26. Electromagnetic Wave Theory and Applications

Academic and Research Staff

Prof. J.A. Kong, Prof. H. Raemer, Prof. C.H. Chen, Prof. L. Tsang, Dr. M.C. Lee, Dr. T.M. Habashy, Dr. R.T. Shin, Q. Gu, A. Sihvola

Graduate Students

K. Adler, R. Basch, M. Borgeaud, D. Gaylor, Y.Q. Jin, J.F. Kiang, R. Kim, C.C. Kuo, C.F. Lee, J.K. Lee, F.C. Lin, S.V. Nghiem, S.Y. Poh, D. Rennie, S. Rogers, A. Sezginer, M. Tsuk, A. Tulintseff, T.Y. Yang, Y.E. Yang

26.1 Electromagnetic Waves in Multilayer Media

Joint Services Electronics Program (Contracts DAAG29-83-K-0003 and DAAL03-86-K-0002)

Jin A. Kong, Tarak M. Habashy, Abdurrahman Sezginer, Ying E. Yang

We have derived the electromagnetic fields for dipole antennas embedded in a two-layer dissipative medium by using the following techniques: (1) the brute-force numerical-integration method, (2) the modal approach by finding the residues for the integrals, (3) the image-source approach in conjunction with the steepest descent method, (4) and the hybrid technique with the combination of the two latter approaches. It is noted that the quasistatic, near field approximation is valid for frequencies less than 100 KHz, and for measurement distances of less than 1/30 of the free space wavelength. For high frequencies or large layer thickness, the multi-image method gives accurate results in an efficient way, while for low frequencies or small layer thickness, the normal mode approach is more attractive. In the intermediate range, the hybrid image-mode approach is useful.

A general formulation is given for electromagnetic pulses which remain localized in a multidimensional space, and which propagate at the speed of light without dispersing (focus wave modes). It is shown that such modes necessarily have infinite electromagnetic energy in the source-free, three-dimensional space. Finite-energy focus wave modes cannot exist without sources. A set of complete focus wave modes with Hermite-Gaussian transverse variation is derived. The relation of focus wave modes to the solution of the paraxial wave equation is established.

Three simplified models, namely, (1) signal lines on a ground plate with transverse ridges, (2) parallel signal lines and a set of additional crossing strips between two parallel ground plates, and (3) signal lines between two parallel mesh ground plates, are used to study the propagation of the signals in the integrated circuits with complicated geometries. In models (1) and (2), transient responses are analyzed for a signal line or a pair of coupled lines consisting of line sections with different characteristic admittances and with capacitances loaded at the junctions. Then, equations for the Laplace transform of the reflection and transmission coefficients of single and coupled lines are derived. When the capacitances are loaded at regular intervals, the corresponding expressions of the transient response waveforms at different terminal ports of these lines for both a step and a ramp input signals are also derived. Numerical results of models (1) and (2) indicate that for the present computer circuitry, the signal distortion will be serious for rise times larger than 50 picoseconds and propagation distance longer than 1 centimeter. In model (3), we present an effective method which is based upon the wave transmission matrices of networks and the fast Fourier transform to analyze the propagation of the transient signals. Numerical results of model (3) indicate that the mesh ground planes will not seriously affect the signal propagation in the line system if line lengths are less than 2.5 centimeters and rise times of the propagating signals are greater than 50 picoseconds.

We also use the method of moments to solve the propagation problem of a pulse through a signal line above a ground plate with transverse ridges. The Floquet condition, which is used to relate the surface current distribution on different unit cells, reduces the number of unknowns in the matrix equation. An integral equation is derived by matching the boundary conditions, namely, the tangential electric fields on the surfaces of the structure vanish. From this integral equation, the dispersion relation is solved numerically by Galerkin's method. It is found from the dispersion relation that the structure behaves as a bandstop filter. The pulse is distorted as it propagates along the transmission line. The seven point average delay time and the root mean square distortion are defined to analyze the properties of the transmission structure.

When applying the method of moments to EM scattering problems involving scatterers with dimension larger than several wavelengths, tremendous amounts of computer CPU time are required to solve the very large matrix equations. However, when only the far field properties such as scattering cross section is of interest, we can use the sparse matrix technique to reduce the amount of computation. The Gaussian elimination algorithm, Cholesky decomposition algorithm, several versions of conjugate gradient methods are adopted to solve the sparse matrix. The number of multiplications and divisions (flops) are counted for comparing the efficiency of these algorithms. The effect of the nonzero element positions to the efficiency is also studied by defining the clustering index.

