power in order to evaluate the influence of atmospheric turbulence as follows:

$$\text{PE}_P = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{\langle E_b \rangle}{N_0}} \right). \quad (38)$$

And then, using  $E_b$  in free space obtained by (34), the BER can be expressed by

$$\text{PE}_P = \frac{1}{2} \text{erfc} \left( \sqrt{S_P \cdot \frac{E_b}{N_0}} \right), \quad (39)$$

where the normalized received power  $S_P$  is given by

$$S_P = \frac{\langle E_b \rangle}{E_b} = \frac{\langle P(z) \rangle}{P_{\text{in}}(z)} = \frac{\text{Re} \left[ \iint_{-\infty}^{\infty} \iint_{-\infty}^{\infty} d\mathbf{r}_+ d\mathbf{r}_- M_{11}(\mathbf{r}_+, \mathbf{r}_-, z) \exp \left( -\frac{2}{a_e^2} r_+^2 - \frac{1}{2a_e^2} r_-^2 \right) \right]}{\text{Re} \left[ \iint_{-\infty}^{\infty} \iint_{-\infty}^{\infty} d\mathbf{r}_+ d\mathbf{r}_- M_{11}^{\text{in}}(\mathbf{r}_+, \mathbf{r}_-, z) \exp \left( -\frac{2}{a_e^2} r_+^2 - \frac{1}{2a_e^2} r_-^2 \right) \right]}. \quad (40)$$

If the DOC is almost unity where the decrease in the spatial coherence of received waves is negligible, the received power can be replaced with the integration of the intensity  $I(\mathbf{r}, z) = |u(\mathbf{r}, z)|^2$  over the receiving antenna. The received intensity in free space  $I_{\text{in}}(z)$  and the average received intensity affected by atmospheric turbulence  $\langle I(z) \rangle$  are respectively given by

$$I_{\text{in}}(z) = \iint_{-\infty}^{\infty} d\mathbf{r} M_{11}^{\text{in}}(\mathbf{r}, \mathbf{0}, z) \exp \left( -\frac{2r^2}{a_e^2} \right) \quad (41)$$

$$\langle I(z) \rangle = \iint_{-\infty}^{\infty} d\mathbf{r} M_{11}(\mathbf{r}, \mathbf{0}, z) \exp \left( -\frac{2r^2}{a_e^2} \right). \quad (42)$$

Under the condition where the DOC is almost unity, we can reduce the number of the surface integral in calculation of (40) and then obtain BER derived from the average received intensity as follows:

$$\text{PE}_I = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{\langle E_b \rangle}{N_0}} \right) = \frac{1}{2} \text{erfc} \left( \sqrt{S_I \cdot \frac{E_b}{N_0}} \right), \quad (43)$$

where the normalized average received intensity  $S_I$  is given by

$$S_I = \frac{\langle E_b \rangle}{E_b} = \frac{\langle I(z) \rangle}{I_{\text{in}}(z)} = \frac{\iint_{-\infty}^{\infty} d\mathbf{r} M_{11}(\mathbf{r}, \mathbf{0}, z) \exp \left( -\frac{2r^2}{a_e^2} \right)}{\iint_{-\infty}^{\infty} d\mathbf{r} M_{11}^{\text{in}}(\mathbf{r}, \mathbf{0}, z) \exp \left( -\frac{2r^2}{a_e^2} \right)}. \quad (44)$$

### 3. Results

#### 3.1 Modulus of complex degree of coherence

##### 3.1.1 Uplink

Substituting (24) and (27) into (30), the DOC at the GEO satellite in the uplink can be described by

$$\text{DOC}(\boldsymbol{\rho}, z_{\text{UL}}) = \int_0^\infty d\kappa_+ \int_0^{2\pi} d\theta \kappa_+ \exp \left[ -\frac{w^2}{8} \kappa_+^2 + \frac{p}{2} \kappa_+ \rho \cos \theta - \frac{\rho^2}{2w_0^2} - H \left( \boldsymbol{\rho} - \frac{z_L}{k} \boldsymbol{\kappa}_+, 0, z_{\text{ht}} \right) \right] \cdot \left\{ 2\pi \int_0^\infty d\kappa_+ \kappa_+ J_0 \left( \frac{\kappa_+ \rho}{2} \right) \exp \left[ -\frac{w^2}{8} \kappa_+^2 - H \left( -\frac{z_L}{k} \boldsymbol{\kappa}_+, 0, z_{\text{ht}} \right) \right] \right\}^{-1}, \quad (45)$$

where

$$H(\boldsymbol{\rho}', 0, z_{\text{ht}}) = \frac{12}{5} (k\pi)^2 L_0^{5/3} \int_0^{z_{\text{ht}}} dz_1 0.033 C_n^2(z_1) \cdot \left[ 1 + \Gamma \left( \frac{1}{6} \right) \left( \frac{1}{\kappa_m L_0} \right)^{5/3} \sum_{i=0}^\infty \frac{1}{i!} \left( \frac{1}{\kappa_m L_0} \right)^{2i} {}_1F_1 \left( -i - \frac{5}{6}; 1; -\frac{\kappa_m^2 \rho'^2}{4} \right) - \exp \left( \frac{\rho'}{L_0} \right) {}_1F_1 \left( -\frac{1}{3}; -\frac{2}{3}; -\frac{2\rho'}{L_0} \right) \right], \quad (46)$$

and

$$\rho' = |\boldsymbol{\rho}'| = \begin{cases} \sqrt{\rho^2 - 2\rho \frac{z_L}{k} \kappa_+ \cos \theta + \frac{z_L^2}{k^2} \kappa_+^2} & \text{in } \boldsymbol{\rho}' = \boldsymbol{\rho} - \frac{z_L}{k} \boldsymbol{\kappa}_+ \\ \frac{z_L}{k} \kappa_+ & \text{in } \boldsymbol{\rho}' = -\frac{z_L}{k} \boldsymbol{\kappa}_+. \end{cases} \quad (47)$$

Fig. 8 shows that the DOC in the uplink is almost unity within the size of an aperture diameter of the receiving antenna of the GEO satellite ( $\rho \lesssim 2a_e$ ). It means that the spatial coherence of received waves keeps enough large within the receiving antenna.

