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EFFECT OF GROUND TERRAIN ON MILLIMETER WAVE PROPAGATION

Massachusetts Institute of Technology

Jin A. Kong and Robert T. Shin

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is a final technical report of the work accomplished in the study of the effect of ground terrain on millimeter wave propagation under the sponsorship of US Air Force Contract F19628-80-C-0052 during the period of January 1980 to August 1981. During this period we have: (1) used the radiative transfer theory to calculate the backscattering cross sections from a Homogeneous layer containing discrete scatterers and to study the problem of thermal microwave emission from two layer random

media; (2) used Born approximation to study the depolarization in the active remote sensing of two-layer random media; (3) derived the modified radiative transfer (MRT) equations appropriate for electromagnetic wave propagation in a bounded random media; (4) studied the scattering of electromagnetic waves from both random and periodic rough surfaces; (5) made use of quantum mechanical potential approach to investigate the multiple scattering phenomenon with the model of randomly distributed discrete scatterers; (6) derived a theory for vector electromagnetic wave propagation in a random medium with strong permittivity fluctuation; and (7) studied the correlation functions for snow and ice fields.

EFFECT OF GROUND TERRAIN ON MILLIMETER WAVE PROPAGATION

J. A. Kong and R. T. Shin

SUMMARY

In the active and passive microwave remote sensing of earth terrain using radars and radiometers, the scattering effects due to medium inhomogeneities and surface roughness play a dominant role in the determination of radar backscattering cross-sections and the brightness temperatures. Two theoretical models have been developed to characterize terrain media: (1) a random medium model where scattering effects can be accounted for by introducing a randomly fluctuating part in the permittivities; (2) the discrete scatterer model where discrete scatterers are imbedded in a homogeneous background medium. The earth terrain is then modelled as layers of such scattering media bounded by rough surface with air above and homogeneous half-space below. In matching the theoretical results with experimental data collected from vegetation and snow fields, the following findings are summarized: (1) for radar observations near nadir, rough surface effects are important; (2) for snow fields the horizontal correlation length is greater than the vertical correlation length whereas for vegetation field their relative sizes depend on the types of vegetation; (3) the vertically polarized backscattering cross section is always larger than the horizontally polarized backscattering cross section for half space scattering media and may become smaller for a two-layer model; (4) for snow field

displaying a diurnal change, a three-layer model including a thin top layer caused by sun-light illumination must be used; (5) the correspondence between the continuum random medium model and the discrete spherical model can be verified when the vertical and horizontal correlation lengths are equal.

TABLE OF CONTENTS

I. Introduction

This is a final technical report of the work accomplished in the study of the effect of ground terrain on millimeter wave propagation under the sponsorship of US Air Force Contract F19628-80-C-0052 during the period of January 1980 to August 1981. During this period we have: (1) used the radiative transfer theory to calculate the backscattering cross sections from a homogeneous layer containing discrete sdatterers and to study the problem of thermal microwave emission from two layer random media [Section II]; (2) used Born approximation to study the depolarization effects in the active remote sensing of two-layer random media [Section III]; (3) derived the modified radiative transfer (MRT) equations appropriate for electromagnetic wave propagation in a bounded random media [Section IV]; (4) studied the scattering of electromagnetic waves from both random and periodic rough surfaces [Section V]; (5) made use of quantum mechanical potential approach to investigate the multiple scattering phenomenon with the model of randomly distributed discrete scatterers [Section VI]; (6) derived a theory for vector electromagnetic wave propagation in a random medium with strong permittivity fluctuation [Section VII]; and (7) studied the correlation functions for snow and ice fields [Section VIII].

II. Radiative Transfer Theory

The radiative transfer theory has been used extensively in the theoretical studies for active and passive remote sensing from scattering media. Even though the radiative transfer approach deals only with the intensities of the field quantities and neglects their coherent nature, it accounts for the multiple scattering and obeys energy conservation. Both the random medium model and the discrete scatterer model have been used with the radiative transfer theory to develop theoretical solutions for passive remote sensing. For active remote sensing, however, the radiative transfer theory has been used only with the random medium model to obtain backscattering cross sections using an iterative approach. Therefore, in order to complete the radiative transfer theory we have used the radiative transfer theory to calculate the backscattering cross sections from a homogeneous layer containing spherical or ellipsoidal scatterers. We have also studied the problem of thermal microwave emission from a two-layer random medium with cylindrical structure and a three-layer random medium with three-dimensional variation using the radiative transfer theory.

