Section 3 Electromagnetics

Chapter 1 Electromagnetic Wave Theory and Applications

Chapter 1. Electromagnetic Wave Theory and Applications

Academic and Research Staff

Professor Jin Au Kong, Dr. Sami M. Ali, Dr. Robert T. Shin, Dr. Ying-Ching E. Yang

Visiting Scientists and Research Affiliates

Dr. Pinchas D. Einziger,[1] Qizheng Gu,[2] Dr. Tarek M. Habashy,[3] Dr. Arthur K. Jordan,[4] Dr. Kevin O'Neill,[5] Dr. Soon Y. Poh,[6] Dr. Tsuneki Yamasaki,[7] Dr. Harold R. Raemer[8]

Graduate Students

Khurram K. Afridi, Jerome J. Akerson, David V. Arnold, Robert G. Atkins, Maurice Borgeaud, Ike Chang, Judy Chen, Nelson C. Chu, Hsiu C. Han, Yoshihisa Hara, Jean-Fu Kiang, Cheung-Wei Lam, Gloria W. Lau, Check-Fu Lee, Kevin Li, Victor Liau, Harold H. Lim, Son V. Nghiem, Kelly Savage, David M. Sheen, Mohammad A. Tassoudji, Michael J. Tsuk, Ann N. Tulintseff, Murat E. Veysoglu, Li-Fang Wang, Jiging Xia, Herng A. Yueh

Undergraduate Students

Daniel Chung, Laura Marmorstein

Technical and Support Staff

Margery Brothers, Kit-Wah Lai, Anh Lieu, Wei Ming-yu Lin

1.1 Electromagnetic Waves in Multilayer Media

Sponsors

Joint Services Electronics Program
Contract DAAL03-89-C-0001
National Science Foundation
Contract ECS 86-20029
Schlumberger-Doll Research
U.S. Army Research Office
Contract DAAL03 88-K-0057

Project Staff

Professor Jin Au Kong, Dr. Sami M. Ali, Dr. Tarek M. Habashy, Dr. Soon Y. Poh, Dr. Ying-Ching E. Yang, Robert G. Atkins, Ike Chang, Qizheng Gu, Check-Fu Lee, Kevin Li, David M. Sheen, Michael J. Tsuk, Ann N. Tulintseff, Jiging Xia

---

1 Department of Electrical Engineering, Technion-Israel Institute, Haifa, Israel.

2 Shanghai Research Institute of Mechanical and Electrical Engineering, Shanghai, China.

3 Schlumberger-Doll Research, Ridgefield, Connecticut.

4 Office of Naval Research, U.S. Navy, Arlington, Virginia.

5 Civil and Geotechnical Engineering, Department of the Army, Hanover, New Hampshire.

6 Digital Equipment Corporation, Andover, Massachusetts.

7 Department of Electrical Engineering, College of Science and Technology, Nihon University, Tokyo, Japan.

8 Electrical and Computer Engineering Department, Northeastern University, Boston.

We are developing a generalized formulation for the electromagnetic fields in multilayered uniaxially anisotropic media containing arbitrary distribution of current sources. A spectral domain dyadic Green's function for multilayered uniaxially anisotropic media containing three-dimensional sources is derived. Tractable forms are shown to be easily deduced from the physical picture of the waves radiated by the primary sources and the multiple reflections from the stratified medium. The formulation decomposes the dyadic Green's function into TE and TM waves. The dyadic Green's function in the source region is properly represented by extracting the delta function singularity. A simple procedure to obtain the fields in any arbitrary layer is described. Recursion relations for appropriately defined reflection and upward and downward propagating transmission coefficients are presented. Forms suitable for transmission line applications in multilayered media are derived.

Finite difference time domain (FDTD) techniques show great promise in their ability to solve three-dimensional problems with arbitrary geometry. Advantages of this method include the ability to model spatially or temporally varying media. These advantages are due to the complete discretization of both space and time. Considering the volume of information being calculated, these techniques are very efficient and well suited to calculation on future parallel processing computers. This method was first formulated by Yee in 1966, and his basic algorithm is still in use.

Recent work has demonstrated the applicability of the FDTD technique to microstrip problems. The centered finite difference approximations used are second order accurate in both space and time yielding good results for reasonable mesh sizes. Numerical techniques used to solve electromagnetic problems must limit the domain over which the fields are calculated. This mandates the use of an absorbing boundary condition to simulate the outward propagation of waves incident on the walls of the mesh. An absorbing boundary condition, developed by Mur and based on the work of Enquist and Majda, is used in this work.

Our work in this area includes development of the algorithms mentioned above into a general purpose computer code which can be used to solve for the transient response of electromagnetic problems having arbitrary geometries. In addition to the transient response, frequency domain parameters can be obtained by Fourier transform of the time domain results. Since the fields are calculated throughout space and time all other desired parameters can be calculated from the field quantities.

Specifically, we are analyzing rectangular microstrip structures with as many as two or more ports. Such structures can be used in MMIC filters or antennas. This problem is of interest for several reasons. First, there are existing frequency domain solutions to the resonance problem of a rectangular microstrip patch, which we compare with the FDTD solution. Secondly, the FDTD technique can be used to analyze coupling of microstrip lines to the rectangular structure. This coupling can be either a direct connection or a gap coupled connection. Advantages of the FDTD solution to this problem are that (1) the full wave solution allows for radiation or surface wave loss, (2) no empirical values such as "effective" dimensions are needed for the analysis, and (3) the geometry can be altered easily to allow for various connections or coupling to the patch. This method is a significant improvement over those that rely on a planar circuit approach in which the substrate thickness must be small compared to wavelength and inherently three-dimensional coupling problems are not easily handled. We will compare our results with various planar circuit approaches.

The leakage phenomenon is important in the area of millimeter-wave integrated circuits and integrated optics. We have performed theoretical analyses and experiments to investigate this phenomenon. The leakage is due to the TE-TM coupling occurring at the geometrical discontinuities, and the leaky power in the form of surface wave propagates in the background medium.

We are using various methods to analyze the dielectric strip waveguides including the approximate field matching, effective dielectric constant (EDC), and mode matching. Because the first two methods are approximate, they can not be used to predict the imaginary part of the propagation constant. When using the third method, we must place ground planes at some distance from the guiding structure and omit the effect of radiation loss.

To solve for the dispersion relation of single and coupled dielectric strip waveguides, we derive an integral equation formulation using dyadic Green's function. We also present a method for predicting the leakage. Three different dielectric strip waveguides are investigated: optical rib waveguide, strip dielectric guide, and insulated image guide. Both single and coupled strip waveguides are studied. The cross section of the dielectric strips are assumed to have rectangular shape. Applying the Galerkin's method, the field distribution on the cross section is represented by a set of unit pulse basis functions. By substituting these basis functions into the integral equations and choosing the same set of basis functions as the testing functions, we can obtain a determinant equation from which the propagation constant can be solved.

For single dielectric strip waveguide, we have observed that the leakage occurs when the effective refractive index is smaller than that of a surface wave mode in the background medium. We also observed that if the lowest TE-like (TM-like) mode is leaky, the lowest TM-like (TE-like) mode is non-leaky. When the lowest order mode leaks, the surface wave mode of opposite polarization is excited. When the higher order mode leaks, the surface wave modes of both polarizations can be excited.

For two symmetrical dielectric strip waveguides, we investigated both the even and odd modes. In the leaky mode, the total leakage is due to the leakage from each individual strip waveguide. At the separation where the even mode has a maximum leakage, it is implied that the surface wave modes excited by each waveguide add in phase. For the odd mode at about the same separation, these surface wave modes add out of phase; hence, a null in the leakage is observed.