##### 3.1.2 Downlink

Substituting (24) and (28) into (30), the DOC at the ground station in the downlink is obtained by

$$\text{DOC}(\boldsymbol{\rho}, z_{\text{DL}}) = \exp \left[ -H(\boldsymbol{\rho}, z_L - z_{\text{ht}}, z_L) \right], \quad (48)$$

where

$$H(\boldsymbol{\rho}, z_L - z_{\text{ht}}, z_L) = \frac{12}{5} (k\pi)^2 L_0^{5/3} \int_{z_L - z_{\text{ht}}}^{z_L} dz_1 0.033 C_n^2(z_1) \cdot \left[ 1 + \Gamma \left( \frac{1}{6} \right) \left( \frac{1}{\kappa_m L_0} \right)^{5/3} \sum_{i=0}^\infty \frac{1}{i!} \left( \frac{1}{\kappa_m L_0} \right)^{2i} {}_1F_1 \left( -i - \frac{5}{6}; 1; -\frac{\kappa_m^2 r^2}{4} \right) - \exp \left( \frac{r}{L_0} \right) {}_1F_1 \left( -\frac{1}{3}; -\frac{2}{3}; -\frac{2r}{L_0} \right) \right]. \quad (49)$$

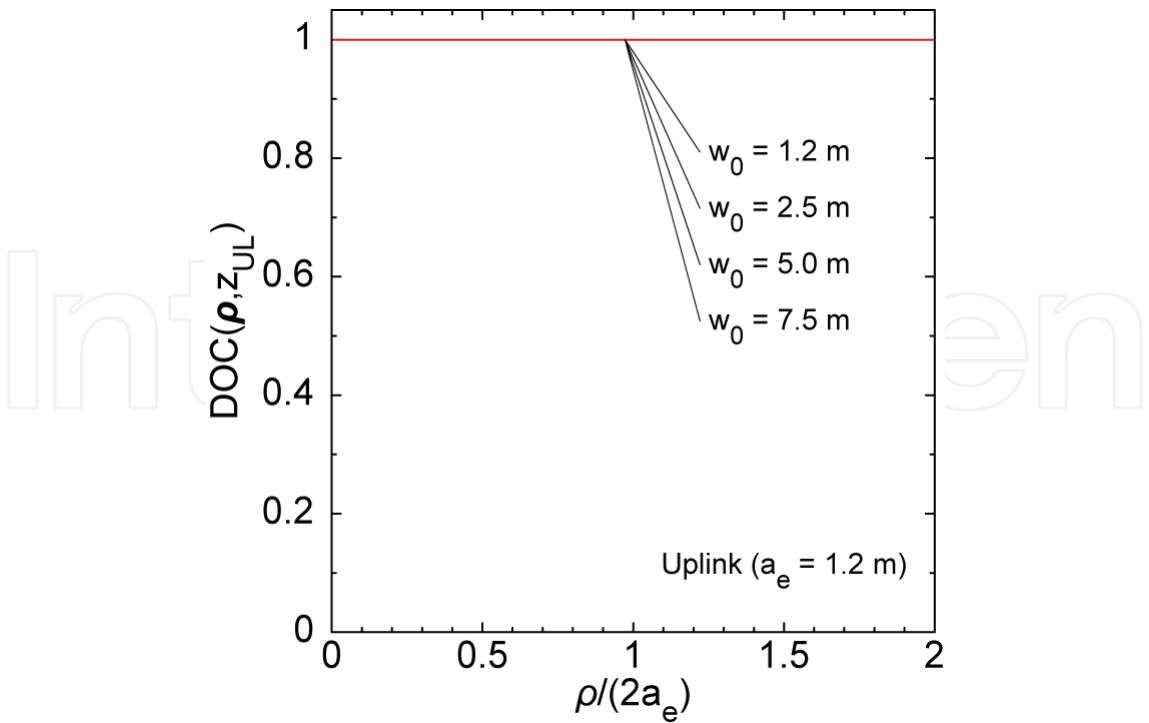


Fig. 8. The modulus of complex degree of coherence of received waves in the uplink for various beam radius at the transmitting antenna as a function of the separation distance between received wave fields at two points in the plane of the receiving antenna scaled by an aperture diameter of the receiving antenna  $2a_e$ .