The radiative transfer theory is used to calculate the backscattering cross sections from a homogeneous layer containing spherical[1] or elliposidal scatterers.[2] For the spherical scatterers the Rayleigh scattering model is used to study the effect of volume scattering, by obtaining backscattering cross sections through iterative and numerical approaches. The iterative approaches give closed form solutions which are valid when the effect of scattering is small (small albedo). The radiative transfer equations and the boundary conditions are first cast into the integral equation forms. Then an iterative process is applied to solve the integral equations to both the first and second orders in albedo. The depolarization of the backscattered power is shown to be a second order effect. The numerical approach provides a solution which is valid for both small and large albedos. A Fourier series expansion in the azimuthal direction is used to eliminate the ϕ-dependence from the radiative transfer equations. Then, the set of equations without the ϕ-dependence is solved using the method of Gaussian quandrature. For a homogeneous layer containing ellipsoidal scatterers, an iterative approach is used to obtain backscattering cross sections to first order in albedo. Unlike the case of spherical scatterers where the depolarization of the backscattered power is a second order effect in albedo, we find that for the case of ellipsoidal scatterers, there is a depolarization effect in the backscattering direction in the first order solution.

The radiative transfer theory is used to study the emissivities of a two-layer random medium with a cylindrical structure[3] and a three-layer random medium with three-dimensional variations[4]. For a two-layer random medium with cylindrical structure, which has a small horizontal correlation length and a large vertical correlation length the first order brightness temperature is obtained with an iterative method and compared with exact solutions. For a three-layer random medium with three-dimensional variations, Gaussian quadrature method is used to solve the radiative transfer equations numerically. However, the computation times required to obtain solutions are very expensive.

III. Wave Theory

In the acitve remote sensing of earth terrain, theoretical models have been developed with the use of random media to account for volume scattering effects. In the random medium model, the earth terrain is treated as a random medium with a correlation function characterizing the size of inhomogeneities and the contrast in fluctuation strength as compared with the background dielectric constant. The problem of scattering by a layer of isotropic random medium with three-dimensional correlation functions has been solved to first order in albedo by applying the Born approximation to the wave equation and obtaining backscattering cross sections.[5] However, it has been shown that there is no depolarization effect in the backscattering direction in the first-order solution for isotropic random media. Therefore, in order to study the depolarization effects, the Born approximation is used to calculate the depolarized backscattering cross sections for isotropic and anisotropic two-layer random media.[6,7] For isotropic two-layer random media, it is shown that the depolarization effects arise as a second-order term in albedo. The terrain media which exhibit anisotropic behavior can be modelled as a random medium with anisotropic background dielectric or with isotropic background but having anisotropic correlation functions or both. The formulation of dyadic Green's function with an iterative procedure is used to calculate analytical expressions for backscattering cross sections that include depolarization effects.

IV. Modified Radiative Transfer Theory

The scattering of electromagnetic waves by continuous random media has been the subject of considerable investigation. In particular, the formalism of radiative transfer (RT) theory has been used extensively in the active and passive remote sensing of earth terrain. This phenomenological theory deals directly with radiation intensities which satisfy an integro-differential equation with appropriate boundary conditions. However, the limitation of the RT theory is that it assumes incoherent interactions among the specific intensities. When interference effects among specific intensities become important, a modified radiative transfer theory (MRT) which includes partial coherent effects must be used. MRT equations have been developed for a two-layer one-dimensional random medium, by applying the nonlinear approximation to Dyson's equation and the ladder approximation to the Bethe-Salpeter equation. These approximations have been shown to be energetically consistent and therefore appropriate in the development of a radiative transfer theory.

The modified radiative transfer equations appropriate for electromagnetic wave propagation in a two-layer random medium with three-dimensional permittivity fluctuations are derived.[8,9] The zeroth-order solution to the nonlinearly approximated vector Dyson's equation is used in the ladder approximated Bethe-Salpeter equation to derive vector MRT equations which govern the field intensities of TE and TM polarizations as well as their cross correlations. Additional constructive interference terms not accounted for in the RT theory are found to occur due to the presence of the bottom boundary. The MRT equations are then solved with the first order renormalization approximation to obtain analytical results for the backscattering cross sections of a two-layer random medium with arbitrary three-dimensional correlation functions.