We are analyzing the propagation properties of single and coupled inhomogeneous slab waveguides and propose an integral equation formulation using the dyadic Green's function which covers both the TE and TM modes. The dispersion relations are obtained by applying Galerkin's method to solve the integral equation. We also investigate the coupling between two symmetrical inhomogeneous slab waveguides. This method is applicable to arbitrary dielectric constant profiles.

Full modal analysis is used to study the dispersion characteristics of microstrip lines periodically loaded with crossing strips in a stratified uniaxially anisotropic medium. Dyadic Green's functions in the spectral domain for the multilayered medium in conjunction with the vector Fourier transform (VFT) are used to formulate a coupled set of vector integral equations for the current distribution on the signal line and the crossing strips. Galerkin's procedure is applied to derive the eigenvalue equation for the propagation constant. We investigate the effect of anisotropy for both open and shielded structures on the stopband properties.

We are analyzing the quasistatic fields generated by an electrode mounted on a perfectly conducting pad of finite extent buried in a planar stratified medium. An integral equation in the spectral domain is derived for the outflowing current density distribution on the pad-electrode surface. The method of moments is then applied to solve the integral equation. We are investigating the effects of the electric properties of the stratified medium and the standoff thickness on the total electrode current. Several conductivity profiles modelling different practical measurement environments are also considered. Numerical results reveal that the total electrode current is insensitive to the standoff thickness, and can be used to prospect for the conductivity of rock formation.

Based on a hybrid transmission lines-lumped element circuit model, we analyze the transient propagation characteristics of VLSI interconnects with discrete capacitive loads at various locations. Exact expressions of the Laplace transform of unit step responses are first obtained through the ABCD matrix formulation. We then apply the equivalent dominant pole approximation to the transfer function with the propagation delays factored out. The approximated transfer function can be inverted in closed form and quickly evaluated. These results provide efficient ways of finding approximately the effects on delays and rise time brought by VLSI off-chip interconnects.

Because of the dramatic increase in device densities on microelectronic chips, the propagation delay for off-chip interconnects has become the factor limiting the speed of VLSI packages. Typical scales of these interconnects will be comparable or larger than the characteristic wavelength of the high frequency components of the signal. Therefore, to calculate the delays caused by these interconnects properly, a hybrid circuit model containing transmission line sections as well as lumped elements must be used in place of the all-lumped elements. Nevertheless, most circuit simulation packages are based on the latter and have to resort to subsection approximation when dealing with transmission lines. This scheme will undoubtedly lead to lengthy computation — which is not desirable when a quick, heuristic estimate of bounds is needed for the initial phase of the design cycle.

We have developed two approaches for obtaining the approximate transient response without lengthy simulation. The first emphasizes the calculation of bounds to voltage responses from the differential equations either by direct integration or by using the optimal control theory. The second analyzes the properties of Laplace transform domain solution. Thus far, their applications are limited to all lumped-element and distributed RC networks, which can only handle on-chip interconnects. For off-chip delay estimation, we took the second approach by incorporating transmission line elements.

Extensive work has been published on radiation by a microstrip patch excited by a probe. Most of the published work did not rigorously model the correct current distribution on the probe. In the case of electrically thin substrates, the probe current is usually approximated as uniform along the probe. This leads to acceptable numerical results for the computation of the radiation pattern by the patch and the mutual impedance between the probe and the patch. However, this approximation is not sufficiently accurate to solve for the current distribution on the patch or for the computation of the self impedance across the terminals of the probe. Furthermore, this approximation is not appropriate in the case of electrically thick substrates.

We rigorously analyzed the radiation problem of a circular patch which is center fed by a coaxial-line driven probe over a ground plane and situated in an arbitrary layered medium. The current distribution on both the patch and the probe is rigorously formulated using a planar stratified medium approach. A set of three coupled integral equations is derived which governs the axial current distribution on the probe, the radial current distribution on the patch and the azimuthal magnetic current sheet across the aperture of the driving coaxial line. This set of equations is then solved using the method of moments. The resulting matrix equation is obtained in terms of Sommerfeld-type integrals that take into account the effect of the layered medium. These integrals are efficiently computed by a simple deformation in the complex wavenumber domain. The probe current distribution, input impedance and radiation pattern are presented and compared to the case of an uniform probe current distribution.

The analysis of microstrip antennas with electrically thick substrates has many applications pertaining to millimeter wave systems and to achieving wide bandwidth. Most of the published work on the input impedance and other parameters of a probe-fed microstrip antenna employ an approximation to the probe feed where it is replaced by a uniform current ribbon of equivalent dimensions. This approximation fails to give sufficiently accurate results for the input impedance of the probe especially for thick substrates. Recently, we have made some progress in this area — we obtained the current distribution on the metallic probe in a closed magnetic wall cavity. Then, we accounted for the radiation losses by lumping them artificially into an effective loss tangent.

We have formulated the problem of a center fed circular microstrip antenna in terms of a Weber transform, which allowed us to develop the Green's function of the layered medium with the probe and the microstrip patch as part of the medium. Using the Weber transform automatically enforces the boundary conditions on the probe and the patch. This allows us to cast the problem as the solution of a set of two coupled integral equations governing the tangential component of the electric field across the aperture of the coaxial line feed and that aperture across the interface where the patch lies. Next, we solve this set of equations using the method of moments. We then compute the current distribution on both the probe and the patch from the component of the magnetic field tangential to their surfaces. Furthermore, from the computed electric field across the aperture of the coaxial line feed, we obtain the reflection coefficient for the TEM mode which allows us to compute the input impedance across the terminals of the probe. The probe current distribution, input impedance and radiation pattern are presented, and the obtained results compared with those using the stratified medium formulation.

The transient fields of a current source on a layered medium are calculated using the double deformation technique, in which complex integrals are deformed in the transverse wavenumber and frequency planes. Singularities from these complex planes correspond to physical modes of the structure, such as guided and leaky waves, and the relative importance of each to the overall response can be discovered. Unlike the Cagniard-de Hoop method, double deformation can be applied to dispersive and dissipative media. Also, the causality of the electromagnetic signal can be shown analytically.

We developed a modification to the double deformation technique, which splits the Fourier transform of the source current into two halves, one for times before the arrival at the observation point, and one after. This greatly increases the range of sources to which the double deformation technique can be applied. Another advantage of the modification is the individual causality and continuity of each mode.

We have computed results for both line and strip currents on the surface of a coated perfect conductor for cases where the dielectric coating is both lossless and dissipative. In most cases, only a small number of modes suffices to reproduce the important features of the response, including the arrivals of reflected and lateral rays. The importance of each type of arrival depends on certain features of the time function, especially the initial slope. The response due to a strip current resembles that of a line current although there is some smoothing of the sharper features.

The complex resonant frequencies of the open structure of a microstrip antenna consisting of two circular microstrip disks in a stacked configuration have been rigorously calculated as a function of the layered parameters and the ratio of the radii of the two disks. Using a dyadic Green's function formulation for horizontally stratified media and the vector Hankel transform, the mixed boundary value problem is reduced to a set of coupled vector integral equations. Employing Galerkin's method in the spectral domain, we calculated the complex resonant frequencies and demonstrated convergence of the results. We show that for each mode, the stacked circular microstrip structure has dual resonant frequencies which are associated with the two coupled constitutive resonators of the structure and a function of the mutual coupling between the two disk resonators. This mutual coupling is a function of the geometrical configuration of the stacked structure; the layered parameters, permittivities, permeabilities, and heights; and the ratio of the radii of the two disks. The dual frequency behavior of the stacked microstrip structure can be used to broaden the bandwidth or to provide for dual frequency use of the antenna.