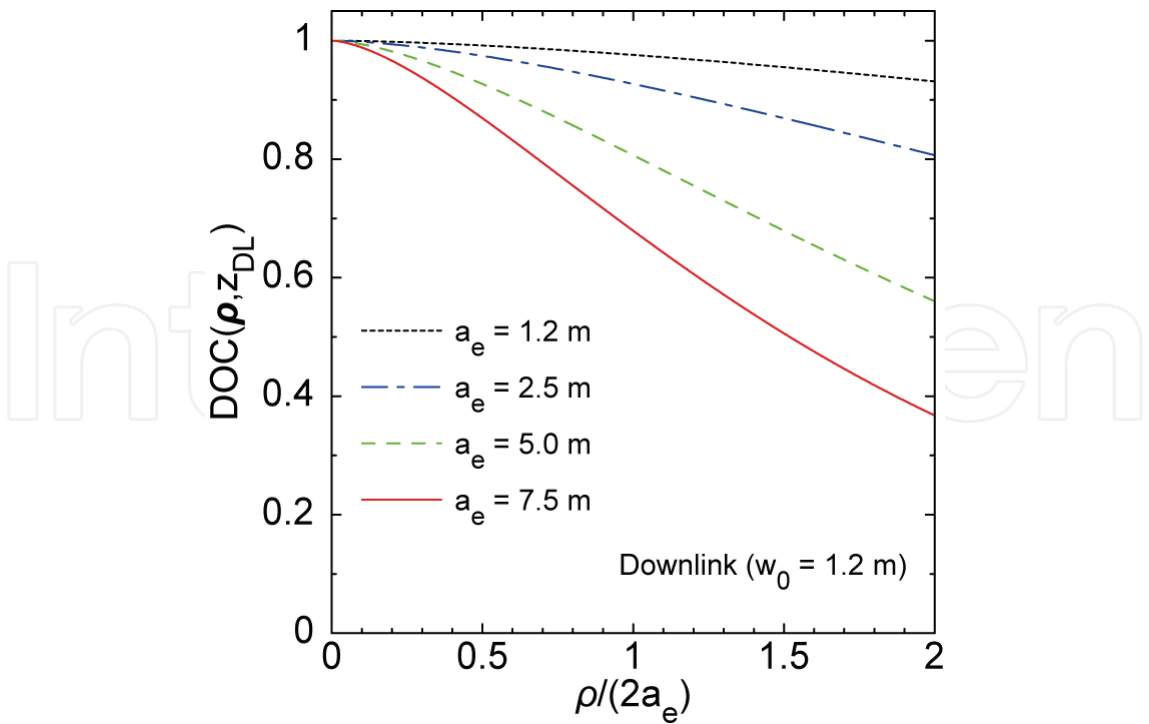


Fig. 9. Same as Fig. 8 except for the downlink where a beam radius at the transmitting antenna  $w_0 = 1.2$  m for various aperture radius of the receiving antenna  $a_e$ .

As shown in Fig. 9, it is found that the decrease in the spatial coherence of received waves can not be neglected within a receiving antenna of the ground station. It indicates that an influence of the spatial coherence of received waves has to be considered in the analysis of BER in the downlink.

### 3.2 BER derived from average received power

#### 3.2.1 Uplink

The BER derived from the average received intensity defined by (43) and (44) can be used for the uplink because the spatial coherence of received waves keeps enough large as shown in Fig. 8. Using (24), (27), (43) and (44), the BER can be expressed by

$$PE_I = \frac{1}{2} \operatorname{erfc} \left( \sqrt{S_I \cdot \frac{E_b}{N_0}} \right) \quad (50)$$

$$S_I = \frac{w^2 + a_e^2}{4} \int_0^\infty d\kappa_+ \kappa_+ \exp \left[ -\frac{w^2 + a_e^2}{8} \kappa_+^2 - H \left( -\frac{z_L}{k} \kappa_+, 0, z_{ht} \right) \right] \quad (51)$$

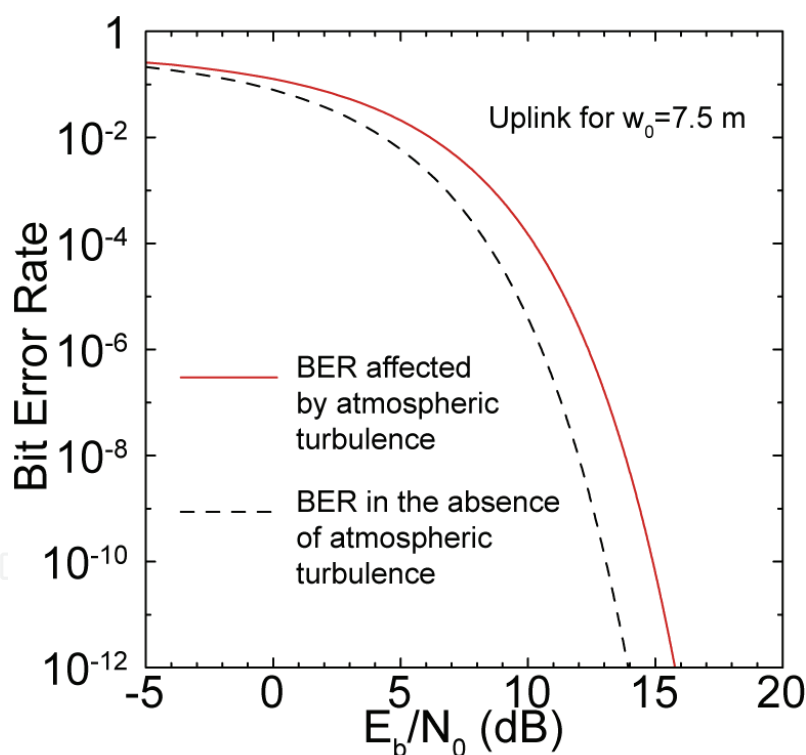


Fig. 10. BER derived from the average received intensity ( $PE_I$ ) in the uplink in  $w_0 = 7.5$  m.



$$H\left(-\frac{z_L}{k}\kappa_+, 0, z_{ht}\right) = \frac{12}{5}(k\pi)^2 L_0^{5/3} \int_0^{z_{ht}} dz_1 0.033 C_n^2(z_1) \cdot \left[1 + \Gamma\left(\frac{1}{6}\right) \left(\frac{1}{\kappa_m^2 L_0^2}\right)^{5/6} \sum_{i=0}^{\infty} \frac{1}{i!} \left(\frac{1}{\kappa_m^2 L_0^2}\right)^i {}_1F_1\left(-i - \frac{5}{6}; 1; -\frac{\kappa_m^2 z_L^2}{4k^2} \kappa_+^2\right) - \exp\left(\frac{z_L \kappa_+}{k L_0}\right) {}_1F_1\left(-\frac{1}{3}; -\frac{2}{3}; -\frac{2z_L}{k L_0} \kappa_+\right)\right]. \quad (52)$$

Fig. 10 shows the BER affected by atmospheric turbulence in the uplink when wave beams are transmitted from the large aperture antenna where  $w_0 = 7.5$  m. As reference, we plot a dashed line as the BER in the absence of atmospheric turbulence given by (37). It is found that BER increases compared with one in the absence of atmospheric turbulence. Because we have already shown that the decrease in the spatial coherence of received waves is negligible, we predict that the increase in BER is caused by the decrease in the average received intensity due to spot dancing shown in Fig. 1.