26.2 Remote Sensing with Electromagnetic Waves

National Science Foundation (Grants ECS82-03390 and ECS85-04381)

Jin A. Kong, Leung Tsang, Robert T. Shin, Jay K. Lee, Freeman C. Lin

In active and passive microwave remote sensing, layered random medium models, which include the anisotropic effects, discrete scatterers, random distribution of discrete scatterers, rough surface effects, have been used to simulate snow-ice fields, forests, vegetation canopies, plowed field, sea ice, and the atmosphere. Scattering and emission of electromagnetic waves by random media bounded by rough interfaces are investigated. Multiple scattering effects of electromagnetic waves by a layer of densely distributed discrete scatterers are studied. The strong fluctuation approach is applied to derive the modified radiative transfer equation which accounts for the multiple scattering effects. Also, active remote sensing with dipole antennae and line sources has been studied for both monochromatic and pulse excitations.

The study of the strong fluctuation theory for a bounded layer of random discrete scatterers has been extended to include higher order co-polarized and cross-polarized second moments. The backscattering cross sections per unit area are calculated by including the mutual coherence of the fields due to the coincidental ray paths and that due to the opposite ray paths which are corresponding to the ladder and cross terms in the Feynman diagrammatic representation.

The Feynman diagrammatic technique is also applied to study the electromagnetic wave propagation and scattering in an anisotropic random medium. The Dyson equation for the mean field is solved by bilocal and nonlinear approximations. The Bethe-Salpeter equation for the correlation of field was solved by ladder approximation. The effective propagation constants are calculated for the four characteristic waves associated with the coherent vector fields propagating in an anisotropic random medium layer, which are the ordinary and extraordinary waves with upward and downward propagating vectors. The z-component of the effective propagation constant of the upward propagating wave is different from the negative of that of the downward propagating wave, not only for the extraordinary wave but also for the ordinary wave. This is due to the tilting of the optic axis which destroys the azimuthal symmetry.

The electromagnetic fields due to dipole antennae in a bounded conducting medium modelling the sea have been formulated in integral forms and solved with the brute force numerical integration method, the modal approach by finding the residues for the integrals, the image-source approach by using the steepest descent method, and the hybrid technique combining the two latter approaches.

Ice fields are simulated by a two-layer anisotropic random medium model for active and passive microwave remote sensing in order to account for the anisotropic effects caused by the randomly distributed air bubbles, brine pockets, and other inhomogeneities, which have elongated shape and are oriented in a specific direction. We have also developed a three-layer random medium model to simulate snow-covered ice fields. All theoretical results match favorably well with the experimental data for thick first-year and multi-year sea ice with and without the cover of dry and wet snow.

26.3 Acoustic and Electromagnetic Wave Studies

Schlumberger–Doll Research Center
Jin A. Kong, Tarek M. Habashy, Abdurrahman Sezginer, Soon Y. Poh

Electromagnetic fields due to dipole antennae embedded in a two–layered dissipative medium, with applications in subsurface probing and communications, has been studied. The formulations are expressed in integral forms and solved with combinations of numerical and analytical techniques effective over different frequency regimes.

Electromagnetic pulses which remain localized in a multidimensional space, and which propagate at the speed of light without dispersing (focus wave modes) are analyzed. It is shown that such modes must have infinite electromagnetic energy in the source–free, three–dimensional space. Finite–energy focus wave modes cannot exist without sources.

The time domain analysis of electromagnetic dipole radiation over layered media is studied. This class of problems finds applications in transient soundings of the Earth surface and the upper atmosphere and is also of fundamental significance in the study of signal propagation in high performance integrated circuits. To evaluate the characteristic double integrals over wavenumber and frequency, the double deformation method, which entails deforming the original paths of integration to more convenient paths for easier integral evaluation, is used. Our goal is to attach physical importance to the various contributions from the enclosed singularities in the complex planes and to alleviate heavy computational requirements. The theory and technique have been extended to the case of transient radiation by transmission lines of finite width over a dielectric and ground plane leading to a better model for integrated circuit networks.

Scalar and vector Mathieu transform pairs have been developed for applications in electromagnetic problems.