V. Rough Surface Effects

The rough surface effects have been observed to be very important in the determination of the brightness temperature measurements and radar backscattering coefficients for vegetation and plowed crop fields. In order to study both the random and periodic rough surfaces, we have used the radiative transfer theory to study the emissivity of a homogeneous layer containing spherical scatterers and used rigorous methods to study the scattering of electromagnetic waves from a periodic surface.

The radiative transfer theory is used to solve the problem of thermal microwave emission from a homogeneous layer containing spherical scatterers.[10] To model volume scattering effects, we use the Mie phase functions. To model rough top and bottom interfaces, we use the bistatic coefficients for a randomly rough surface obtained using a combination of Kirchhoff theory and geometrical optics approach. Because the bistatic coefficients violate energy conservation there is ambiguity in the emissivity. However, using two formulations, the upper and lower limits of the emissivity are calculated. The effect of rough surfaces is incorporated into the radiative transfer theory by modifying the boundary conditions for the intensities. The radiative transfer equations are then solved numerically by using a Gaussian quadrature method and the results are illustrated by plotting the brightness temperatures as a function of observation angle for different polarizations. It is shown that the presence of bottom rough surfaces increases the brightness temperature, except for high angles for vertical polarization. The rough surface at the top boundary makes the angular behavior flatter, resulting in smaller differences between two polarizations.

The scattering of electromagnetic waves from periodic surfaces is studied.[11] Three analytical methods for conducting sinusoidal surfaces are compared in detail. The three methods are: (1) the MMM method developed by Masel, Merrill and Millar, (2) the Modified Physical Optics (MPO) method, and (3) Waterman's Plane Harmonics (WPH) approach. The MMM method is found to be the most efficient one in terms of the rate and range of convergence. For dielectric media with periodic rough surfaces, an improved method is developed to calculate the reflected and transmitted powers. The results are also used to compare with experimental data obtained at optical frequencies. It is shown that good agreement is achieved when the complex permittivity of the metal for the grating at the corresponding frequency is used. This explains the serious discrepancy between theory and experiment over the wavelength scale in the literature where only a perfect conductor model was used. Also, a theory is developed to study the scattering of electromagnetic waves from periodic rough surfaces of dielectric media for a general angle of incidence. In the past, for all the cases studied in the literature, the incident wave vector has been assumed to be perpendicular to the row direction and most papers only treat the case of perfectly conducting surfaces. The problem of wave scattering from a periodic rough surface of penetrable dielectric media with a general incident wave vector is studied. The E_z and H_z components of the electric and magnetic fields are used as the unknown scalar functions (a similar approach is used in waveguide theory) and the vector property of the problem is reduced to a scalar formulation. Then the matrix equations governing the scattering field amplitudes are derived so that the final results can be put in a clear matrix form and easy to program. The E mode and the H mode are shown to be coupled together in general. In the special case when the incident wave is perpendicular to the row direction, the E and the H modes are decoupled and the previous results are obtained.

VI. Multiple Scattering by Randomly Distributed Scatterers

An experimentally observed fact in scattering of electromagnetic waves by dense distribution of discrete scatterers is the assumption that independent scattering leads to overestimation of scattering effects. To account for this phenomenon the quantum mechanical operator formalism is used to study the multiple scattering of electromagnetic waves by a random distribution of discrete scatterers.[12] An equivalent potential operator in electromagnetic scattering is identified by deriving an integral equation for the dyadic Green's function which holds everywhere irregardless of whether the observation point is inside or outside the scatterers. Then the effective field approximation and the quasicrystalline approximations are used to calculate the effective propagation constants of the coherent waves. Also, the coherent potential is introduced to make the approximations self-consistent. The coherent-potential approach leads to the use of the propagation of the effective medium in the integral equations of the dispersion relations. Useful observations have been made on the dispersion relations that remove the need of solving the integral equations for complex momentum and give simpler formulas for calculating the complex effective propagation constant in the low frequency limit. In the case of spherical scatterers, the functional properties of the unkonwn variables are used to convert the integral equations to algebraic equations which are valid for arbitrary frequencies. Solutions of these algebraic equations are then illustrated for the low-frequency limit. Numerical results of the effective dielectric constants and the scattering attenuation rates are functions of the fractional volume occupied by the scatterers are illustrated using the parameters that are frequently encountered in microwave remote sensing of snow and soil moisture. It is shown that the result of quasicrystalline-coherent potential approximation is superior to the other approximations and accounts for the overestimate factor of 3-10 of independent scattering in snow.