### 3.2.2 Downlink

For the downlink, the decrease in the spatial coherence of received waves can not be ignored as shown in Fig. 9. Therefore, we have to analyze the BER derived from the average received power defined by (39) and (40) which include an influence of the spatial coherence of received waves. Using (24), (28), (39) and (40), we obtain the BER as follows:

$$PE_P = \frac{1}{2} \operatorname{erfc}\left(\sqrt{S_P \cdot \frac{E_b}{N_0}}\right) \quad (53)$$

$$S_P = \frac{1}{a_e^2} \int_0^\infty dr_- r_- \exp\left[-\frac{r_-^2}{2a_e^2} - H(\mathbf{r}_-, z_L - z_{ht}, z_L)\right] \quad (54)$$

$$H(\mathbf{r}_-, z_L - z_{ht}, z_L) = \frac{12}{5}(k\pi)^2 L_0^{5/3} \int_{z_L - z_{ht}}^{z_L} dz_1 0.033 C_n^2(z_1) \cdot \left[1 + \Gamma\left(\frac{1}{6}\right) \left(\frac{1}{\kappa_m L_0}\right)^{5/3} \sum_{i=0}^{\infty} \frac{1}{i!} \left(\frac{1}{\kappa_m L_0}\right)^{2i} {}_1F_1\left(-i - \frac{5}{6}; 1; -\frac{\kappa_m^2 r_-^2}{4}\right) - \exp\left(\frac{r_-}{L_0}\right) {}_1F_1\left(-\frac{1}{3}; -\frac{2}{3}; -\frac{2r_-}{L_0}\right)\right]. \quad (55)$$

Fig. 11 shows the BER affected by atmospheric turbulence in the downlink when wave beams are received by the large aperture antenna where  $a_e = 7.5$  m. It is found that the decrease in the spatial coherence of received waves causes the decrease in the average received power and result in the increase in BER. Note that an influences of spot dancing is negligible because a statistical characteristics of received waves can be considered as a plane wave as mentioned in the introduction of (28)

### 3.3 Effects of antenna radius of ground station on BER performance

In the system design of the ground station, we may increase an aperture radius of the ground station's antenna in order to satisfy the required Effective Isotropic Radiated Power (EIRP) of the transmitter system or the G/T of the receiver system. In this section, we estimate an effect of increasing an aperture radius of the ground station's antenna on BER affected by atmospheric turbulence.

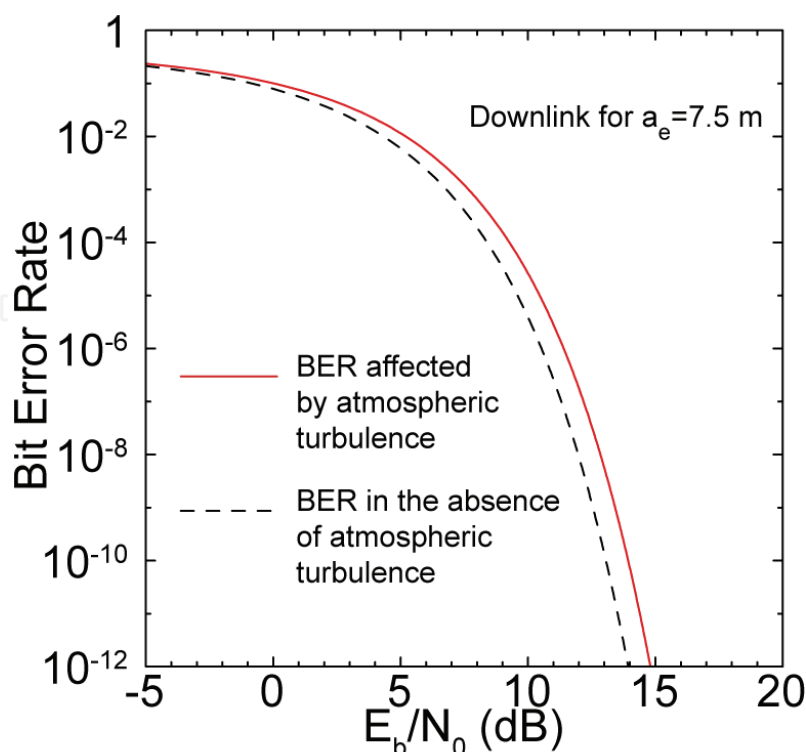


Fig. 11. BER derived from the average received power ( $PE_P$ ) in the downlink in  $a_e = 7.5$  m

The EIRP of the transmitter system is defined as the product of a transmitting power and an antenna gain of the transmitting antenna. The transmitting power  $P_t$  is obtained by

$$P_t = \frac{1}{Z_0} \cdot \iint_{-\infty}^{\infty} d\mathbf{r} |u_{in}(\mathbf{r}, 0)|^2 = \frac{A}{Z_0}, \quad (56)$$

where  $u_{in}(\mathbf{r}, 0)$  is given by (15). The antenna gain of the transmitting antenna  $G_t$  is defined by

$$G_t = \frac{4\pi z_L^2 S}{P_t}, \quad (57)$$

where  $S$  denotes the received power density at  $(0, z_L)$ :

$$S = \frac{|u(0, z_L)|^2}{Z_0} = \frac{1}{Z_0} \cdot \frac{2A}{\pi w^2}. \quad (58)$$

Thus, the antenna gain can be expressed by

$$G_t = \frac{4\pi z_L^2 S}{P_t} = \frac{8z_L^2}{w^2} = \frac{8z_L^2}{w_0^2(1 + p^2)} \simeq 2(kw_0)^2, \quad (59)$$

where it is assumed that  $p^2 = 4z_L^2 / (k^2 w_0^4) \gg 1$ , which is satisfied in this model of analysis. Using (56) and (59), the EIRP of the transmitter system can be described by

$$\text{EIRP} = P_t \cdot G_t = \frac{2A(kw_0)^2}{Z_0}. \quad (60)$$

The G/T of the receiver system can be expressed by the ratio of an antenna gain of the receiving antenna to the system noise temperature. The antenna gain of the receiving antenna  $G_r$  can be described by

$$G_r = \frac{4\pi}{\lambda^2} S_e = 4\pi \cdot \left( \frac{k}{2\pi} \right)^2 \cdot \frac{\pi a_e^2}{2} = \frac{(ka_e)^2}{2}, \quad (61)$$