Publications

Ali, S.M., T.M. Habashy, and J.A. Kong. "Dyadic Green's Functions for Multilayered Uniaxially Anisotropic Media." Submitted to *J. Electromag. Waves Appl.*

Ali, S.M., T.M. Habashy, and J.A. Kong. "Probe Excitation of a Center-Fed Circular Microstrip Antenna Employing a Stratified Medium Formulation." In *IEEE AP-S International Symposium and URSI Radio Science Meeting,* San Jose, California, June 26-30, 1989.

Habashy, T.M., S.M. Ali, and J.A. Kong. "Probe Excitation of a Center-Fed Circular Microstrip Antenna Employing the Weber Transform." In *IEEE AP-S International Symposium and URSI Radio Science Meeting,* San Jose, California, June 26-30, 1989.

Kiang, J.F., S.M. Ali, and J.A. Kong. "Integral Equation Formulation of Inhomogeneous Slab Waveguides." Submitted to *IEEE J. Quantum Electron.*

Kiang, J.F., S.M. Ali, and J.A. Kong. "Integral Equation Solution to the Guidance and Leakage Properties of Coupled Dielectric Strip Waveguides." In *IEEE Trans. Microwave Theory Tech.* Forthcoming.

Kiang, J.F., T.M. Habashy, and J.A. Kong. "Electrostatic Fields Due to an Electrode Mounted on a Conducting Pad of Finite Extent in a Planar Stratified Medium." *IEEE Trans. Antennas Propag.* 37 (9):1140-1149 (1989).

Kiang, J.F., S.M. Ali, and J.A. Kong. "Analysis of Dielectric Strip Waveguides Using Integral Equation Formulation." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Lam, C.W., S.M. Ali, and J.A. Kong. "The Propagation Characteristics of Signal Lines with Crossing Strips in Multilayered Anisotropic Media." *J. Electromag. Waves Appl.* Forthcoming.

Poh, S.Y., M.J. Tsuk, and J.A. Kong. "Transient Response of Sources Over Layered Media Using the Double Deformation Method." *IEEE AP-S International Symposium and URSI Radio Science Meeting,* San Jose, California, June 26-30, 1989.

Sheen, D.M., S.M. Ali, M.D. Abouzahra, and J.A. Kong. "Application of the Three Dimensional Finite Difference Time Domain Method to the Analysis of Planar Microstrip Circuits." Submitted to *IEEE Trans. Microwave Theory Tech.*

Sheen, D.M., S.M. Ali, M.D. Abouzahra, and J.A. Kong. "Analysis of Multiport Rectangular Microstrip Structures Using a Three Dimensional Finite Difference Time Domain Technique." In *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Tulintseff, A.N., S.M. Ali, and J.A. Kong. "Resonant Frequencies of Stacked Circular Microstrip Antennas." In *IEEE AP-S International Symposium and URSI Radio Science Meeting,* San Jose, California, June 26-30, 1989.

Tulintseff, A.N., S.M. Ali, and J.A. Kong. "Resonant Frequencies of Stacked Circular Microstrip Antennas." Submitted to *IEEE Trans. Antennas Propagat.*

Yang, Y.E., and J.A. Kong. "Transient Analysis of Capacitively Loaded VLSI Off-Chip Interconnections," In *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

1.2 Remote Sensing of Earth Terrain

Sponsor

National Aeronautics and Space Administration
Contract NAGW-1617

Project Staff

Professor Jin Au Kong, Dr. Pinchas D. Einziger, Dr. Robert T. Shin, David V. Arnold, Robert G. Atkins, Nelson C. Chu, Harold H. Lim, Son V. Nghiem, Herng A. Yueh

We are developing models of various kinds of earth terrain using a two-layer configuration to investigate the polarimetric scattering properties of remotely sensed media. The scattering layer is an anisotropic random medium characterized by a three-dimensional correlation function with lateral and vertical correlation lengths and variances. Based on the wave theory under Born approximations, we applied this model to derive the fully polarimetric backscattering coefficients of the Mueller and covariance matrices. We considered a single scattering process, taking into account all the multiple reflections at the boundaries. For an anisotropic random medium with optic axis tilted off the vertical axis, the corresponding Mueller and covariance matrices do not contain any zero elements. To account for the azimuthal randomness in the growth direction of leaves in tree and grass fields, an averaging scheme is applied to obtain the backscattering coefficients. In this case, the Mueller matrix contains eight zero elements, the covariance matrix has four zero elements, and the cross-polarization term σ_{vh} does not vanish. Theoretical predictions are matched with experimental data for sea ice and vegetation fields.

During the transionospheric propagation of a high power radio wave beam, the nonuniform electromagnetic field interacts with the background plasma, leading to a ponderomotive force and a thermal pressure force. Both of the two nonlinear forces mainly act on the electrons, but eventually will have an effect on the ions through the ambipolar diffusion process. The spatial redistribution of the plasma density caused by the actions of these forces will change the local plasma permittivity along the beam path and consequently lead to the focusing of the radio wave beam.

We examine the self-focusing phenomena by taking into account both the ponderomotive force and the thermal pressure force as the two primary mechanisms. The threshold power intensity is determined by balancing the natural diffraction and the nonlinear focusing effects of the wave beam. The focal length for the concerned process is then estimated after solving the nonlinear wave equation.

To illustrate the self-focusing process, we carried out a series of numerical simulations for high frequency beams with various initial beam widths propagating in the ionospheric plasmas. The peak field intensity and the electron temperature along the beam path were calculated numerically. We showed that the thermal pressure force is predominant over the ponderomotive force in large incident beam width cases; however, the ponderomotive force is more significant if the beam width is small.

Earth terrains are modeled by a two-layer configuration to investigate the polarimetric scattering properties of the remotely sensed media. The scattering layer is a random medium characterized by a three-dimensional correlation function with correlation lengths and variances respectively related to the scatter sizes and the permittivity fluctuation strengths. Based on the wave theory with Born approximations carried to the second order, this model is applied to derive the Mueller and the covariance matrices which fully describe the polarimetric scattering characteristics of the media. Physically, the first- and second-order Born approximations account for the single and double scattering processes.

For an isotropic scattering layer, the five depolarization elements of the covariance matrix are zero under the first-order Born approximation. For the uniaxial tilted permittivity case, the covariance matrix does not contain any zero elements. To account for the randomness in the azimuthal growth direction of leaves in vegetation, the backscattering coefficients are azimuthally averaged. In this case, the covariance matrix contains four zero elements although the tilt angle is not zero. Under the second-order Born approximation, the covariance matrix is derived for the isotropic and the uniaxial untilted random permittivity configurations. The results show that the covariance matrix has four zero elements and a depolarization factor is obtained even for the isotropic case.

To describe the effect of the random medium on electromagnetic waves, the strong permittivity fluctuation theory, which accounts for the losses due to both of the absorption and the scattering, is used to compute the effective permittivity of the medium. For a mixture of two components, the frequency, the correlation lengths, the fractional volume, and the permittivities of the two constituents are needed to obtain the polarimetric backscattering coefficients. Theoretical predictions are illustrated by comparing the results with experimental data for vegetation fields and sea ice.

The phase fluctuations of electromagnetic waves propagating through a scattering medium, such as a forest, is studied with the random medium model. It is of practical reasons interest to determine the effectiveness of the synthetic aperture radar (SAR) in detecting and imaging objects within the scattering medium. As an electromagnetic wave propagates through the scattering medium, its energy is attenuated and a random phase fluctuation is introduced. The magnitude of this random phase fluctuation is important in estimating the effectiveness of SAR imaging techniques for objects within the scattering medium. We are investigating the phase degradation of the one-way problem, i.e., transmitter outside the scattering medium and receiver inside the scattering medium.