VII. Strong Fluctuation Theory

The problem of wave scattering by random media has been studied extensively and has found approximation in the propagation of waves through turbulent atmosphere where the random fluctuation in permittivity is characterized by a small variance. Recently, the random medium theory has also been applied to remote sensing of earth terrain, where the permittivity function can have a large variance. However, the random medium theories that have been used in microwave remote sensing applications are only valid for cases of weak fluctuations of dielectric constants, because the singular nature of the dyadic Green's function has not been taken into account. For scalar wave propagation in a random medium, in the limit of low frequency, the renormalization method is valid for both weak and strong fluctuations of refractive index. However, for vector wave propagation in a random medium, additional secular terms are generated because of the singular nature of the dyadic Green's functions. Thus a straightforward extension of the scalar theory to the vector electromagnetic case leads to an additional criterion of the small variance of refractive index. The existence of the weak fluctuation criterion largely restricts the domain of usefulness of the theory.

In the bilocal approximated Dyson's equation, both the observation point and the source point of the dyadic Green's function are within the random medium and can coinside with each other within the domain of integration. Thus consideration of the singular nature of the dyadic Green's function is imperative. Physically, this corresponds to the fact that the scatterers act as sources of radiation. By properly taking into account the singularity of the dyadic Green's function a strong fluctuation theory of electromagnetic propagation can be derived that is applicable to both small and large variances of permittivity function.[13,14] Theory is then illustrated for random media with isotropic and anisotropic correlation functions. To verify the claim of the strong fluctuation theory, we compare the results with those from the discrete scatterer theory where large dielectric constrast between the scatterers and the background medium is allowed. It is shown that the results of the discrete scatterer theory under the effective field approximation and distorted Born approximation are identical with the corresponding results from the strong fluctuation theory in the common regime of validity. This is true for all values of dielectric constants of the scatterers. On the other hand, the significant differences between the weak and strong fluctuation theories are found for medium to large values of dielectric constrast between the scatterers and the background medium. By employing the distorted Born approximation, backscattering coefficients of a half space random medium with strong fluctuations are also illustrated using parameters typically encountered in microwave remote sensing of forests and vegetation.

VIII. Correlation Function Studies

In both active and passive remote sensing of earth terrain, it has been found very useful to model terrain media such as snow and ice with a random medium characterized by a correlation function which describes the random permittivity fluctuations with its associated mean, variance and correlation lengths. The success of the random medium model has been demonstrated with the interpretation and data matching of various experimental results obtained from field measurements. The parameters used in the correlation function have been obtained by proper choice which enables the theoretical results to match the data behavior as functions of frequency and viewing angles. A natureal question arises as to whether the random medium parameters so obtained indeed describes the physical characteristics of the terrain medium. Or, in other words, is there a physical way of obtaining these parameters and the specific correlation functions by a proper analysis of the ground truth data pertaining to each particular terrain medium? This important question is addressed by studying the correlation functions for the snow and ice fields using several cross sectional samples of snow and ice.[15] The correlation function is shown to be exponential in character with correlation lengths which correspond to the actual size of the ice particles in snow or air bubbles in ice.

IX. Publications

A. Journal Articles

A.1 L. Tsang and J. A. Kong, "Thermal microwave emission from a three-layer random medium with three-dimensional variations," IEEE Trans. on Geo. Remote Sensing, GE-18, no. 2, 212-216, April 1980.

A.2 M. Zuniga, J. A. Kong, and L. Tsang, "Depolarization effects in the active remote sensing of random media," J. Appl. Phys., 51, no. 5, 2315-2325, May 1980.

A.3 L. Tsang and J. A. Kong, "Multiple scattering of electromagnetic waves by random distributions of discrete scatterers with coherent potential and quantum mechanical formulism," J. Appl. Phys., 51, no. 7, 3465-3485, July 1980.

A.4 M. A. Zuniga and J. A. Kong, "Modified radiative transfer theory for a two-layer random medium," J. Appl. Phys., 51, no. 10, 5228-5244, Oct. 1980.

A.5 S. L. Chuang, J. A. Kong, and L. Tsang, "Radiative transfer theory for passive microwave remote sensing of a two-layer random medium with cylindrical structures," J. Appl. Phys., 51, no. 11, 5588-5593, Nov. 1980.