where  $S_e = \pi a_e^2/2$  because the aperture efficiency of the receiving antenna, whose field distribution is given by (32), is 0.5. The system noise temperature  $T_s$  is obtained by

$$T_s = \frac{N_0}{k_B}, \quad (62)$$

where  $k_B$  denotes Boltzmann's Constant. Thus, the G/T of the receiver system can be described by

$$G/T = \frac{G_r}{T_s} = \frac{k_B}{N_0} \cdot \frac{(ka_e)^2}{2}. \quad (63)$$

On the other hand, using (19) and (34),  $E_b/N_0$  in free space is obtained by

$$\frac{E_b}{N_0} = \frac{P_{in}(z_L) \cdot T_b}{N_0} = \frac{T_b}{N_0} \cdot \frac{A}{Z_0} \frac{a_e^2}{w^2 + a_e^2} \simeq \frac{T_b}{k_B T_s} \cdot \frac{A}{Z_0} \frac{a_e^2}{w^2} = \frac{T_b}{k_B T_s} \cdot \frac{A}{Z_0} \cdot a_e^2 \cdot \frac{k^2 w_0^2}{4z_L^2}, \quad (64)$$

where it is assumed that  $a_e/w \ll 1$ . Using the EIRP and the G/T obtained by (60) and (63) respectively,  $E_b/N_0$  in free space can be expressed by

$$\begin{aligned} \frac{E_b}{N_0} &= \frac{T_b}{k_B} \cdot \frac{A}{Z_0} \cdot 2(kw_0)^2 \cdot \frac{1}{(2kz_L)^2} \cdot \frac{(ka_e)^2}{2T_s} = \frac{T_b}{k_B} \cdot P_{in} \cdot G_t \cdot \frac{1}{(2kz_L)^2} \cdot \frac{G_r}{T_s} \\ &= \frac{T_b}{k_B} \cdot \text{EIRP} \cdot \frac{1}{(2kz_L)^2} \cdot G/T. \end{aligned} \quad (65)$$

Note that  $(2kz_L)^2$  is the free space path loss.

### 3.3.1 Uplink

Using (65), we can describe BER derived from the average received intensity given by (50) in the uplink:

$$\text{PE}_I = \frac{1}{2} \text{erfc} \left( \sqrt{S_I \cdot \frac{T_b}{k_B} \cdot \text{EIRP} \cdot \frac{1}{(2kz_L)^2} \cdot G/T} \right). \quad (66)$$

Fig. 12 shows the BER as a function of  $kw_0$  under the condition that G/T and EIRP keep constant, where the transmitting power  $A/Z_0$  changes in inverse proportion to the square of  $kw_0$  in (60). It is found that the BER affected by atmospheric turbulence increases as  $kw_0$  becomes large, whereas the BER in the absence of atmospheric turbulence plotted by the dashed line does not change. Fig. 13 shows the BER for various beam radius at the transmitting antenna  $w_0$  as a function of  $E_b/N_0$  obtained by (65). It is shown that BER increases as  $w_0$  becomes larger as well as Fig. 12.

The reason for the increase in BER is as follows.

We have shown that spot dancing of wave beams due to atmospheric turbulence causes the increase in BER for the uplink in Sec. 3.2.1. From each profile of the intensity in the absence of atmospheric turbulence plotted by the dashed line in Figs. 14 to 17, it is found that the

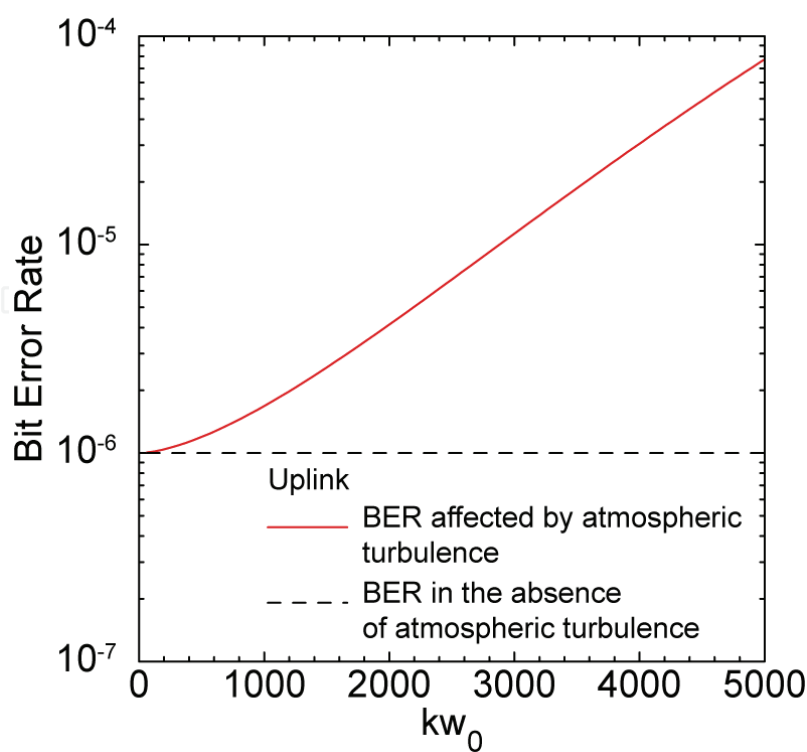


Fig. 12. BER derived from the average received intensity in the uplink as a function of  $kw_0$  when the EIRP of the transmitter system keeps constant.