26.4 Remote Sensing of Vegetation and Soil Moisture

National Aeronautics and Space Administration (Contract NAG 5–141)
Jin A. Kong, Robert T. Shin

The strong fluctuation theory is applied to study the volume scattering effect of vegetation canopies and soil moisture due to the large contrast in permittivities of the water droplets, the air and/or the clay. Theoretical results are illustrated by matching the experimental data from controlled field measurements. The scattering effect due to rough surface is modelled by a randomly perturbed, quasi-periodic surface for active remote sensing of plowed fields. In passive remote sensing of plowed fields, thermal emission has been solved by using a rigorous modal theory, which has been developed with the extended boundary condition approach. These models have been used to interpret remote sensing data from plowed fields showing a strong dependence to the change in the viewing direction relative to the row direction. The strong fluctuation theory is also applied to the study of electromagnetic wave scattering by a layer of random discrete scatterers.

26.5 Passive Microwave Snowpack Experiment

National Aeronautics and Space Administration (Contract NAS 5-26861)
Robert T. Shin, Jin A. Kong, Freeman C. Lin

During the winter of 1983-1984, in North Danville, Vermont, controlled field measurements had been conducted to investigate the volume scattering effect, the multilayer effect, and the diurnal change of the snowpack. Microwave radiometers at the frequencies of 10.8, 18, and 37 GHz were used to collect the experimental data. Before snowfall, the test sites were prepared so that microwave emission could be continuously monitored throughout the winter as snow accumulated. Aluminum-plate covered ground and artificial rough ground, simulating the plowed agricultural field, were prepared. The profile of the snow layer was attributed to the weather cycles in that area. The density and the physical sizes of the granular ice particles in the snow pack changed from one layer to another layer and ice layers were formed in the snowpacks. These ice layers cause interference effects which modify the emission characteristics of the snowpack. Analysis of preliminary results indicates that there are distinctive interference effects due to ice layers that appear in the incidence angle dependence of the brightness temperature of the snowpack. The collected ground truths have been archived for theoretical models in order to simulate the snowpack.

26.6 Remote Sensing of Earth Terrain

National Aeronautics and Space Administration (Contract NAG 5-270)
Jin A. Kong, Robert T. Shin, Yaqiu Jin, Freeman C. Lin

The theory of electromagnetic waves scattering from randomly distributed dielectric scatterers has been employed to relate remote sensing data of earth terrain to the actual physical parameters. We have used the strong fluctuation theory to derive the backscattering cross section. The study of the strong fluctuation theory for a bounded layer of random discrete scatterers is further extended to include higher order co-polarized and cross-polarized second moments. The backscattering cross sections per unit area are calculated by including the mutual coherence of the fields due to the coincidental ray paths and that due to the opposite ray paths which are corresponding to the ladder and cross terms in the Feynman diagrammatic representation. It is proved that the contributions from ladder and cross terms for co-polarized backscattering cross sections are the same, while the contributions for the cross-polarized ones are of the same order. The bistatic scattering coefficients in the second-order approximation for both the ladder and cross terms are also obtained. The enhancement in the backscattering direction can be attributed to the contributions from the cross terms.

A two-layer anisotropic random medium model is developed for the active and passive microwave remote sensing of ice fields. The diadic Green's function for this two-layer anisotropic medium is derived. With a specified correlation function for the randomness of the dielectric constant, the backscattering cross sections are calculated with the Born approximation. It is shown that the depolarization effects exist in the single-scattering process. Treating sea ice as a tilted uniaxial medium, the observed strong cross-polarized return in the bistatic scattering coefficients is successfully predicted from the theoretical model. It is also shown that the backscattering cross section of horizontal polarization can be greater than that of vertical polarization even in the half-space case. The principle of reciprocity and the principle of energy conservation are invoked to calculate the brightness temperatures. The bistatic scattering coefficients are first calculated and then integrated over the upper hemisphere to be subtracted from unity, in order to obtain the emissivity for the random medium layer. It is shown that both the absorptive and randomly fluctuating properties of the anisotropic medium affect the behavior of the resulting brightness temperatures both in theory and in actual controlled field measurements. The active and passive results match favorably well with the experimental data obtained from the first-year and the multiyear sea ice as well as from the corn stalks with detailed ground-truth information.

We have applied the Feynman diagrammatic technique to study the electromagnetic wave propagation and scattering in an anisotropic random medium. The Dyson equation for the mean field is solved by bilocal and nonlinear approximations. The Bethe-Salpeter equation for the correlation of field was solved by ladder approximation. The effective propagation constants are calculated for the four characteristic waves associated with the coherent vector fields propagating in an anisotropic random medium layer, which are the ordinary and extraordinary waves with upward and downward propagating vectors. The z-component of the effective propagation constant of the upward propagating wave is different from the negative of that of the downward propagating wave, not only for the extraordinary wave but also for the ordinary wave. This is due to the tilting of the optic axis which destroys the azimuthal symmetry.