We use the two-layer random medium model, which consists of a scattering layer between free space and ground, to calculate the phase fluctuations introduced between a transmitter located above the random medium and a receiver located within the random medium. The scattering property of the random medium is characterized by a correlation function of the random permittivity fluctuations. The effective permittivity of the random medium is first calculated using the strong fluctuation theory, which accounts for the large permittivity fluctuations of the scatterers. The distorted Born approximation is then used in the past to calculate the backscattering coefficients. In calculating the phase fluctuations of the received field, we introduced a perturbation series for the phase of the received field and solved to first order in permittivity fluctuations.

Phase fluctuations are first calculated for the case of the transmitter located directly over the receiver, which corresponds to the normal incidence case. The first-order scattered field normalized to the zeroth-order transmitted field is calculated using the Green's function for the unbounded medium (thereby neglecting boundary effects). We compute the variance of the normalized scattered field at the receiver, which can be directly related to the magnitude of the phase fluctuations. We then compare the results obtained under these approximations to the results obtained using the paraxial approximation. The results are then extended to account for the effects of boundaries by using the two-layer Dyadic Green's function. We also consider the extension of the results to oblique angles of incidence and multilayer random media. The theoretical results are illustrated by comparing the calculated phase fluctuations and attenuation of the electromagnetic waves propagating through the random medium to the available experimental data over forested areas.

We present a finite difference time domain technique for two dimensional time domain scattering of electromagnetic waves. The triangular grids and the control region approximation are employed to discretize Maxwell's equations. The finite difference time domain techniques with uniform rectangular grids have been used in the past. The scatterers are modeled using staircases and, recently, we have investigated the accuracy of this approximation. We have proposed several types of other grids to improve the staircase approximation. Generalized nonorthogonal grid can model scatterer without staircasing. It has been applied to spherical systems, yet they appear to be cumbersome for general scatterers. The "distorted rectangular grid" model approximates the computational domain using rectangular grids and distorts the boundary grids to fit the interfaces. The triangular grid is used, which is very flexible in dealing with arbitrary scatterers and absorbing boundaries.

The control region approximation, which calls for Delaunay and Dirichlet tessellation, has been successfully applied to the frequency domain problems in the past. Two double integral terms are obtained by integrating the Helmholtz equation about the Delaunay tessellation. The term involving the Laplace operator can be converted to a closed loop integral of normal derivatives, which can easily be approximated in finite difference manner by utilizing the orthogonal property of Delaunay and Dirichlet tessellation. The remaining term can be approximated by multiplying the field at the node with the area. In the time domain problem, the same approximation is applied to the wave equation, except the term involving time derivatives is used in time marching scheme. Alternatively, as in Yee's algorithm, the first order Maxwell's equations are solved by spatially and temporally separating the electric and magnetic fields. In the case of electric polarization, the electric fields are placed at the nodes and the magnetic fields are placed at the center of triangular edges. The curl H equation is integrated by applying Stoke's theorem and converting it to a closed loop integral of tangential magnetic fields. This equation can be used to advance electric fields in time. To update magnetic fields, the second curl equation is used. This equation is approximated in the finite difference manner by utilizing the orthogonality property of the tessellation. The equations for the magnetic polarization case can also be derived following the similar procedure.

In order to limit the computation domain, the scatterers are enclosed with artificial outer boundaries. Continuous smooth outer boundaries, such as circles and ellipses, are chosen. The second-order time domain absorbing boundary conditions derived from the pseudo-differential operator approach is imposed at the outer boundaries. These boundary conditions are implemented with the control region approximation to determine necessary field quantities at the boundary. The results of the time domain control region approach are presented for simple scatterer geometries, such as conducting and coated cylinders and strips, by calculating both the transient and time-harmonic responses.

The finite element and finite difference methods are increasingly popular in the computational electromagnetics community. A major issue in applying the methods to electromagnetic wave scattering problems is confining the computation domain. This is accomplished by selecting an outer boundary and imposing absorbing boundary conditions to simulate the free space. The absorbing boundary conditions used can be exact or approximate conditions. In general, exact absorbing boundary conditions are computationally inefficient, so approximate absorbing boundary conditions, which are efficient and have sufficient accuracy, are widely used. Two distinct approximate absorbing boundary conditions have been used in the past. For the circular outer boundary, Engquist and Majda obtained the absorbing boundary conditions via the pseudo-differential operator approach. Bayliss and Turkel derived a circular boundary operator by assuming the Wilcox type expansion for the scattered fields and developing a series of operators to eliminate the inverse power series. The most widely used operator, the second-order operator, has higher absorbability than the corresponding Engquist and Majda condition.

The pseudo-differential operator approach provides a systematic way to obtain absorbing boundary conditions in orthogonal coordinate systems. Furthermore, following careful observation, we can improve the absorbability of the boundary conditions derived by Engquist and Majda. The first-order condition contains the normal propagation term and a portion of tangential variation term. The decay term along the normal direction appears in the second-order condition only. Since Sommerfeld's radiation condition contains both normal propagation and decay terms, the first-order condition alone cannot be reduced to the Sommerfeld's condition. In the case of cylindrical coordinate, the Laplace operator contains both first and second order normal derivative terms. These two terms can be grouped together by completing the square. A factorization scheme is then proposed which yields a first-order absorbing boundary condition that contains the Sommerfeld's radiation condition and a second-order condition.

The pseudo-differential operator approach is then extended to the elliptic boundary case. For scattering by elongated scatterers, the elliptic outer boundary can be used to reduce the computational domain. The elliptic coordinate system is employed which has two dimensionless parameters. In the circular boundary case, the normal parameter has the dimension of length and the decay term comes from the first order derivative. Thus, a new normal parameter, which is the arc length along a constant tangential parameter, is defined in the elliptic coordinate. The Helmholtz equation is then converted to include first-order derivative of the new normal parameter. The absorbing boundary conditions for the elliptic boundary is obtained following a similar procedure as in the circular boundary case. It is shown that in the limit of vanishing interfocal distance, the boundary conditions for the elliptic boundary reduces to the results of the circular boundary case.

The effectiveness of the second-order absorbing boundary condition on the elliptic outer boundary is illustrated by calculating scattered fields from various objects. The results obtained with elliptic boundaries are compared with those obtained using circular boundaries. The advantage of using the elliptic outer boundary in reducing the computational domain is illustrated by calculating scattering from elongated objects, such as strip. Furthermore, the choices for the ellipticity of the outer boundary for a given scatterer dimension are discussed.

The correlation function plays the important role in relating the electrical response of the geophysical medium to its physical properties. In the past, the volume scattering effect of electromagnetic waves from geophysical media such as vegetation canopies and snow-ice fields has been studied by using random medium models. Even though theoretical treatments were rigorous within certain constraints, the correlation functions were chosen according to researchers' knowledge and experience on physical properties of scatterers. Correlation functions have been extracted from digitized photographs of cross-sectional samples for snow and lake ice, and artificially grown saline ice. It was shown that the extracted correlation lengths corresponded to the physical sizes of ice grains, air bubbles, and brine inclusions. Also the functional forms of the extracted correlation functions were shown to be dependent on the shape and orientation of embedded inhomogeneities. To illustrate the importance of the correlation function study, the extracted correlation lengths for saline ice sample were then used to derive the effective permittivity and compared with in situ dielectric measurements of the sample. However, without any mathematical model, it is very difficult to relate the distribution, size, shape, and orientation of the scatterers to the variances, correlation lengths, and functional dependence of the correlation function.

