ANALYSIS OF ANTENNA GAIN REDUCTION DUE TO IONOSPHERIC AND ATMOSPHERIC TURBULENCE

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I. INTRODUCTION

In satellite communication, the medium such as the atmosphere and the ionosphere is varying randomly in time and space. The randomness of the medium has ill effects on satellite communication. One of them is the antenna gain reduction. A pilot study of the gain reduction due to the atmospheric turbulence was made theoretically and experimentally about 15 years ago[1]; now, the theoretical analysis should be renewed. Recently we evaluated the gain reduction and the scattering loss due to the ionospheric turbulence only [2]. As a matter of fact, the effects of not only the atmosphere but also the ionosphere must be taken into account in the gain reduction. Moreover, the gain reduction is not exactly equal to the linear sum of the reduction due to the atmosphere and that due to the ionosphere. In this paper, we analyze simultaneously both effects of the ionosphere and the atmosphere, by using the multiple scattering theory.

II. FORMULATION

In satellite communication, the statistical property of turbulence depends on the altitude. When the wave propagates along the z axis, the medium is assumed to be described by the following parameters: the dielectric constant ε, the magnetic permeability μ, and the electric conductivity σ, which are expressed by

$$\varepsilon = \varepsilon_0(1+\delta\varepsilon(\mathbf{r},z)) \qquad \mu = \mu_0 \qquad \sigma = 0 \tag{1}$$

Here, $\mathbf{r} = \mathbf{i}x+\mathbf{j}y$ ($\mathbf{i}$, $\mathbf{j}$ denote the unit vectors of x and y coordinates), ε_0 and μ_0 are constant, and $\delta\varepsilon(\mathbf{r},z)$ is a Gaussian random function with the properties

$$\langle \delta\varepsilon(\mathbf{r},z) \rangle = 0 \qquad \langle \delta\varepsilon(\mathbf{r}_1,z_1)\delta\varepsilon(\mathbf{r}_2,z_2) \rangle = B(\rho, z_+, z_-) \tag{2}$$

in which $\rho = \mathbf{r}_1 - \mathbf{r}_2$, $z_+ = (z_1+z_2)/2$, $z_- = z_1 - z_2$, and the angular brackets denote the ensemble average. The medium can be assumed that for any z,

$$k\ell(z) >> 1 \qquad B(0,z,0) << 1 \tag{3}$$

where k is the wave number in free space $(=\omega\sqrt{\varepsilon_0\mu_0})$, and $\ell(z)$ is the local correlation length. Under the condition (3), the scalar approximation and the small angle approximation are applicable.

Let the incident Gaussian wave beam $u_{in}(\mathbf{r},z)$ with the minimum spot size w_0 at $z=0$ propagate through the above random medium. According to the previous paper[2], the antenna gain reduction α_g and the scattering loss α_s for the Gaussian wave beam incidence, respectively, are approximately given by

$$\alpha_g \equiv 10 \log G_0/G_r = 20 \log Sa - 10 \log \left[\int_{Sa} ds \int_{Sa} dt \exp(-\zeta_1)\right] \tag{4}$$

$$\alpha_s \equiv 10 \log |u_{in}(\mathbf{r},z)|^2 / \langle |u(\mathbf{r},z)|^2 \rangle = 10 \log (w^2+\zeta_2)/w^2 \tag{5}$$

where $G_0 = S_a k^2/\pi$, in which S_a is the receiving antenna aperture, is the antenna gain in propagation in free space, G_r is the antenna gain in propagation through the random medium, $u(r,z)$ is the wave beam in the random medium, w is the spot size of the beam propagated in free space, and ζ_1, ζ_2 are

$$\begin{pmatrix} \zeta_1 \\ \\ \zeta_2 \end{pmatrix} = \frac{k^2}{4}\int_0^z dz_1 \int_0^{z-z_1} dz_2 \begin{pmatrix} 1 \\ \\ \frac{4}{k^2 z_2^2}\frac{1}{r'}\frac{\partial}{\partial r'} \end{pmatrix} D(r', z - z_2 - \frac{z_1}{2}, z_1) \tag{6}$$

in which $$D(\rho, z_+, z_-) = 2[B(0, z_+, z_-) - B(\rho, z_+, z_-)] \tag{7}$$

$$r' = (1 + p^2 - pp')r_-/(1 + p^2) \qquad p = 2z/(kw_0^2) \qquad p' = 2z_2/(kw_0^2) \tag{8}$$