A three-layer random medium model is adopted to study the volume scattering effects for the active and passive microwave remote sensing of snow-covered ice fields. We simulate the snow layer by an isotropic random medium and the ice layer by an anisotropic random medium. In snow, the fluctuation of the permittivity and the physical sizes of the granular ice particles are characterized by the variance and two correlation lengths. In ice, the anisotropic effect is attributed to the elongated structures and the specific orientations of the air bubbles, the brine inclusions, and other inhomogeneities. Two variances are required to characterize the fluctuations of the permittivities along or perpendicular to the tilted optic axis. The physical sizes of those scattering elements are also described by two correlation lengths.

26.7 Remote Sensing of Upper Atmosphere

National Aeronautics and Space Administration (Contract NAG 5-270)
Min C. Lee, Jin A. Kong

Nonlinear EM wave interactions with the upper atmosphere have been investigated on the following subjects: (1) the simultaneous excitation of ionospheric density irregularities and earth's magnetic field fluctuations, (2) the electron acceleration by Langmuir wave turbulence, and (3) the occurrence of artificial spread F. While processes (2) and (3) can be caused only by HF waves, process (1) occurs with EM frequencies as low as in the VLF band and as high as in the SHF band.

Radio measurements of Total Electron Content (TEC) and optical detection of airglow variations show that large scale plasma patches appearing in the high latitude ionosphere have irregular structures, evidenced by the satellite phase and amplitude scintillations. Whistler waves, intense quasi-DC electric fields, atmospheric gravity waves, and electrojets are potential sources of various plasma instabilities. The role of thermal effects in generating ionospheric irregularities by these sources have been investigated. A model has been developed to explain the discrete spectrum of the resonant ULF waves that have been commonly observed in the magnetosphere. The resonant electron diffusion is suggested to be an effective saturation process of the auroral kilometric radiation.[26] The calculated intensity of the saturated radiation has a significantly lower value in comparison with that caused by the quasi-linear diffusion process as an alternative saturation process.

Research effort has also been extended to EM wave interactions with laboratory plasmas. Plasma heating at the electron cyclotron frequency and the lower hybrid wave frequency has been studied. During electron cyclotron resonant heating by intense millimeter waves, the thermal filamentation instability can be excited to cause significant fluctuations in plasma density and magnetic field. These EM wave-induced perturbations may affect plasma confinement. Stimulated scattering instability of lower hybrid waves can generate forward scattered lower hybrid sidebands with smaller parallel phase velocities that are conducive to the bulk electron acceleration along the magnetic field. Mirror plasmas with an electron loss-cone distribution can drive the cyclotron maser instability to act as an EM radiator. An upper-bound of the radiation has been estimated. A single nonlinear differential equation is derived to describe the spatial evolution of the wave field in a gyrotron amplifier of the cylindrical guide geometry. This equation is then used to determine the efficiencies and optimized interaction lengths for gyrotrons operated with TEn1 modes at the N-th cyclotron harmonics.

26.8 Active and Passive Remote Sensing of Ice

U.S. Navy – Office of Naval Research (Contract N00014-83-K-0258)
Jin A. Kong, Robert T. Shin, Jay K. Lee, Freeman C. Lin, Maurice Bourgeaud

In order to account for the anisotropic effect of the earth terrain medium, we have developed (1) a two-layer anisotropic random medium model to study the active and passive remote sensing of ice and vegetation fields, in which the anisotropy is due to the alignment and shape of the brine inclusions in sea ice and air bubbles in lake ice, and row structures of the vegetation canopy, (2) the electromagnetic propagation and scattering theory in anisotropic random media, and (3) a three-layer model to simulate snow-covered ice. Since the brine inclusions and air bubbles can also be treated as randomly distributed scatterers with specific orientation, a strong fluctuation theory has been developed for considering the electromagnetic scattering in a bounded layer of discrete random medium.

