DRTM Analysis of Propagation Characteristics along
Inhomogeneous Random Rough Surface

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1. Introduction

Recently, the sensor network technology among many wireless communication systems have attracted researchers’ interest. The sensor devices are usually located on terrestrial surfaces such as dessert, hilly terrain, forest, sea surface and so on. Since these surfaces are assumed to be statistically random, it is important to investigate propagation characteristics along random rough surfaces in order to construct realistic sensor network systems [1].

In this paper, we numerically calculate electromagnetic fields along rough surfaces by using the Discrete Ray Tracing Method (DRTM) proposed recently [2]. This method carries out two types of discretization, discretization of rough surface as well as ray. It saves computer memory and computation time. We deal with inhomogeneous rough surface which well show connection of two types of homogeneous rough surfaces, for example, dessert and sea surface. Numerical calculations are carried out for propagation characteristics of electromagnetic waves traveling along such an inhomogeneous random rough surface.

2. 1D Inhomogeneous Random Rough Surface

Random rough surfaces are realized by the convolution method, and distribution functions are assumed to be Gaussian, power law or exponential [1][3][4]. We have so far treated homogeneous random rough surfaces. However, when we consider realistic complicated rough surface such as complex mixture of dessert and sea surface, homogeneous random rough surfaces are insufficient. Therefore, we consider inhomogeneous rough surface with different parameters as shown in Figs.1 and 2. We use Gaussian spectrum in both left (surface 1) and right (surface 2) rough surfaces in Fig.1, and we select different spectrum in Fig.2, that is Gaussian for surface 1 and exponential spectrum for right one (surface 3). We choose correlation length \(c_l = 50[m]\) and deviation of surfaces’ height \(d_v = 1.0[m]\) as random rough surface parameters for surface 1. We select \(c_l = 50[m]\) and \(d_v = 1.5[m]\) for surfaces 2 and 3.

When we generate inhomogeneous random rough surface, we need to determine a weight function of random rough surface of which statistics parameters are continuously varied in transition region. As shown in Figs.1 and 2, we assume that the statistical parameters are determined as one type of rough surface in the surface 1, another type of rough surface in the surface 2 or 3, and transition region between them (surface 1 ↔ 2 or 3). We define the array of weighting function of rough surface in each regions as follows:

\[
\tilde{w}_k = \begin{cases} 
\tilde{w}_k(1) & (surface 1) \\
\tilde{w}_k(1)g_{n}(1|2) + \tilde{w}_k(2)g_{n}(2|1) & (surface 1 ↔ 2 or 3) \\
\tilde{w}_k(2) & (surface 2 or 3)
\end{cases}
\]  

(1)

where \(\tilde{w}_k(1)\) is weighting function in surface 1, and \(\tilde{w}_k(2)\) is weighting function in surface 2 or 3. Moreover, surface 1, both surface 2 and 3, and surface 1 ↔ 2 or 3 correspond to \((n = 0, \cdots , N_1 - 1)\), \((n = N_2 + 1, \cdots , N - 1)\), and \((n = N_1, \cdots , N_2)\), respectively. As for the another weights \(g_{n}(1|2)\) and
g_{n}(2|1)$, we propose a linear approximation in the transition region as follows:

$$g_{n}(1|2) = \begin{cases} 
1 & (n = 0, \cdots, N_1 - 1) \\
\frac{N_2 - n}{N_2 - N_1} & (n = N_1, \cdots, N_2) \\
0 & (n = N_2 + 1, \cdots, N - 1) 
\end{cases} \quad (2)$$

$$g_{n}(2|1) = \begin{cases} 
0 & (n = 0, \cdots, N_1 - 1) \\
\frac{n - N_1}{N_2 - N_1} & (n = N_1, \cdots, N_2) \\
1 & (n = N_2 + 1, \cdots, N - 1) 
\end{cases} \quad (3)$$

3. Discrete Ray Tracing Method and Field Computation

In this section, we first describe the principle of DRTM. Two types of discretization are performed in the DRTM [2]. The first discretization is for rough surface, and we divide the rough surface into $n$ parts as follows:

$$\rho_i = (x_i, h_i) \quad (i = 0, 1, 2, \cdots, n_x) \quad (4)$$

where

$$x_i = D_x i, \quad h_i = H(x_i) \quad (i = 0, 1, 2, \cdots, n_x) \quad (5)$$

and $H(x)$ is the function of rough surface height. We can determine the normal vector of each edge as follows:

$$n_i = (u_z \times a_i)/|u_z \times a_i| \quad (i = 0, 1, 2, \cdots, n_x - 1). \quad (6)$$

$u_z$ is the unit vector in $z$-direction. Each edge is expressed in vector form as follows:

$$a_i = (\rho_{i+1} - \rho_i) \quad (i = 0, 1, 2, \cdots, n_x - 1). \quad (7)$$

All informations for tracing rays are given by $\rho_i$ and $n_i$.