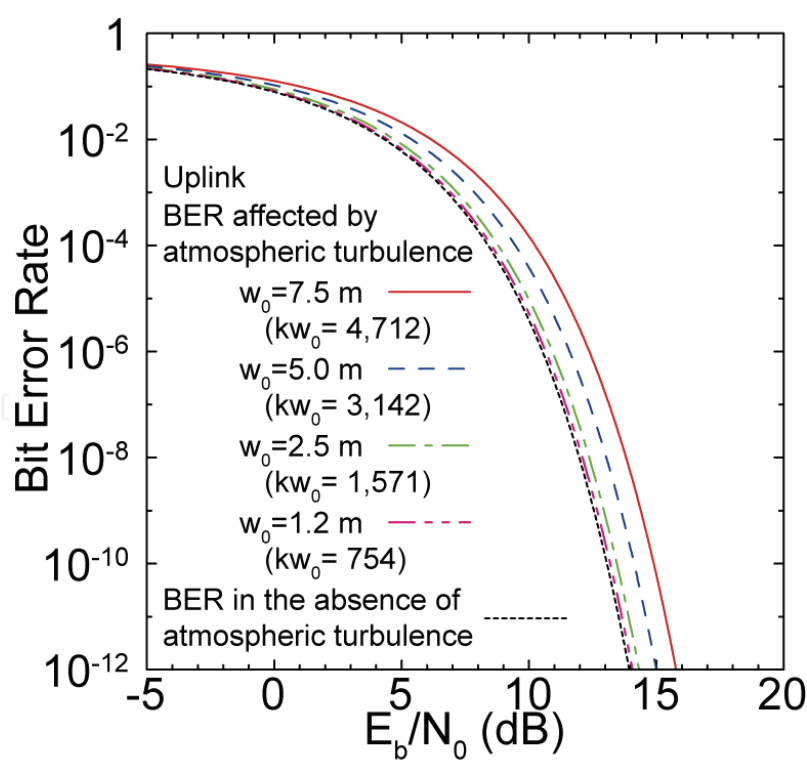


Fig. 13. BER derived from the average received intensity in the uplink for various beam radius at the transmitting antenna  $w_0$  as a function of  $E_b/N_0$ .

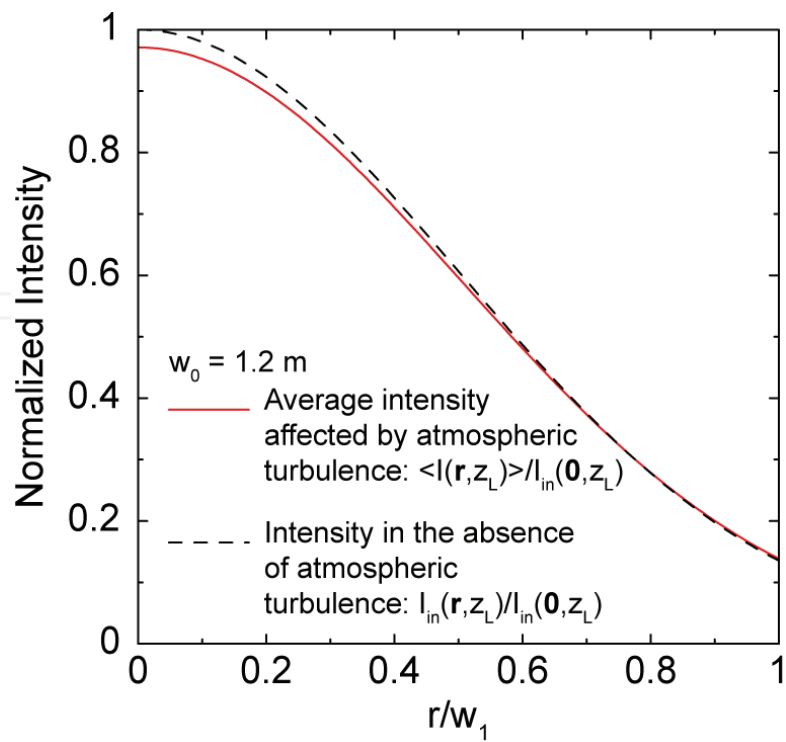


Fig. 14. Average intensity for the uplink in the beam radius at the transmitting antenna  $w_0 = 1.2$  m normalized by the intensity on a beam axis in free space as a function of the distance from the center of the receiving antenna scaled by  $w_1$ , which denotes the beam radius at the plain of the receiving antenna for  $w_0 = 1.2$  m.

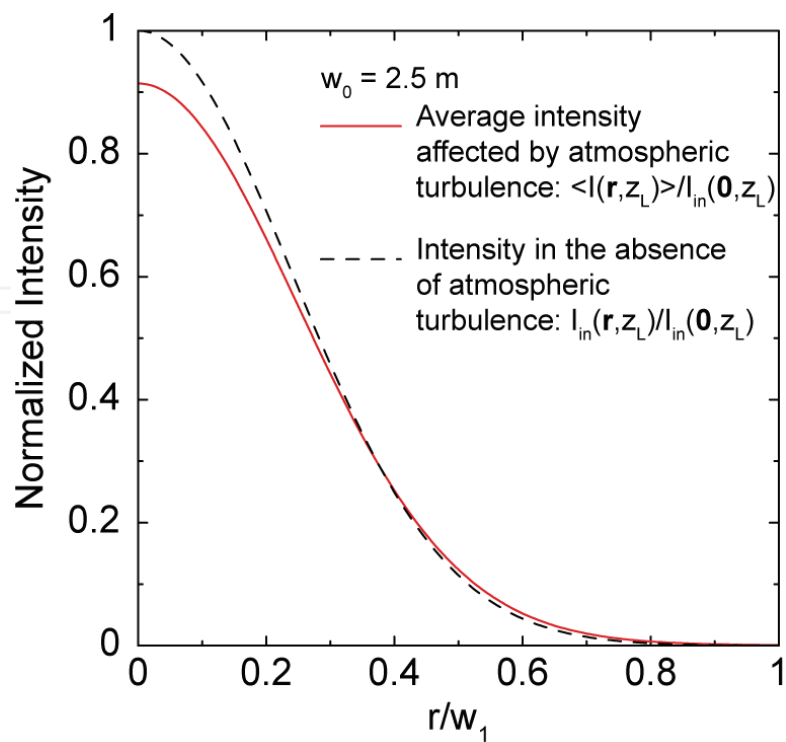


Fig. 15. Same as Fig 14 except for  $w_0 = 2.5$  m.