We have derived the diadic Green's function for a two-layer anisotropic medium. The Born approximation is used to calculate the scattered fields. With a specified correlation function describing the randomness of the dielectric constant, the backscattering cross sections are evaluated. The analytic expressions for backscattering coefficients are shown to include depolarization effects in the single-scattering approximation. Treating sea ice as a tilted uniaxial medium, the observed strong cross-polarized return in the bistatic scattering coefficients is successfully predicted from the theoretical model. It is also shown that the backscattering cross section (per unit area) of horizontal polarization can be greater than that of vertical polarization even in the case of half-space. The principle of reciprocity is invoked to calculate the brightness temperatures for passive microwave remote sensing of a two-layer anisotropic random medium. The bistatic scattering coefficients are first calculated and then integrated over the upper hemisphere to be subtracted from unity, in order to obtain the emissivity for the random medium layer. It is shown that both the absorptive and randomly fluctuating properties of the anisotropic medium affect the behavior of the resulting brightness temperatures both in theory and in actual controlled field measurements. The active and passive results are favorably matched with the experimental data obtained from the first-year and the multiyear sea ice as well as from the corn stalks with detailed ground-truth information.

Electromagnetic wave propagation and scattering in an anisotropic random medium are studied with the Feynman diagrammatic technique. The effective propagation constants are calculated for the four characteristic waves associated with the coherent vector fields propagating in an anisotropic random medium layer, which are the ordinary and extraordinary waves with upward and downward propagating vectors. It is noticed that the z-component of the effective propagation constant of the upward propagating wave is different from the negative of that of the downward propagating wave, not only for the extraordinary wave but also for the ordinary wave. This is due to the tilting of the optic axis which destroys the azimuthal symmetry.

Radar backscattering from a snow-covered ice field provides a challenging modelling problem from the electromagnetic wave point of view. Both snow and ice exhibit volume scattering effects. For snow, the scattering is caused by the granular ice particles, and for ice, the air bubbles, the brine inclusions, and other inhomogeneities. We model both snow and ice as random media characterized by different dielectric constants and correlation functions. In order to model the brine inclusions of sea ice, the random medium is assumed to be anisotropic. A three-layer model is pursued to simulate snow-covered ice field with the top layer being snow, the middle layer being ice, and the bottom one being ground or water. The theoretical results are illustrated for thick first-year sea ice covered by dry snow at Point Barrow and for artificial thin first-year sea ice covered by wet snow at CRREL. The radar backscattering cross sections are seen to increase with snow cover for snow-covered sea ice because snow gives more scattering than ice. The results are also used to interpret experimental data obtained from field measurements.

A bounded layer of randomly distributed discrete scatterers is studied by the strong fluctuation theory. The backscattering cross sections per unit area are calculated by including the mutual coherence of the fields due to the coincidental ray paths and that due to the opposite ray paths which are corresponding to the ladder and cross terms in the Feynman diagrammatic representation.

26.9 Microwave Emission and Scattering

National Aeronautics and Space Administration (Contract NAG 5-725)
Min C. Lee, Jin A. Kong, Freeman C. Lin

In passive microwave remote sensing of geophysical media, such as soil, agriculture fields, snow-ice fields, etc., the thermal emission of radiation by the substance is studied by the continuous or discrete random medium model. Taking into account of the layered structure, isotropic or anisotropic effect, and the shape of the discrete scatterers, the brightness temperature is calculated from the emissivity, satisfying the principle of reciprocity and energy conservation. In the study of active microwave remote sensing of earth terrain media, such as forests, vegetation canopies, snow-ice fields, etc., and atmospheric constituents, such as aerosols, turbulent gases in ionosphere, atmospheric precipitation, etc., the multiple scattering of EM wave is examined by the formal wave scattering theory in conjunction with the perturbation method. The bistatic coefficients of like-polarization and cross-polarization consist of parameters characterizing the properties of the medium.

The backscattering and propagation of electromagnetic pulses with spatial and temporal Gaussian shape in snow and ice fields are studied with the isotropic and anisotropic random medium model. The bistatic scattering coefficients are computed with both the Born and the distorted Born approximations. We study the pulse shape distortion by considering a two-layer random medium model with different correlation lengths and varying variances. With high modulated carrier frequencies, the paraxial approximation is used to derive analytical forms. Both the like-polarized and cross-polarized radar backscattering coefficients will be examined and illustrated.

We are developing the modified radiative transfer theory for sea ice in order to account for the coherent interaction effects in the layered structure of lake and sea ice.

Aside from the random medium model that we have discussed above, we must study the other complementary model which is based on the fact that the scatterers in ice, like those in snow, are discrete scatterers. This second discrete scatterer theory, which is still being developed, seeks to unify the statistical random medium model and the deterministic discrete scatterer model.