The total loss α_t due to the random medium is the sum of (4) and (5):

$$\alpha_t = \alpha_g + \alpha_s \tag{9}$$

III. THE MODEL OF TURBULENCE

For simplicity, the dielectric constant in the ionosphere is assumed to be specified by the plasma frequency $\omega_p = \sqrt{hn}$

$$\varepsilon = \varepsilon_0(1 - hn/\omega^2) \tag{10}$$

where h is a constant, and n is the electron density and now a random function. When $n = \langle n\rangle + \Delta n$, we obtain for microwaves

$$\varepsilon = \langle\varepsilon\rangle[1 - \Delta\varepsilon] \tag{11}$$

where $$\langle\varepsilon\rangle = \varepsilon_0[1 - h\langle n\rangle/\omega^2] \simeq \varepsilon_0 \qquad \Delta\varepsilon = \frac{h\Delta n}{\omega^2}\frac{\varepsilon_0}{\langle\varepsilon\rangle} \simeq \frac{h}{\omega^2}\Delta n \tag{12}$$

so that $\Delta\varepsilon$ is equal to $\delta\varepsilon(\mathbf{r},z)$ in (1). We assume that the autocorrelation function (2) is expressed by

$$B(\rho, z_+, z_-) = B(z_+)\exp[-(\rho^2 + z_-^2)/\ell^2(z_+)] \tag{13}$$

where $B(z_+)$ and $\ell(z_+)$ are the local intensity and the local correlation length, respectively. Here, $B(z_+)$ is assumed to change like Fig.1. This assumption means that the ionospheric turbulence is not a strong one localized in a particular area but exists constantly; of course, the introduction of the strong turbulence into our analysis is possible with ease. In addition, the thickness h_a of the atmospheric turbulence is mainly determined by the elevation angle. The peak value of $B(z_+)$ in the ionospheric turbulence, written as B_i in Fig.1, is given by

$$B_i \equiv \langle(\Delta\varepsilon)^2\rangle = \beta^{-4}\times10^{-q}\times2.6\times10^{-8} \tag{14}$$

where $$\langle(\Delta n/\langle n\rangle)^2\rangle = 10^{-q} \qquad f = \omega/2\pi = \beta \text{ (GHz)} \tag{15}$$

For example, when $q = 1$, then we have $B_i = 2.6\times10^{-9}$, 1.0×10^{-11}, 2.0×10^{-12} for $\beta = 1,4,6$, respectively. In the calculation below, the peak value of $B(z_+)$ in the atmospheric turbulence, written as B_a, is assumed to be 10^{-10}, 10^{-11}(strong turbulence). Although the local correlation length $\ell(z_+)$ also changes in the medium, it is assumed for convenience that $\ell(z_+) = 20$(m) in the atmosphere and $\ell(z_+) = 100$(m) in the ionosphere. The previous analysis[2] suggests that the loss of the received power increases with decreasing $\ell(z_+)$.

VI. NUMERICAL RESULT

The gain reduction and the scattering loss are computed for earth-to-satellite (6GHz) and satellite-to-earth (4GHz) propagations. We assume h_a = 12(km) in Fig.1. This corresponds to the propapgation distance in the atmospheric turbulence layer of the thickness 5(km) at the elevation angle 25°. In the earth-to-satellite propagation, the wave beams with w_0= 1 to 20(m) over the aperture are transmitted toward satellite and received by the 2(m) antenna. The results are shown in Figs.2 and 3, where the total loss is denoted by the solid line and nearly equal to the scattering loss, the broken line shows the total loss due to the atmospheric turbulence only and the dot-dashed line shows that due to the ionospheric turbulence only. Here, the solid line = the broken line + the dot-dashed line is valid within the errors of less than 2%.

In the satellite-to-earth propagation, the transmitted wave beam with w_0 = 1(m) on satellite is received by the antenna of aperture diameter from 2 to 40(m). The computed results are shown in Figs.4 and 5, where each line shows the same total loss as that defined in Figs.2 and 3, and similarly the loss is approximately expressed by the sum of the loss due to the atmospheric turbulence only and that due to the ionospheric turbulence only. In this case the total loss is nearly equal to the gain reduction, which is quite different from the result in the above case. This difference is due to the inhomogeneity of turbulence as pointed out previously[2].

V. CONCLUSION

We analize numerically the antenna gain reduction and the scattering loss due to the atmospheric and ionospheric turbulence by the application of the multiple scattering theory. The loss of power received on earth and satellite can be approximately given by the sum of the losses due to each turbulence. Because of the inhomogeneity of turbulence, the power loss in the earth-to-satellite propagation is almost the scattering loss, while the loss in the satellite-to-earth propagation is nearly the gain reduction. It can also be shown that the gain reduction decreases as the gain factor of the antenna decreases and that the experimental result[1] is explaned by the present analysis.

Acknowledgement We would like to thank Dr. M. Yamada of KDD for offering the publications dealing with the gain reduction.

References [1] H.Yokoi, M.Yamada and T.Satoh, Publ. Astr. Japan, 22, 511-524 (1970). [2] M.Tateiba, Proc. 1984 Int. Symp. on EMC, 17PC1, 474-478(1984).