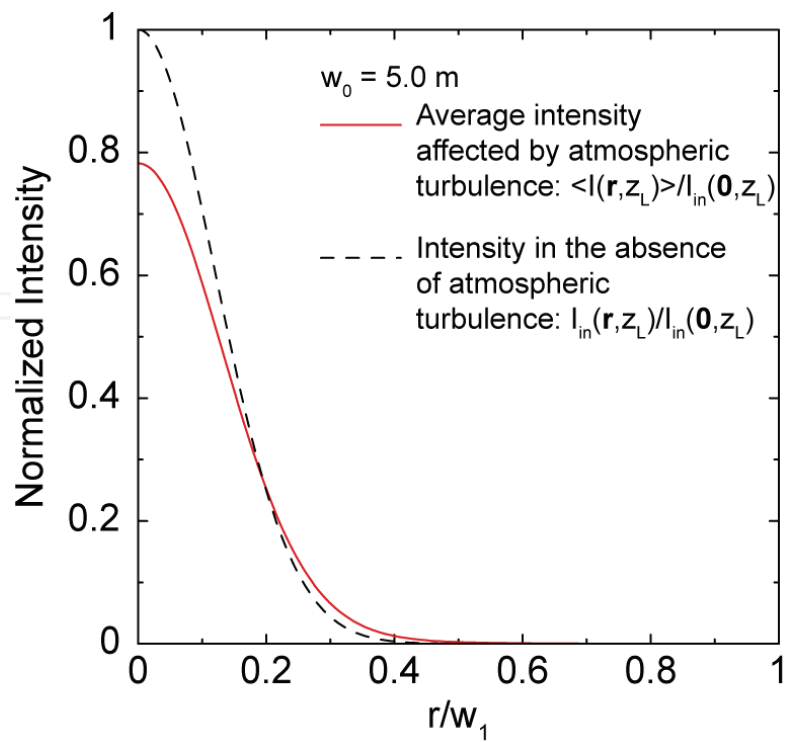


Fig. 16. Same as Fig 14 except for  $w_0 = 5.0$  m.

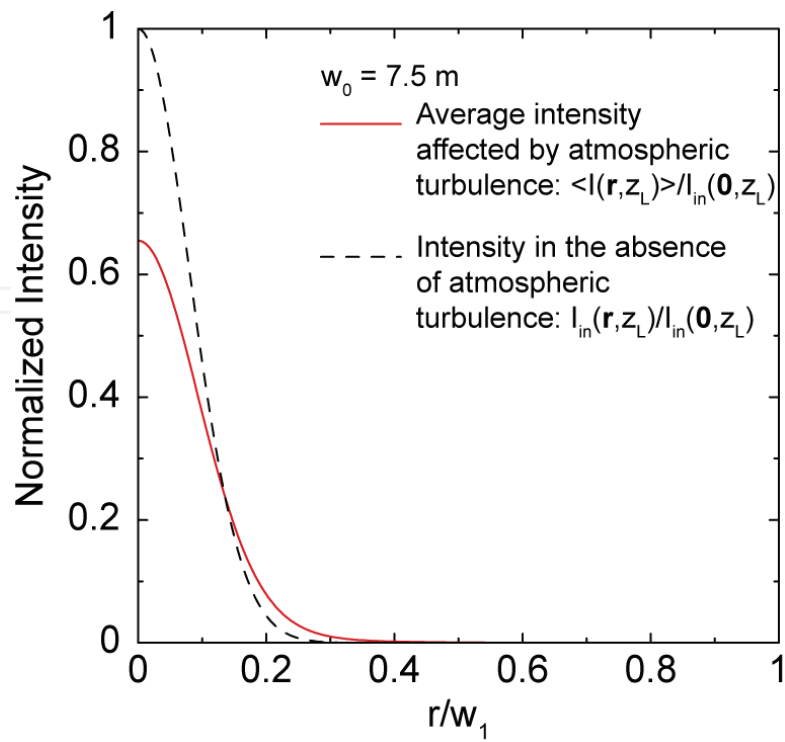


Fig. 17. Same as Fig 14 except for  $w_0 = 7.5$  m.

beam spot size at the plain of the receiving antenna becomes smaller as  $w_0$  increases. The displacement of the arrived beam axis due to spot dancing makes the received intensity decrease considerably faster as the beam spot size becomes smaller. Therefore, the average intensity affected by atmospheric turbulence decreases at the center of the receiving antenna and the profile is spread as  $w_0$  increases as shown in Figs. 14 to 17. This is why BER in the uplink increases as an aperture radius of the ground station's antenna becomes larger.

From these results, we find that the increase in the transmitting power is better than the increase in the aperture radius of the ground station's antenna in order to satisfy the required EIRP from the point of view of the decrease in an influence of atmospheric turbulence on BER in the uplink.

### 3.3.2 Downlink

For the downlink, we can obtain BER derived from the average received power given by (53):

$$PE_P = \frac{1}{2} \operatorname{erfc} \left( \sqrt{S_P \cdot \frac{T_b}{k_B} \cdot \text{EIRP} \cdot \frac{1}{(2kz_L)^2} \cdot G/T} \right). \quad (67)$$

Fig. 18 shows the BER as a function of  $ka_e$  under the condition that EIRP and G/T keep constant, where the noise power density  $N_0$  changes in inverse proportion to the square of  $ka_e$  in (63). It is found that the BER affected by atmospheric turbulence increases as  $ka_e$  becomes larger. Fig. 19 shows the BER for various aperture radius of the receiving antenna as a function of  $E_b/N_0$  obtained by (65). It is shown that BER increases as  $a_e$  becomes larger as well as Fig. 18. From results of the DOC in Fig. 9, it is found that the spatial coherence radius becomes smaller relative to a radius of the receiving antenna and then the spatial coherence