26.10 Wave Transmission and Coupling in Multilayered Media

International Business Machines, Inc.
Jin A. Kong, Qizheng Gu, Soon Y. Poh, Abdurrahman Sezginer, Ying-ching E. Yang

As the packaging of integrated circuits has become more compact and operating frequencies have reached the GHz range, it has become necessary to study electromagnetic wave phenomena in such circuits to predict no longer negligible signal distortion and crosstalk. The signal transmission lines are embedded in a dielectric and sandwiched between two conductive reference planes. Generally, these signal lines are separated into layers running in orthogonal directions. Signal lines in different layers are connected through vertical conductors called vias. Transients on striplines in a complicated integrated circuit geometry are studied with three simplified models.

In one geometry, the integrated circuit contains one or two parallel strip transmission lines in a homogeneous dielectric, enclosed by upper and lower ground planes, with perpendicularly crossing strips. In an idealized circuit model, the strip transmission lines are modelled as consisting of two families of sections, with and without crossing strips. The edges of crossing strips are modelled as junction capacitances between adjacent sections. Equations for the Laplace transform of the reflection and transmission coefficients of single and coupled lines are derived. Transient reponses are analyzed for a single line and a pair of coupled lines, calculated as a function of geometry and number of crossing strips. The numerical results show that for the present computer circuitry, signal distortion will be serious as rise times are larger than 50 pico-seconds and the propagation distance is longer than 1 centimeter.

In a second model, rather than segmented, two parallel strip transmission lines are characterized as nonuniformly coupled, dispersionless transmission lines, where the coupling coefficient of the system is assumed to be slowly varying with respect to position. We present a method which transforms the coupled equations into a form for which the method of characteristics, more versatile than frequency domain methods, applies.

In the third model, we consider a transmission line sandwiched between two parallel mesh ground plates. The unit cells of the periodic structure of the mesh ground plates consist of transmission line sections and some lumped elements connected in cascade. Based on this periodic or coupled periodic structure, we can make use of the wave transmission matrix of the network and the fast Fourier transform technique to calculate the reflection and transmission coefficients. Numerical results show that the mesh ground planes will not seriously distort the signal propagating in the line system if the length of the line is less than 2.5 centimeters and the rise time of the propagating signal is not less than 50 pico–seconds.

The method of moments is also used to solve the transient problem of pulse propagating through a transmission line above a ground plate with transverse ridges. The ridges are used to model the other transmission lines passing between the transmission line and the ground plate. The Floquet condition, which is used to relate the surface current distribution on different unit cells, reduces the number of unknowns in the matrix equation. An integral equation is derived by matching the boundary conditions, namely, the tangential electric fields on the surfaces of the geometry vanish. From this integral equation, the dispersion relation is solved numerically by Galerkin's method. It is found from the dispersion relation that this geometry functions as a bandstop filter. The pulse is distorted as it propagates along the transmission line. The seven point average delay time and the root mean square distortion are defined to analyze the properties of this geometry.

26.11 Electromagnetic Wave Scattering from Targets

Lincoln Laboratory
Robert T. Shin, Check F. Lee

The problem of electromagnetic wave scattering from targets is studied using the method of moment and the physical theory of diffraction. The method of moments (MoM) is widely used to calculate the radar cross sections (RCS) of arbitrarily-shaped objects. However, its application is limited to small objects due to large computation time required. A hybrid method which combines the MoM with the physical theory of diffraction (PTD) may be used to speed up the computation time and extend the applicability of MoM to electrically large objects. In the hybrid method, rather than directly inverting the impedance matrix, an iterative method is used to solve for the induced surface current, with the approximate surface currents obtained using PTD. For flat plates, the physical optics and the edge diffraction currents are used. For cylindrical objects, the physical optics current, the creeping wave current, and the approximate expression for the transition region current are used. The region over which MoM is applied may be the whole object, or it may be limited to the regions where the PTD currents are not accurate. Iteration methods, such as conjugate gradient and successive over-relaxation, are used. It is shown that by using the approximate PTD currents, the iteration converges faster. Also, when calculating the RCS as a function of incident angle, it is shown that the iteration converges very fast if the current calculated for the previous angle of incidence is used as an initial guess. The convergence is even faster if the initial guess for the phase of the current is modified by the differences in the phases of the physical optics currents for the two angles of incidence. The theoretical results are illustrated by calculating radar cross sections and comparing with experimental data.