The first analytical survey of correlation functions for randomly distributed inhomogeneities with arbitrary shape can be traced back to the work by Debye and his co-workers. In order to explain the fourth-power law of the intensity distribution of x-rays scattered by porous materials (hole structures) at larger angles, Debye et al., derived the correlation function for two-phase isotropic random medium. Debye showed that materials with holes of perfectly random shape, size and distribution can be characterized by a spherically symmetric correlation function of exponential form. The correlation length was related to the fractional volume and the specific surface which are among the important factors in determining the catalytic activity.

To demonstrate the feasibility of the method, we first derive in detail the correlation function and the correlation length for isotropic random medium with spherical inclusions. Then, we extend the correlation function study to consider randomly distributed prolate spheroids with preferred alignment in the vertical direction for the anisotropic random medium. We employ a scaling scheme to transform the surface equation of prolate spheroids to spheres so that we can utilize the same approach in the isotropic case to derive the correlation function. Since most geophysical media are complex materials such as wet snow — which is a mixture of air, ice grains, and water content — and multiyear sea ice — which consists of pure ice, air bubbles, and brine inclusions — we also establish the correlation function study for three-phase mixtures. We considered two different kinds of inclusions with spherical and spheroidal shapes. We found that there is a close relationship between the form of the correlation function and the distribution, geometrical shape, and orientation of the scatterers. Also, the calculated correlation lengths are related to the fractional volumes and total common surface areas. These results can be utilized to identify the feature signature and characteristics through its microscopic structure. For instance, dry or slush snow can be distinguished from grain sizes, water contents, and density via the comparison of the variances and correlation lengths. The form of the correlation function provides information about the physical shape and alignment of brine inclusions, in addition to the concentration of brine inclusions versus air bubbles for the tracing of the sea-ice signatures (such as thick first-year sea ice and multiyear sea ice).

As radio waves propagate through the ionosphere, wave scattering can occur as a result of ionospheric density irregularities which give rise to fluctuations in Faraday rotation angles, known as Faraday Polarization Fluctuations (FPF). FPF have been observed with low-orbit satellite beacon signals transmitted at frequencies 20, 40, and 54 MHz, and also with geostationary satellite signals at 136 MHz. Experimentally, it has been shown that when the linearly polarized waves, decomposed into two characteristic wave modes, were measured separately after transionospheric propagation, there was a loss of correlation between the two characteristic wave modes. It has been suggested that diffractive scattering of radio waves by ionospheric density irregularities is responsible for this phenomenon. The density irregularities have been considered to be isotropic and modeled by correlation functions having the same correlation length in all directions. Ionospheric plasma, however, is magnetized by the geomagnetic field, and ionospheric density irregularities tend to elongate along the magnetic field. The elongation results in the formation of field-aligned rod-like irregularities. Sheet-like irregularities have also been predicted theoretically and measured recently. The geomagnetized ionosphere with density irregularities is modeled as a gyrotropic random medium and the effects of both rod-like and sheet-like random density irregularities in causing FPF of VHF radio signals are studied by means of three-dimensional correlation functions.

The model is used to explain the intense FPF observed in polarimetric records of 136-MHz satellite signals received at Ascension Island in 1980 and 1981. The VHF signals were transmitted from the geostationary satellite SIRIO and propagated through the ionosphere near the Appleton equatorial anomaly crest where the ambient plasma density was high especially during the 1980 solar-maximum period. For rod-like irregularities, the theoretical results predict the field-aligned enhancement of FPF. The enhancement is shown to be stronger for longer rod-like irregularities. Furthermore, the results also demonstrate an inverse relation between the strength of FPF and the wave frequency. For sheet-like irregularities, the results also exhibit the field-aligned enhancement of FPF and the decreasing FPF strength with increasing propagation angle. The difference, however, is that the FPF strength due to the sheet-like irregularities have slower decreasing rates at small propagation angle and have larger values at large propagation angle than the FPF due to the rod-like irregularities. For VHF waves, the RMS FPF due to the rod-like and the sheet-like irregularities are quite distinctive. This suggests that the RMS FPF data with multi-frequencies and multipropagation angles can be used to infer the size and shape of ionospheric irregularities.

A multivariate K-distribution is proposed to model the statistics of fully polarimetric radar data from earth terrain with polarizations HH, HV, VH, and VV. In this approach, correlated polarizations of radar signals, as characterized by a covariance matrix, are treated as the sum of N n-dimensional random vectors; N obeys the negative binomial distribution with a parameter α and mean $\overline{N}$. Subsequently, an n-dimensional K-distribution, with either zero or nonzero mean, is developed in the limit of infinite $\overline{N}$ or illuminated area. The probability density function (PDF) of the K-distributed vector, normalized by its Euclidean norm, is independent of the parameter α and is the same as that derived from a zero-mean Gaussian-distributed random vector. The above model is well supported by experimental data provided by MIT Lincoln Laboratory and the Jet Propulsion Laboratory in the form of polarimetric measurements.

Publications

Borgeaud, M., S.V. Nghiem, R.T. Shin, and J.A. Kong. "Theoretical Models for Polarimetric Microwave Remote Sensing of Earth Terrain." *J. Electromag. Waves Appl.* 3 (1):61-81 (1989).

Borgeaud, M., J.A. Kong, R.T. Shin, and S.V. Nghiem. "Polarimetric Remote Sensing of Earth Terrain with Two-Layer Random Medium Model." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Chu, N.C., S.V. Nghiem, R.T. Shin, and J.A. Kong. "Phase Fluctuations of Waves Propagating Through a Random Medium." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Han, H.C., and J.A. Kong. "Self-focusing of a Radio Wave Beam During the Transionospheric Propagation." *International*

Union of Radio Science Commission H Meeting, Boulder, Colorado, January 4-7, 1989.

Lee, C.F., R.T. Shin, J.A. Kong, and B.J. McCartin. "Finite Difference Time Domain Techniques for Two Dimensional Triangular Grids." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Lee, C.F., R.T. Shin, J.A. Kong, and B.J. McCartin. "Absorbing Boundary Conditions on Circular and Elliptic Boundaries." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Lee, C.F., R.T. Shin, J.A. Kong, and B.J. McCartin. "Absorbing Boundary Conditions on Circular and Elliptic Boundaries." *J. Electromag. Waves Appl.* Forthcoming.

Lin, F.C., H.A. Yueh, J.A. Kong, and R.T. Shin. "Correlation Function Study for Random Media with Multiphase Mixtures." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Yueh, H.A., R.T. Shin, and J.A. Kong. "Scattering from Randomly Perturbed Periodic and Quasiperiodic Surfaces." In *Progress In Electromagnetics Research.* New York: Elsevier, 1989, Vol. 1, Chapter 4, pp. 297-358

Yueh, H.A., J.A. Kong, J.K. Jao, R.T. Shin, and L.M. Novak. "K-distribution and Polarimetric Terrain Radar Clutter." *J. Electromag. Waves Appl.* 3 (8):747-768 (1989).

1.3 Remote Sensing of Sea Ice

Sponsor

U.S. Navy - Office of Naval Research
Contract N00014-89-J-1107

Project Staff

Professor Jin Au Kong, Dr. Robert T. Shin, Maurice Borgeaud, Son V. Nghiem

We are studying fully polarimetric scattering of electromagnetic waves from snow and sea ice with a three-layer random medium model. This model can account for snow covered sea ice. The snow layer is modeled as an isotropic random medium characterized by a scalar permittivity. The sea ice is modeled as an anisotropic random medium with a symmetric permittivity tensor due to the elongated form of brine inclusions. The underlying sea water is considered as a homogeneous half-space. Volume scattering effects of both random media are described by three-dimensional correlation functions with variances and correlation lengths corresponding to the strengths of the permittivity fluctuations and the physical sizes of the inhomogeneities, respectively. We use the strong fluctuation theory to derive the mean fields in the random media under the bilocal approximation, taking into account the singularities of the dyadic Green's functions and calculating the effective permittivities of the random media with two-phase mixing formulas. We then apply the distorted Born approximation to obtain the covariance matrix which describes the fully polarimetric scattering properties of the remotely sensed media.