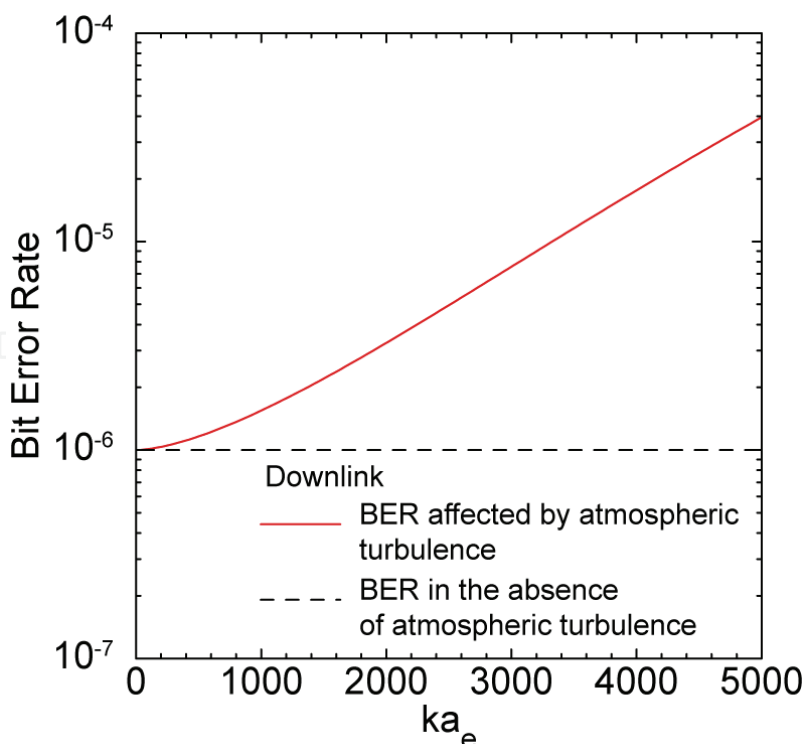


Fig. 18. BER derived from the average received power in the downlink as a function of  $ka_e$  when the G/T of the receiver system keeps constant.

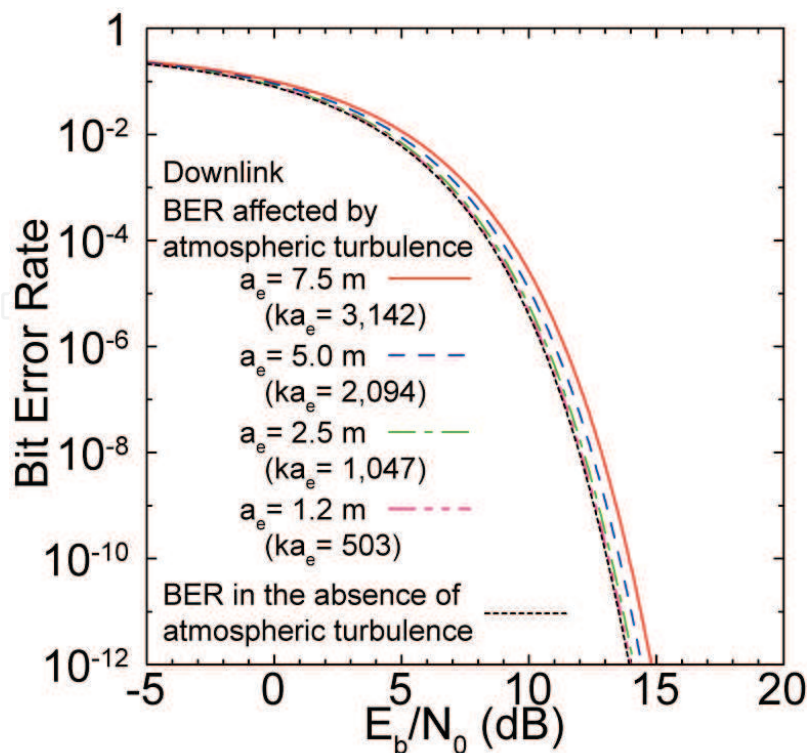


Fig. 19. BER derived from the average received power in the downlink for various aperture radius of the receiving antenna  $a_e$  as a function of  $E_b/N_0$ .

of received waves decreases as the radius of the antenna increases. The effect of the spatial coherence of received waves causes the decrease in the average received power and results in the degradation of BER performance.

From these results, it is found that the decrease in the system noise temperature by the improvement of a receiver's noise is better than the increase in an aperture radius of the ground station's antenna in order to decrease an influence of atmospheric turbulence on BER for the downlink in the design to satisfy the required G/T.

#### 4. Conclusion

We analyzed BER derived from the average received power, which is deduced by the second moment of a Gaussian wave beam, for the GEO satellite communications in Ka-band at low elevation angles affected by atmospheric turbulence. We find the followings:

1. For the uplink, the decrease in the average received intensity caused by spot dancing of wave beams degrades the BER performance. However, the spatial coherence of received wave beams decreases little and there are little influences of this spatial coherence on BER.
2. For the downlink, the decrease in the spatial coherence of received wave beams degrades the BER performance. However, spot dancing of wave beams influences little on BER.
3. In the design of the ground station, the increase in a transmitting power for the uplink or the decrease in the noise temperature of the receiver system for the downlink is better than the increase in an aperture radius of the ground station's antenna in order to satisfy the required EIRP of the transmitter system or G/T of the receiver system from the point of view of the decrease in an influence of atmospheric turbulence on BER performance.



In this chapter, we do not consider effects of the higher moment of a Gaussian wave beams on BER. At the next stage, we will analyze effects of the fourth moment of received wave beams on BER for the GEO satellite communications. Furthermore, we have to consider the probability density function (PDF) about the bit error of satellite communications affected by atmospheric turbulence in order to make a more actual analysis. An introduction of the PDF is a future problem.

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Satellite communication systems are now a major part of most telecommunications networks as well as our everyday lives through mobile personal communication systems and broadcast television. A sound understanding of such systems is therefore important for a wide range of system designers, engineers and users. This book provides a comprehensive review of some applications that have driven this growth. It analyzes various aspects of Satellite Communications from Antenna design, Real Time applications, Quality of Service (QoS), Atmospheric effects, Hybrid Satellite-Terrestrial Networks, Sensor Networks and High Capacity Satellite Links. It is the desire of the authors that the topics selected for the book can give the reader an overview of the current trends in Satellite Systems, and also an in depth analysis of the technical aspects of each one of them.

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