Publications

Kong, J.A., "Electromagnetic Characterization of Inhomogeneous Media Exhibiting Volume Scattering Effects," Workshop on Waves in Inhomogeneous Media, Schlumberger-Doll Research, Ridgefield, Connecticut, August 8-9, 1985.

Habashy, T.M., J.A. Kong, and L. Tsang, "Quasistatic Electromagnetic Fields due to Dipole Antennas in Bounded Conducting Media," IEEE Trans. Geo. Remote Sensing, GE-23, 325-333, May 1985.

Habashy, T.M., J.A. Kong, and W.C. Chew, "Scalar and Vector Mathieu Transform Pairs," J. Math. Phys., submitted for publication.

Sezginer, A.,"A General Formulation of Focus Wave Modes," J. Appl. Phys. 57, 3, 678-683, February 1985.

Jin, Y.Q., and J.A. Kong, "Ladder and Cross Terms in Second Order Distorted Born Approximation," J. Math. Phys. 26(5), 994-1011, May 1985.

Jin, Y.Q., and J.A. Kong, "Modified Radiative Transfer Equation in Strong Fluctuation Approach," National Radio Science Meeting, Boston, Massachusetts, June 25-28, 1985.

Jin, Y.Q., and J.A. Kong, "Strong Fluctuation Theory of Random Medium and Applications in Remote Sensing," International Symposium on Antennae and EM Theory (ISAE), Beijing, China, August 26-28, 1985.

Lee, J.K., and J.A. Kong, "Active Microwave Remote Sensing of an Anisotropic Random Medium Layer," IEEE Trans. Geosci. Remote Sensing GE-23, 6, 910-923, November 1985.

Lee, J.K., and J.A. Kong, "Passive Microwave Remote Sensing of an Anisotropic Random Medium Layer," IEEE Trans. Geosci. Remote Sensing, GE-23, 6, 924-932, November 1985.

Lee, J.K., and J.A. Kong, "Electromagnetic Wave Scattering in a Two-Layer Anisotropic Random Medium," J. Opt. Soc. Am., 1985, accepted for publication.

Lee, J.K., and J.A. Kong, "Mean Diadic Green's Function for a Two-layer Anisotropic Random Medium: Nonlinear Approximation to the Dyson Equation," International Symposium on Antennae and Propagation, Kyoto, Japan, August 20-22, 1985.

Lee, J.K., and J.A. Kong, "Electromagnetic Wave Scattering by a Two-Layer Anisotropic Random Medium," IGARSS 85 and URSI Meeting, University of Massachusetts, Amherst, Massachusetts, October 7-9, 1985.

Lin, F.C., J.K. Lee, J.A. Kong, and R.T. Shin, "Radar Backscattering from Snow-Covered Ice," Proceedings Snow Symposium V, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, August 13-15, 1985.

Gu, Q., and J.A. Kong,"A Transient Analysis of Single and Coupled Lines With Capacicitively Loaded Junctions," IEEE Trans. Microwave Theory Tech., 1985.

Yang, Y.E., J.A. Kong, and Q.Gu, "Time Domain Perturbational Analysis of Nonuniformly Coupled Transmission Lines," IEEE Trans. Microwave Theory Tech. MTT-33, 11, 1120-1130, November 1985.

Chen, C.F., "A New Look at Schur-Cohn Criterion for Discrete Systems," Proceedings of the IASTED International Symposium on Robotics and Automation, Lugano, Switzerland, 1985, pp. 165-168.

Chen, C.F., "The Schur-Cohn Criterion in a Composite Matrix Form," Proceedings of the 28th Midwest Symposium on Circuits and Systems, 1985, pp. 157-159.

Chen, C.F., "Solving Liapunov Matrix Equations via Grassman Algebra," to be presented at the 1986 International Conference on Circuits and Systems, San Jose, California, 1986.

Lee, M.C., J.A. Kong, H.C. Carlson, Jr., and S.P. Kuo, "Ionospheric Modifications by HF Heaters," Proceedings of the NATO AGARD Spring 1985 Electromagnetic Wave Propagation Panel Symposium on Propagation Effects on Military Systems in the High Latitude Region, Fairbanks, Alaska, June 3-7, 1985.

Lee, M.C., and S.P. Kuo, "Simultaneous Excitation of Large-scale Geomagnetic Field Fluctuations and Plasma Density Irregularities by Powerful Radio Waves," Radio Sci. 20, 539, 1985.

Kuo, S.P., M.C. Lee, and S.C. Kuo, "A Theoretical Model of Artificial Spread F," Radio Sci. 20, 546, 1985.

