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ORIGINAL ARTICLE

Fast integral equation algorithms for the solution of electromagnetic wave propagation over general terrains

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Abstract In this paper a fast numerical algorithm to solve an integral equation model for wave propagation along a perfectly conducting two-dimensional terrain is suggested. It is applied to different actual terrain profiles and the results indicate very good agreement with published work. In addition, the proposed algorithm has achieved considerable saving in processing time. The formulation is extended to solve the propagation over lossy dielectric surfaces. A combined field integral equation (CFIE) for wave propagation over dielectric terrain is solved efficiently by utilizing the method of moments with complex basis functions. The numerical results for different cases of dielectric surfaces are compared with the results of perfectly conducting surface evaluated by the IE conventional algorithm.

Introduction

The study of electromagnetic wave propagation is of significant importance in the planning and evaluation of wireless communication systems and data networks. The wave propagation is affected by the presence of the earth, the atmosphere, and the ionosphere. Consequently, the propagating wave is subjected to diverse mechanisms of reflection, diffraction, refraction, and scattering (Collin, 1985). These mechanisms are dynamic and highly affected by roughness, irregularity, and dimensionality of the terrain surface, also the electric and magnetic properties of the ground. The solution of terrain-based propagation problems involves the accurate determination of the field predictions at different locations along the terrain, taking into account all propagation phenomena and factors.

There are many field-computation models for the solution of electromagnetic wave propagation problems. Simple parametric models like the Hata model (Hata, 1980) and the spherical earth with knife-edges (SEKE) (Ayasli, 1986) have been used. However, these models are inaccurate since they are incapable of predicting the fluctuations in field strength due to shadowing and diffraction. But the analytical solution of wave propagation over general complex terrain geometry is not possible, and so one must go to computational electromagnetic methods (CEM).

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The availability of powerful PCs paved the way for intensive use of IE in wave propagation problems. Various integral equation (IE) based methods have been used for the solution of field scattering over perfectly and imperfectly conducting rough terrain profiles (Hviid et al., 1995; Yagbasan et al., 2010; Bluck et al., 2001; Wang et al., 2006; Nie, 2005; Liepa, 1968; Bruke, 1990; DaHan and Sarabandi, 2009, 2010; Tuc et al., 2005). The IE models are widely adopted in terrain based propagation problems when the atmosphere characteristics are constant and the significant variation in the medium occurs through the shape and characteristics of the ground boundary, thus the surface scattering is the predominant physical phenomenon. In Hviid et al. (1995) an IE model for the wave propagation over irregular terrain using the dual of the magnetic field integral equation has been derived. The derived equation relates the surface magnetic current on a perfect magnetic conducting 2-D terrain to the source electric field. The assumption of perfect magnetic conductivity for vertical polarization refers to a reflection coefficient of -1, which is a good approximation of the reflection coefficient for grazing incidence over a real ground at high frequency. However, the assumption of 2-D surface is not essential and it is considered in order to reduce the numerical computations. The algorithm suggested in Hviid et al. (1995) for the solution of the IE is slow since the processing time depends on the square of the number of unknowns, which increases linearly with frequency (Akorly and Costa, 2001; Aberegg and Peterson, 1995; Moroney and Cullen, 1995); yet more efficient algorithms can be developed. The unknown magnetic currents on the terrain surface are expressed in terms of a set of complex basis functions or natural basis set (Aberegg and Peterson, 1995; Moroney and Cullen, 1995) as an alternative of the standard pulse basis functions used in the conventional algorithm. After the substitution of the new basis functions in the integral equation, the complex amplitudes of the unknown magnetic currents are evaluated only at a few nodal points within each terrain segment. The values at intermediate points are then calculated by quadratic interpolation on the nodal points.