The second discretization is for tracing rays. We determine whether the two edges are on the line of sight (LOS) or not by checking whether two representative points on the two edges can be seen each other or not. We approximate this algorithm by judging whether one representative point within edges are on the LOS or not. As a result, this algorithm for tracing ray are much simplified, and computation time is much saved.

The ray with respect to reflection, that is, imaging diffraction ray, is determined by connecting the representative points of edges which are in LOS. As a special case, when the reflection angle is equal to
the incident angle, the rays become a conventional reflection ray. It should be noted that continuity of electromagnetic fields at the reflection boundaries are satisfied by this image diffraction ray.

We consider source diffraction in illuminated region and shadow region. The number of diffracted rays is increased by including multiple diffractions. Because the effect of high-order multiple diffraction is small, we include only the diffracted rays with the shortest distance in the simplified Ray-Tracing Method (RTM). There are two types of rays as a source diffraction: one is the diffraction ray connecting two edges which are not in the line of sight (NLOS) in the shadow region, and the other is the diffraction ray in the illuminated region. In this paper, we consider only the one times diffraction in the illuminated region, and we take into account only the rays with the shortest path in case of source diffraction.

Although the detailed discussions are omitted here, the received field in general is expressed as follows [2]:

\[ E = \sum_{n=1}^{N} \left[ \prod_{m=1}^{m=M_n^t} (D_{nm}^t) \cdot \prod_{k=1}^{k=M_n^s} (D_{nk}^s) \cdot E_0 \right] e^{-jkr_n} \]  

where \( E_0 \) is the electric vector of the n-th ray at the first source or diffraction point, \( \kappa = \omega \sqrt{\epsilon_\mu_0} \) is the wave number in the free space, and \( N \) is the total number of ray, \( M_n^t \) is the number of times of its image diffractions, and \( M_n^s \) is the number of times of its source diffractions. The distance of n-th ray from source to receiver is given by

\[ r_n = \sum_{k=0}^{k=M_n^t+M_n^s} r_{nk} \quad (n = 1, 2, \ldots, N) \]  

where \( r_{nk} \) is the \( k-th \) distance from one reflection or diffraction point to the next one.

The diadic function \( D^t \) for the image diffraction is given by the ray data and two functions; one is the Fresnel’s reflection coefficients for horizontal (h) and vertical (v) polarizations given by Eq.(10), and the other is the complex type of Fresnel function defined by Eq.(11). On the other hand, the diadic function \( D^s \) for the source diffraction is given by the ray data and the Fresnel function. Detailed discussions are omitted here for brevity.

\[ R^h = \frac{\cos \theta - \sqrt{\epsilon_c - \sin^2 \theta}}{\cos \theta + \sqrt{\epsilon_c - \sin^2 \theta}} , \quad R^v = \frac{\epsilon_c \cos \theta - \sqrt{\epsilon_c - \sin^2 \theta}}{\epsilon_c \cos \theta + \sqrt{\epsilon_c - \sin^2 \theta}} \]  

\[ F(X) = \frac{e^{\pi j}}{\sqrt{\pi}} \int_{-\infty}^{\infty} e^{-ju^2} du \quad (X > 0) , \quad X = \sqrt{kr(1-\cos \theta)} \]  

4. Numerical Example

Figure 3 shows source point and observation points. The source point is set at 1m high above rough surface, and the observation points are placed at 0.5m high along rough surface. Figure 4 shows an example of rays between source and receiver. Sample receiver is placed at \( x = 1360m \). The order of scattered rays include up to two times of reflections and one time of diffraction.

Figures 5 and 6 show field intensity distributions along homogeneous and inhomogeneous random rough surfaces. Ensemble average is 50. Operating frequency is given by \( f = 1.0[GHz] \). We choose dielectric constant \( \epsilon_r = 5.0, \sigma = 0.0023[S/m] \), correlation length \( cl = 50[m] \) and height deviation \( dv = 1[m] \) for the homogeneous random rough surface. In the inhomogeneous case, on the other hands, we select the same parameters as homogeneous for the left part and \( \epsilon_r = 20.0, \sigma = 0.03[S/m], cl = 20[m] \) and \( dv = 1.5[m] \) for the right part. Spectrum type is assumed to be Gaussian in Fig.5, while in Fig.6, it is assumed to be Gaussian for the left part and exponential for the right part. It is found from these figures that the field intensity along inhomogeneous rough surface is more attenuated than that of homogeneous case.
5. Conclusion

In this paper, we have investigated propagation characteristics along inhomogeneous random rough surface with different parameters. It is found from numerical examples that the field intensity along inhomogeneous rough surface is more attenuated than that of the homogeneous case.

In this paper, we have treated only 1D random rough surfaces. We need to treat 2D random rough surface to deal with a more realistic situation. This is our near future work.

Acknowledgments

The work was supported in part by a Grand-in Aid for Scientific Research (C) (21560421) from Japan Society for the Promotion of Science.

References