The three-layer configuration is first reduced to two-layer to observe polarimetric scattering directly from snow, first-year sea ice, and multiyear sea ice. We investigate the distinctive characteristics of the media with the conventional backscattering coefficients and the complex correlation coefficient ρ between σ_{hh} and σ_{vv}. The correlation coefficient ρ is shown to be important for identifying the characteristics of snow and sea ice. We then use the three-layer configuration to investigate the effects on polarimetric radar returns from snow covered sea ice.

Using a 14-GHz scatterometer and a collocated IR wave gauge, we made tower-based measurements of sea-state bias. The measured bias was found to be an increasing fraction of the significant wave height (SWH) with increasing wind speed. Theoretical modeling of the scattering from a two-dimensional two-scale model of the sea surface leads to a prediction of sea-state bias based on the wave height-dependent scattering cross section in the physical optics approximation. We are examining the implications of the measurements and modeling for sea-state bias algorithms.

EM bias is an error in the altitude measurement of an ocean altimeter caused because the troughs of ocean waves are better reflectors of electromagnetic waves than the crests. In the past, other researchers have attempted to predict the EM bias using a geometric optics solution based on a knowledge of the joint height-slope probability density function of the ocean surface. This solution does not predict any frequency dependence of the EM bias contrary to experiment, because it assumes that the curvature of the ocean surface is negligible compared to its slope (which might not be correct).

The EM bias can be solved more accurately by modeling the ocean surface with a two-scale model and solving for the EM bias using the physical optics solution. Using the saddle point method, we can solve a gaussian height probability density, (for normal incidence) and the physical optics integral (for small slopes of the large-scale ocean waves) for the backscattered power. The solution is a superposition of two terms: (1) the geometric optics solution, and (2) a correction term added due to the curvature of the ocean surface.

The ocean can be divided into large and small scales by choosing a separation wavenumber k_0. The small-scale height variance can be measured from experimental data and the small-scale slope and curvature variances can be estimated by using a suitable wavenumber spectrum. Assuming a one-dimensional wavenumber spectrum of the k^{-3} form with an upper cuttoff wavenumber k_s, the slope and curvature variances are obtained.

By using the experimental results of Cox and Munk, we can find an approximate upper cutoff wavenumber. Consequently, when we know the wind speed and small-scale height variance, we can estimate the EM bias by calculating the centroid of the backscattered power. Finally, the results are compared with experimental data.

In the research on the satellite-borne antennas, the study of electromagnetic radiation from sources in the ionospheric plasmas has received much attention. For many years, special attention has been given to the radiation in very low frequency (VLF) bands due to its applications in down-link communication systems and local ionospheric plasma diagnostics. Many authors have published results of both theoretical and experimental investigations on single element radiations. However, limited by low radiation efficiency, the utility of a practically-sized single VLF radiator could highly depend upon the focusing effects, which are characterized by inflection points on the *k*-surface associated with the medium. In recent years, the construction of a large space-based antenna array has been made feasible through the progress of spacecraft technology. With a properly phased large VLF linear or planar array, a narrow beam width and, consequently, high directivity can be achieved.

We analytically examined the far field pattern of a two-dimensional VLF phased array located in the ionosphere. We presented several designs of a phasing scheme which allows the planar array to be physically rotated 360 degrees with respect to an axis perpendicular to the plane of the array. The main beam stays in the same direction as that of the geomagnetic field line at the same time. We discussed the tradeoffs between the beamwidth, the operating frequency and the size of the array and compared the performances of the array of different designs.

We also discussed the applicability of the principle of pattern multiplication. More specifically, when there is more than one stationary phase point during the process of evaluating the radiation integral, or, in other words, when the *k*-surface of the medium possesses inflection points, the simple multiplication of the array factor and the element pattern will not result in the correct overall far field pattern of the array. For these cases, we took into account the type (e.g., electric dipole or magnetic dipole) and the orientation (e.g., parallel or perpendicular to the geomagnetic field line) of the radiating elements as well as the array configuration in calculating the far field pattern.

The scattering of electromagnetic waves from a two-dimensional slot in a ground plane is solved using the method of moments. The contribution of the surface features, such as slots and other discontinuities, to the total radar cross section (RCS) of objects is of practical interest in the RCS community. In formulating the integral equation for the transverse magnetic field case, the problem is separated into two regions: the region below and above the ground plane. The region below the ground plane is treated as a parallel plate waveguide. In the region above the ground plane, the slot aperture is replaced with a magnetic surface current sheet and the ground plane is removed by adding the necessary image sources. The integral equation for the magnetic surface current sheet over the slot aperture is then obtained by matching the boundary conditions over the aperture. The resulting integral equation is then solved with the method of moments using Galerkin's method with the pulse basis function.

Then, we extend the solution to the case when the slot is terminated and/or filled with dielectric/magnetic materials. This is a straightforward extension, since we can express simply the waveguide modes for the parallel plate waveguide filled with materials. We illustrated the scattering characteristics of surface slots by plotting the two-dimensional RCS as functions of incidence angle and frequency and presented the effects of filling the slots with conducting materials. We also discussed other useful techniques for studying the electromagnetic wave scattering characteristics of various two-dimensional surface features.

We developed the random medium model with three-layer configuration to study fully polarimetric scattering of electromagnetic waves from geophysical media. This model can account for the effects on wave scattering due to weather, diurnal and seasonal variations, and atmospheric conditions such as ice under snow, meadow under fog, and forest under mist. The top scattering layer is modeled as an isotropic random medium which is characterized by a scalar permittivity. The middle scattering layer is modeled as an anisotropic random medium with a symmetric permittivity tensor whose optic axis can be tilted due to the preferred alignment of the embedded scatterers. The bottom layer is considered as a homogeneous half-space. Volume scattering effects of both random media are described by three-dimensional correlation functions with variances and correlation lengths corresponding to the strengths of the permittivity fluctuations and the physical sizes of the inhomogeneities, respectively. We used the strong fluctuation theory to derive the mean fields in the random media under the bilocal approximation, properly taking singularities of the dyadic Green's functions account, and to calculate effective permittivities of the random media with two-phase mixing formulas. We then applied the distorted Born approximation to obtain the covariance matrix, which describes the fully polarimetric scattering properties of the remotely sensed media.

First, the three-layer configuration is reduced to two-layers to observe fully polarimetric scattering directly from geophysical media such as snow, ice, and vegetation. Such media exhibit reciprocity as experimentally manifested in the close proximity of the measured backscattering radar cross sections σ_{vh} and σ_{hv}, and as theoretically established in the random medium model with symmetric permittivity tensors. The theory is used to investigate the signatures of isotropic and anisotropic random media on the complex correlation coefficient ρ between σ_{hh} and σ_{vv} as a function of incident angle. For the isotropic random medium, ρ has the value of approximately 1.0. For the untilted anisotropic random medium, ρ has complex values with both the real and imaginary parts decreased as the incident angle is increased. The correlation coefficient ρ is shown to contain information about the tilt of the optic axis in the anisotropic random medium. As the tilted angle becomes larger, the magnitude of ρ is maximized at a larger incident angle, where the phase of ρ changes its sign. It should be noted that the tilt of the optic axis is also related to the nonzero depolarization terms in the covariance matrix (which will also be considered).