While the treatment of terrain as perfectly conducting, gives good results at UHF when compared to measurements, it is natural to consider the effect of finite conductivity on the field predictions over irregular terrain. Accordingly, the treatment of the solution of wave propagation problems using IE techniques will be extended to study the general problem of propagation over lossy dielectric terrains. The first step is to utilize the well known combined field integral equation (CFIE) formulation, which describes the propagation over a two dimensional dielectric surface in terms of the equivalent electric and magnetic surface currents (Umashankar and Taflove, 1993). Then introducing the complex basis functions (natural basis set) representation of the surface currents, and solving the resultant equations by using the point matching (collocation) method. For the purpose of verification three cases can be considered, namely: good dielectrics, lossy dielectrics and good conductors. They are defined using a well-known dimensionless quantity defined as the electric loss tangent (Balanis, 1989). However, while the case of good conductor can be easily verified by comparison with measurements and previous models, the other cases cannot be easily verified for massive scale problems due to the limitations in reference models or measurements. Nevertheless, the method provides an evidence for the accuracy and the applicability of the conventional forward algorithm for the perfectly conducting case. In addition, indications for the deviation of the lossy dielectric case from the perfectly conducting one can be noticed.

Conventional and proposed efficient algorithms for the solution of IE

The IE derived in Hviid et al. (1995) which relates the magnetic current density at an arbitrary point on the terrain to the source contribution and to the scattering from other points on the surface, is given by Hviid et al. (1995).

$$M^S(p) = 2M_i^S(p) + \frac{1}{2\pi}\int_C M^S(p')(\mathbf{n}\cdot\mathbf{R_2})\frac{jk}{R_2}e^{-jkR_2} \times \sqrt{\lambda_0\frac{R_1R_2}{R_1+R_2}}dP' \tag{1}$$

where p, p' are the observation and the source points respectively, n is a unit vector normal to the surface at the observation point p pointing upward, R_1 and R_2 are the distances indicated on the terrain geometry shown in Fig. 1, $k = 2\pi/\lambda_0$ is the wave number, λ_0 is the wavelength, and R_2 is the unit vector directed from the source point to the observation point.

The conventional algorithm suggested in Hviid et al. (1995) utilizes the point matching (collocation) method to solve the IE in Eq. (1) for the unknown magnetic currents. The surface is sampled into a set of N intervals or cells and the magnetic current is approximated by the sub sectional pulse basis functions defined on these intervals. Then the IE is enforced on the center of each interval, and the integral along each interval is approximated by the value of the integrand at the interval's center multiplied by its length (Hviid et al., 1995). Consequently, this procedure transforms Eq. (1) into a system of linear equations (full matrix of order $N\times N$) given by

$$M_n^S = 2M_{n,i}^S + \frac{1}{2\pi}\sum_{m=1}^{N}M_m^S(\mathbf{n}\cdot\mathbf{R_2})e^{j\frac{\pi}{4}}\frac{k}{R_2}e^{-jkR_2} \times \sqrt{\lambda_0\frac{R_1R_2}{R_1+R_2}}\Delta\mathrm{x_m} \tag{2}$$

The back scattering is neglected in Eq. (1), this has the effect of setting the upper half of the interaction matrix to zero, which represents the backscattering interactions leaving the lower triangular matrix equation which is given by:

$$M_n^S = 2M_{n,i}^S + \frac{1}{2\pi}\sum_{m=1}^{n-1}M_m^S(\mathbf{n}\cdot\mathbf{R_2})e^{j\frac{\pi}{4}}\frac{k}{R_2}e^{-jkR_2} \times \sqrt{\lambda_0\frac{R_1R_2}{R_1+R_2}}\Delta\mathrm{x_m} \tag{3}$$

In this case the set of unknown magnetic currents are evaluated directly by forward substitution. The conventional algorithm of Eq. (3) indicates that the magnetic current at a specific

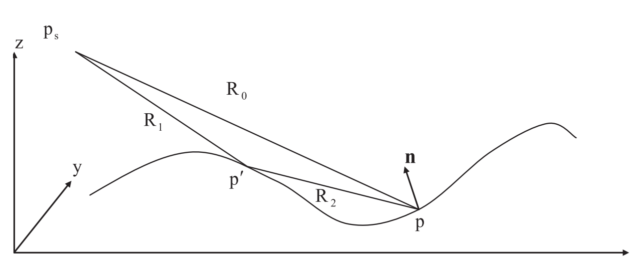

Figure 1 Terrain geometry.