Lee, M.C., J. Buchau, H.C. Carlson, Jr., J.A. Klobuchar, and E.J. Weber, "Formation and Detection of High Latitude Ionospheric Irregularities," Proceedings of the NATO AGARD Spring 1985 Electromagnetic Wave Propagation Panel Symposium on Propagation Effects on Military Systems in the High Latitude Region, Fairbanks, Alaska, June 3-7, 1985.

Lee, M.C., J. Buchau, H.C. Carlson, Jr., J.A. Klobuchar, and E.J. Weber, "Polar Ionospheric Irregularities and Possible Source Mechanisms," presented at the 1985 North American Radio Science Meeting and International IEEE/AP-S Symposium, Vancouver, Canada, June 17-21, 1985.

Lee, M.C., and S.P. Kuo, "Generation of E Region Density Irregularities by Thermal Plasma Instabilities," presented at the 1985 North American Radio Science Meeting and International IEEE/AP-S Symposium, Vancouver, Canada, June 17-21, 1985.

Kuo, S.P., M.C. Lee, and A. Wolfe, "A Model for the Discrete Spectrum of the Resonant VLF Waves," Proceedings of the Workshop on Hydromagnetic Waves in the Earth's Magnetosphere, Columbia University, New York, Oct. 17-18, 1985.

Lee M.C., and S.P. Kuo, "Resonant Electron Diffusion as a Saturation Process of the Synchrotron Maser Instability," Plasma Phys., 1985, accepted for publication.

Lee, M.C., J.A. Kong, and S.P. Kuo, "Thermal Filamentation Instability of Millimeter Waves in Laboratory Plasmas," the condensed paper published in the Conference Digest of the 10th International Conference on Infrared and Millimeter Waves, Florida, Dec. 9-13, 1985; the full paper to be published in the International J. of Infrared and Millimeter Waves, 1985.

Kuo, S.P., and M.C. Lee, "Stimulated Backscattering of Lower Hybrid Waves," Phys. Fluids, 1985, accepted for publication.

Kuo, S.P., and M.C. Lee, "Saturation of Cyclotron Maser Instability Driven by an Electron Loss-Cone Distribution," the condensed paper published in the Conference Digest of the

10th International Conference on Infrared and Millimeter Waves, Florida, Dec. 9–13, 1985; the full paper to be published in the International J. of Infrared and Millimeter Waves, 1985.

Kuo, S.P., S.C Kuo, B.R. Cheo, and M.C. Lee, "Analysis of the Harmonic Gyrotron Travelling Wave Amplifier," the condensed paper published in the Conference Digest of the 10th International Conference on Infrared and Millimeter Waves, Florida, Dec. 9–13, 1985; the full paper to be published in the International J. of Infrared and Millimeter Waves, 1985.

Lin, F.C., J.A. Kong, R.T. Shin, and Y.E. Yang, "Backscattering and Propagation of Radar Pulses in Earth Terrain Media," IEEE IMTC/86 Meeting, Colorado.

Lee, C.F., and R.T. Shin, "Radar Cross Section Prediction Using a Hybrid, URSI Meeting Commission B, Philadelphia, June 9–13, 1986.

Rogers, S.W., and R.T. Shin, "Radar Cross Section Prediction for Coated Perfect Conductors with Arbitrary Geometries," URSI Meeting Commission B, Philadelphia, June 9–13, 1986.

Borgeaud, M., R.T. Shin, and J.A. Kong, "Theoretical Modeling of Polarimetric Radar Clutter," URSI Meeting Commission F, Philadelphia, June 9–13, 1986.

Poh, S.Y., J.A. Kong, M. Tsuk, "Transient Response of Dipole Antennas on Two-Layer Media," URSI Meeting Commission F, Philadelphia, June 9–13, 1986.

Lee, J.K., and J.A. Kong, "Modified Radiative Transfer Theory for a Two-Layer Anisotropic Random Medium," URSI Meeting Commission F, Philadelphia, June 9–13, 1986.

Gaylor, D., T.M. Habashy, and J.A. Kong, "Fields Due to a Dipole Antenna Mounted on Top of a Conducting Pad of Finite Extent in a Layered Stratified Medium," URSI Symposium Commission B, June 9–13, 1986.

Borgeaud, M., J.A. Kong, and F.C. Lin, "Microwave Remote Sensing of Snow-Covered Sea Ice," IGARSS '86, Zurich, Switzerland, 8–11, September, 1986.