We identified the effects on polarimetric wave scattering due to the top layer by comparing the three-layer results with those obtained from the two-layer configuration. We used the theory to investigate the effects on polarimetric radar returns due to a low-loss and a lossy dry-snow layer covering a sheet of thick first-year sea ice. For the low-loss snow cover, both σ_{hh} and σ_{vv} are enhanced compared to those observed from bare sea ice. Furthermore, the boundary effect is manifested in the form of the oscillation on σ_{hh} and σ_{vv} The oscillation can also be seen on the real and imaginary parts of the correlation coefficient ρ. The magnitude of ρ, however, does not exhibit the oscillation while clearly retaining the same characteristics as observed directly from the uncovered sea ice. In contrast to the low-loss case, the lossy top layer can diminish both σ_{hh} and σ_{vv} and depress the boundary-effect oscillation. When the thickness of the lossy top layer increases, the behavior of the correlation coefficient ρ becomes more and more similar to the isotropic case, signifying that the information from the lower anisotropic layer is masked. At appropriate frequency, the fully polarimetric volume scattering effects can reveal the information attributed to the lower layer even if it is covered under another scattering layer. Due to the physical base, the random medium model renders the polarimetric scattering information useful in the identification, classification, and radar image simulation of geophysical media.

The three-layer random medium model is developed for microwave remote sensing of snow-covered sea ice. The electromagnetic wave theory and strong fluctuation theory are employed to study the propagation and volume scattering of electromagnetic waves in the medium. With the application of the Feynman diagrammatic technique and the renormalization method, mean fields for the isotropic and anisotropic random media are derived under the bilocal approximation. Then, the effective permittivities for both random media are obtained from the dispersion relations of the mean fields. Further, with the discrete-scatterer concept for two-phase mixtures, the scattering parts of effective permittivities are computed, in the low-frequency limit, for both isotropic and anisotropic random media with specified correlation functions. The distorted Born approximation is then used to compute the co-polarized and cross-polarized backscattering coefficients which are compared with scatterometer data at 9 GHz and 13 GHz for bare and dry-snow covered thick first year (TFY) sea ice taken at Point Barrow, N.W.T.

Publications

Arnold, D.V., J.A. Kong, W.K. Melville, and R.W. Stewart. "Theoretical Prediction of EM Bias." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Han, H.C., J.A. Kong, and T.M. Habashy. "Far Field Pattern of a VLF Antenna Array in the Ionspheric Plasmas." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Han, H.C., J.A. Kong, T.M. Habashy, and M.D. Grossi. "Principles of VLF Antenna Array Design in Magnetized Plasmas." *URS National Radio Science Meeting,* Boulder, Colorado, January 3-5, 1990.

Li, K., R.T. Shin, and J.A. Kong. "Radar Cross Section Prediction of Slots in Ground Planes Using Method of Moments." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Lin, F.C., J.A. Kong, and R.T. Shin. "Application of Three-Layer Random Medium Model for Microwave Remote Sensing of Snow-covered Sea Ice." Submitted to *J. Geophys. Res.*

Melville, W.K., J.A. Kong, R.H. Stewart, W.C. Keller, A. Jessup, D. Arnold, and A. Slinn. "The Measurement and Modelling of Sea-State Bias in SAXON." *IGARSS '89 and 12th Canadian Symposium on Remote Sensing,* Vancouver, Canada, July 10-14, 1989.

Nghiem, S.V., F.C. Lin, J.A. Kong, R.T. Shin, and H.A. Yueh. "Three-Layer Random Medium Model for Fully Polarimetric Remote Sensing of Geophysical Media." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Nghiem, S.V., J.A. Kong, R.T. Shin, and H.A. Yueh. "Application of Three-Layer Random Medium Model to Polarimetric Remote Sensing of Snow and Sea Ice." *North American Sea Ice Workshop,*

Amherst, Massachusetts, June 26-28, 1989.

1.4 SAR Image Interpretation and Simulation

Sponsors

National Aeronautics and Space Administration
Contracts NAGW-1272 and 958461
Simulation Technologies
Contract DAAH01-87-C-0679
U.S. Army Corp of Engineers
Contract DACA39-87-K-0022
WaveTracer, Inc.

Project Staff

Professor Jin Au Kong, Dr. Robert T. Shin, Dr. Ying-Ching E. Yang, Hsiu C. Han, Herng A. Yueh, Mohammad A. Tassoudji

Supervised and unsupervised classification procedures are developed and applied to synthetic aperture radar (SAR) polarimetric images in order to identify their various earth terrain components. For supervised classification processing, we used the Bayes technique to classify fully polarimetric and normalized polarimetric SAR data. We also considered simpler polarimetric discriminates, such as the absolute and normalized magnitude response of the individual receiver channel returns, in addition to the phase difference between the receiver channels. In addition, we discussed another processing algorithm, based on comparing general properties of the Stokes parameters of the scattered wave to that of simple scattering models. This algorithm, which is an unsupervised technique, classifies terrain elements based on the relationship between the orientation angle and handedness of the transmitting and receiving polarization states. These classification procedures have been applied to San Francisco Bay and Traverse City SAR images (supplied by the Jet Propulsion Laboratory). We showed that supervised classification yields the best overall performance when accurate classifier training data is used, whereas unsupervised classification is applicable when training data is not available.

Polarimetric radar backscatter data observed with satellite and airborne synthetic aperture radars (SAR) have demonstrated potential applications in geologic mapping and terrain cover classification. Accurate calibration of such polarimetric radar systems is essential for polarimetric remote sensing of earth terrain. A polarimetric calibration algorithm using three in-scene reflectors is developed which will be a useful tool in the radar image interpretation.

The transmitting and receiving ports of the polarimetric radar are modeled by two unknown polarization transfer matrices. The measured scattering matrix is equal to the product of the transfer matrix of the receiving port, scattering matrix of the illuminated target, the transfer matrix of the transmitting port, and a common phase factor. The objective of polarimetric radar calibration is to determine these two unknown polarization transfer matrices using measurements from targets with known scattering matrices.

The transfer matrices for the transmitting and receiving ports are solved in terms of measurements from three in-scene reflectors with arbitrary known scattering matrices. The solutions for several sets of calibration targets with simple scattering matrices are first presented. Then, the polarimetric calibration using three targets with general arbitrary scattering matrices is derived using the method of simultaneous diagonalization of two matrices. A transformation matrix is found to convert the general scattering matrices into the simple cases, and the problem is solved in the transformed domain. We can then express solutions to the original problem in terms of the solutions obtained for the simple scattering matrices. We discussed all possible combinations of calibration targets and presented the solutions of each case. Thus, if three scatterers with known scattering matrices are known to exist within a radar image, then the whole image can be calibrated using the exact solution presented. We also illustrated the effects of misalignment of calibration targets and of receiver noise for several sets of calibration targets.

Polarimetric terrain backscatter data observed with satellite and airborne synthetic aperture radars (SAR) demonstrate potential applications in geologic mapping and terrain cover classification. In previous publications on this subject, Gaussian statistics have frequently been assumed for the radar return signals to build the Bayes terrain classifier. However, abundant experimental evidence shows that the terrain radar clutter is non-Gaussian, i.e., non-Rayleigh in amplitude distribution. Among many non-Gaussian statistics, the K-distribution has proven useful in characterizing the amplitude distribution of electromagnetic echoes from various objects, including diverse ground surfaces, sea surface and wave propagation through atmospheric turbulence.

There has been considerable interest in the use of additional information provided by the polarization in the remote sensing of earth terrain. By measuring the amplitudes and phases of the HH, HV, and VV returns in the backscattered direction, fully polarimetric scattering characteristics of the earth terrain can be obtained. Once the scattering matrix is known, then the scattered power for any receiving and transmitting polarizations can be synthesized. The variation of the synthetic aperture radar (SAR) images due to the changes in the polarization has motivated the study in terrain discrimination and classification using the fully polarimetric SAR images. First, we presented the problem of determining the optimal polarizations that maximizes contrast between two scattering classes. Then, we presented the more general problem of classifying the SAR images into multiple classes using the polarimetric information.