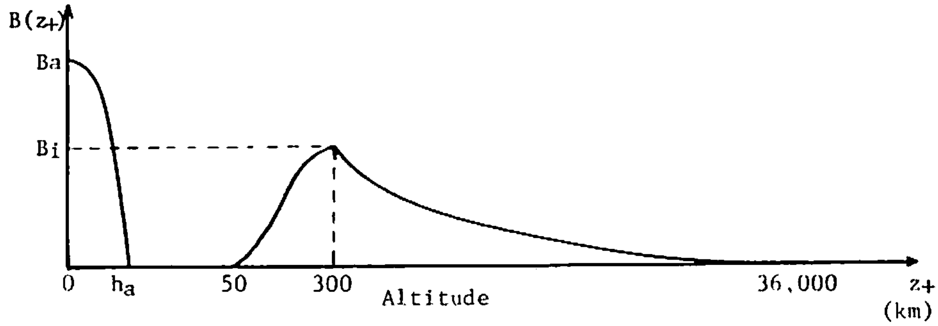

Fig.1 The Height Pattern of the Intensity of the Turbulence between Earth and Satellite.

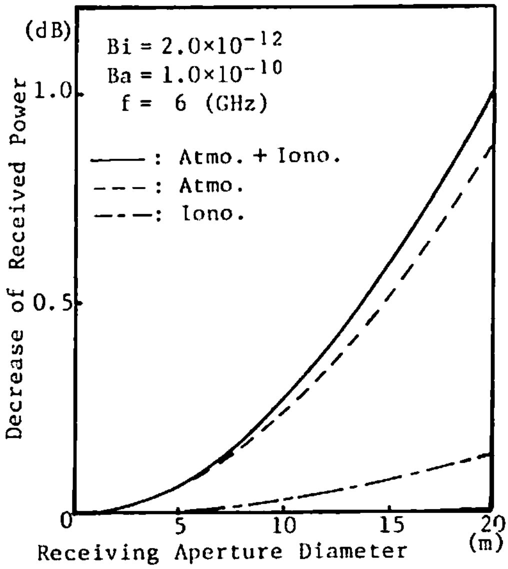

Fig.2 The Total Loss of Power Received on Satellite.

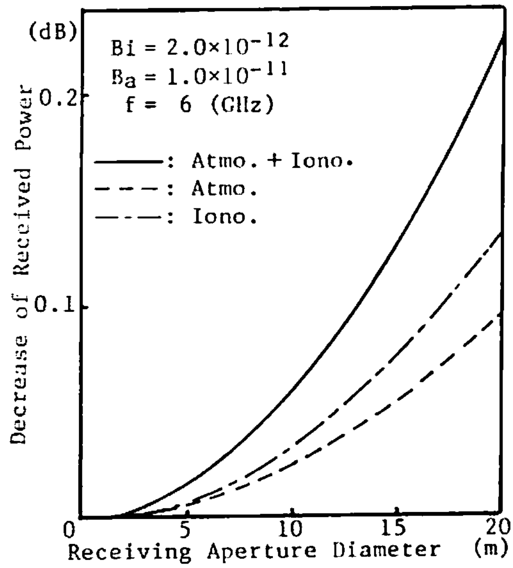

Fig.3 The Total Loss of Power Received on Satellite.

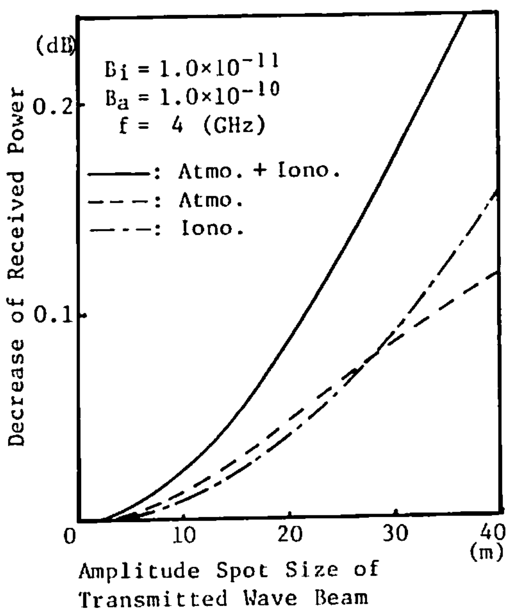

Fig.4 The Total Loss of Power Received on Earth.

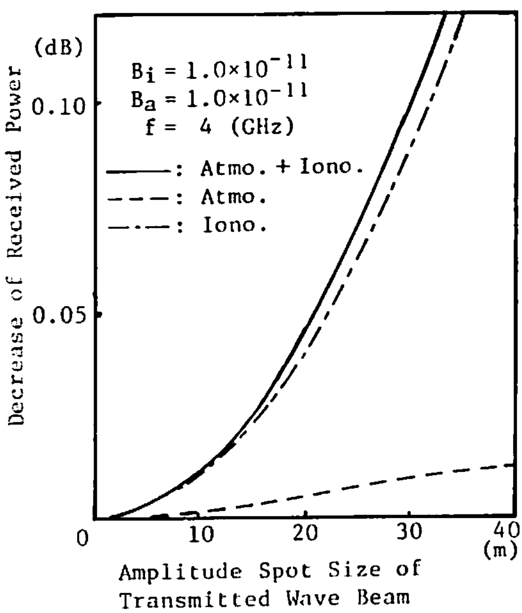

Fig.5 The Total Loss of Power Received on Earth.