A.6 L. Tsang and J. A. Kong, "Application of strong fluctuation random medium theory to scattering from vegetation-like half space," IEEE Trans. on Geo. Remote Sensing, GE-19, no. 1, 62-69, Jan. 1981.

A.7 L. Tsang and J. A. Kong, "Scattering of electromagnetic waves from random media with strong permittivity fluctuations," Radio Science, 16, no. 3, 303-320, May-June 1981.

A.8 L. Tsang, M. C. Kubacsi, and J. A. Kong, "Radiative transfer theory for active remote sensing of a layer of small ellipsoidal scatterers," Radio Science, 16, no. 3, 321-329, May-June 1981.

A.9 R. T. Shin and J. A. Kong, "Radiative transfer theory for active remote sensing of homogeneous layer containing spherical scatterers," J. Appl. Phys., 52, 4221-4230, June 1981.

A.10 F. Vallese and J. A. Kong, "Correlation function studies of snow and ice," J. Appl. Phys., 52, no. 8, 4921-4925, August 1981.

A.11 M. A. Zuniga and J. A. Kong, "Mean dyadic Green's function for two layer random medium," Radio Science, accepted for publication.

A.12 L. Tsang, J. A. Kong, and R. W. Newton, "Application of strong fluctuation theory to scattering of electromagnetic waves from a half-space of dielectric mixture," IEEE Trans. Ant. Prop., accepted for publication.

B. Conference Papers

B.1 M. A. Zuniga, S. L. Chuang, J. A. Kong, and J. K. Lee, "Active microwave remote sensing of an anisotropic two-layer random medium," URSI Meeting, Quebec, Canada, June 2-6, 1980.

B.2 M. A. Zuniga and J. A. Kong, "Modified radiative transfer theory for active sensing of a two-layer random medium," URSI Meeting, Quebec, Canada, June 2-6, 1980.

B.3 M. E. McGillan, "Radiative transfer theory applied to remote sensing of homogeneous media containing discrete scatterers," URSI Meeting, Quebec, Canada, June 2-6, 1980.

B.4 S. L. Chuang, J. A. Kong, and L. Tsang, "Radiative transfer theory for a two-layer random medium with cylindrical structure," URSI Meeting, Quebec, Canada, June 2-6, 1980.

B.5 R. Shin, J. A. Kong, and L. Tsang, "Radiative transfer theory for active and passive microwave remote sensing of homogeneous layer containing spherical scatterers," URSI Meeting, Quebec, Canada, June 2-6, 1980.

B.6 M. Kubacsi and R. Shin, "Radiative transfer theory for active remote sensing of homogeneous layer containing ellipsoidal scatterers," URSI Meeting, Quebec, Canada, June 2-6, 1980.

B.7 J. A. Kong, "Effect of scattering on active and passive remote-sensing of earth terrain," International Conference on Communication, Seattle, WA, June 8-12, 1980.

B.8 R. T. Shin, S. L. Chuang, and J. A. Kong, "Radiative transfer theory for thermal microwave emission from an inhomogeneous medium with rough surfaces," URSI Meeting, Boulder, Colorado, January 12-16, 1981.

B.9 J. A. Kong, R. T. Shin, F. J. Vallese, S. L. Chuang, and L. Tsang, "Theory and application for microwave remote sensing of earth," URSI Meeting, Boulder, CO, January 12-16, 1981.

B.10 J. A. Kong, R. T. Shin, and S. L. Chuang, "Active and passive microwave remote sensing of earth terrain," IEE Second International Conference, University of York, U.K., April 13-16, 1981.

B.11 S. L. Chuang and J. A. Kong, "Remote sensing of dielectric media with periodic rough surfaces," 1981 International Geoscience and Remote Sensing Symposium, Washington, DC, June 8-10, 1981.

B.12 F. Vallese and J. A. Kong, "Correlation function studies for microwave remote sensing of snow and ice," 1981 International Geoscience and Remote Sensing Symposium, Washington, DC, June 8-10, 1981.

B.13 M. A. Zuniga and J. A. Kong, "Mean dyadic Green's function for remote sensing of a two layer random media," 1981 International Geoscience and Remote Sensing Symposium, Washington, DC, June 8-10, 1981.

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B.15 J. A. Kong, R. T. Shin, F. J. Vallese, S. L. Chuang, and J. K. Lee, "Random medium model for microwave remote sensing of earth terrain," URSI Meeting, Los Angeles, CA, June 15-19, 1981.

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