The problem of determining the optimal polarization that maximizes the contrast between two terrain classes in the polarimetric radar images has many practical application in terrain discrimination. A systematic approach is presented for obtaining the optimal polarimetric matched filter, i.e., that filter which produces maximum contrast between two scattering classes. The maximization procedure involves solving an eigenvalue problem where the eigenvector corresponding to the maximum contrast ratio is optimal polarimetric matched filter. To exhibit the physical significance of this filter, it is transformed into its associated transmitting and receiving polarization states and written in terms of horizontal and vertical vector components. For the special case where the transmitting polarization is fixed, the receiving polarization which maximizes the contrast ratio is also obtained. Polarimetric filtering is then applied to synthetic aperture radar (SAR) images obtained from the Jet Propulsion Laboratory. We have shown, both numerically and through the use of radar imagery, that maximum image contrast can be realized when data is processed with the optimal polarimetric matched filter.

We developed a polarimetric radar calibration algorithm using three in-scene reflectors based on the exact solution for general target choices. The transmitting and receiving ports of the polarimetric radar are modeled by two unknown polarization transfer matrices. These transfer matrices are solved in terms of measurements from three independent calibration targets with known scattering matrices. First, we presented the solutions for several sets of calibration targets with simple scattering matrices. Then, when at least two of the target scattering matrices can be simultaneously diagonalized, polarimetric calibration is derived using the method of simultaneous diagonalization of two matrices. A transformation matrix is found to convert the general scattering matrices into the simple cases, and the problem is solved in the transformed domain. The solution to the original problem then can be expressed in terms of the solutions obtained for the simple scattering matrices. All possible combinations of calibration targets are discussed and the solutions are presented for the cases that at least two of the scattering matrices can be simultaneously diagonalized.

Conventional classification techniques for identification of vehicle types from their range profiles, or pulse responses, have been shown to be limited in their practical ability to distinguish targets of interest. These limitations arise from the need for large signature libraries and time consuming processing for profile matching algorithms, and from the assumptions made toward the statistics of extracted features for parametric methods. To overcome the practical constraints of existing techniques, we are examining a new method of target recognition which utilizes neural nets. The effectiveness of this neural net classifier is demonstrated with synthetically generated range profiles for two sets of geometries, as produced using RCS prediction techniques. The first set consists of three simple canonical geometries for which

RCS predictions can be done directly. For these targets, two neural net configurations are compared, and the effects of varied aspect sampling density for the training profiles and noise corruption in the test profiles are demonstrated. Comparisons are made between the neural net classifier and several conventional techniques to determine the relative performance and cost of each algorithm. A similar set of comparisons is performed for the second group of targets, consisting of more realistic air vehicle models, each composed from a collection of canonical shapes. In both cases, the neural net classifier is shown to match or exceed the performance of conventional algorithms while offering a more computationally efficient implementation.

We used strong permittivity fluctuation theory to solve the problem of scattering from a medium composed of completely randomly oriented scatterers under the low frequency limit. Based on Finkelberg's approach, Gaussian statistics is not assumed for the renormalized scattering sources. The effective permittivity is obtained under the low frequency limit and the result is shown to be isotropic due to no preferred direction in the orientation of the scatterers. Numerical results of the effective permittivity are illustrated for oblate and prolate spheroidal scatterers and compared with the results for spherical scatterers. The results derived are shown to be consistent with the discrete scatterer theory. The effective permittivity of random medium embedded with nonspherical scatterers shows a higher imaginary part than that of spherical scatterer case with equal correlation volume. Under the distorted Born approximation, the polarimetric covariance matrix for the backscattered electric field is calculated for the half-space randomly oriented scatterers. The nonspherical geometry of the scatterers shows significant effects on the cross-polarized backscattering returns σ_{hv} and the correlation coefficient ρ between HH and VV returns. The polarimetric backscattering scattering coefficients can provide useful information in distinguishing the geometry of scatterers.

Publications

Atkins, R.G., R.T. Shin, and J.A. Kong. "A Neural Net Method for High Range Resolution Target Classification." *J. Electromag. Waves Appl.* Forthcoming.

Kong, J.A., R.T. Shin, H.A. Yueh, H.H. Lim, and J.J. van Zyl. "Classification and Maximum Contrast of Earth Terrain Using Polarimetric Synthetic Aperture Radar Images." *Progress In Electromagnetics Research.* New York: Elsevier, 1990.

Lim, H.H., A.A. Swartz, H.A. Yueh, J.A. Kong, R.T. Shin, and J.J. Van Zyl. "Classification of Earth Terrain Using Synthetic Aperture Radar Images." *J. Geophys. Res.* 94 (B6):7049-7057 (1989).

Lim, H.H., H.A. Yueh, J.A. Kong, R.T. Shin, and J.J. van Zyl. "Contrast and Classification Studies of Polarimetric SAR Images for Remote Sensing of Earth Terrain." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-27, 1989.

Shin, R.T., and J.A. Kong. "Radiative Transfer Theory for Active Remote Sensing of Two-Layer Random Medium." In *Progress In Electromagnetics Research.* New York: Elsevier, 1989, Vol. 1, Chapter 5, pp. 359-417.

Yueh, H.A., J.A. Kong, R.M. Barnes, and R.T. Shin. "Calibration of Polarimetric Radars Using In-Scene Reflectors." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Yueh, H.A., J.A. Kong, R.M. Barnes, and R.T. Shin. "Calibration of Polarimetric Radar Using In-Scene Reflectors." *J. Electromag. Waves Appl.* 4 (1):27-49 (1990).

Yueh, H.A., R.T. Shin, and J.A. Kong. "Scattering from Randomly Oriented Scatterers with Strong Permittivity Fluctuations." *J. Electromag. Waves Appl.* Forthcoming.

Yueh, H.A., J.A. Kong, R.T. Shin, H.A. Zebker, and T. Le Toan. "K-distribution and Multi-frequency Polarimetric Terrain

Radar Clutter." *J. Electromag. Waves Appl.* Forthcoming.

Yueh, H.A., J.A. Kong, and R.T. Shin. "Calibration of Polarimetric Radars Using In-scene Reflectors." In *Progress In Electromagnetics Research.* New York: Elsevier, 1990.

1.5 Microwave and Millimeter Wave Integrated Circuits

Sponsors

U.S. Navy - Office of Naval Research
Contract N00014-89-J-1019
U.S. Air Force Systems -
Electronic Systems Division
Contract F19628-88-K-0013

Project Staff

Professor Jin Au Kong, Dr. Sami M. Ali, Dr. Tarek M. Habashy, Dr. Soon Y. Poh, Dr. Ying-Ching E. Yang, Jean F. Kiang, Cheung-Wei Lam, Check-Fu Lee, David M. Sheen, Michael J. Tsuk, Ann N. Tulintseff, Jiging Xia

We have found many applications for cylindrical microstrip antennas which pertain to high speed aircrafts and space vehicles. This is due to their conformity with the aerodynamical structure of such vehicles. Recently, there has been some progress in the theoretical study of these antennas — where the radiation from various cylindrical microstrip elements was computed by assuming an electric surface current distribution on the microstrip patch. The excitation problem of realizing such a current distribution must still be addressed. Furthermore, the input impedance for the cylindrical microstrip antennas has not yet been reported.

We presented a rigorous analysis of the resonant frequency problem of both the cylindrical-rectangular and the wraparound microstrip structures using two different approaches: integral equation formulation and a perturbational approach. Using Galerkin's method in solving the integral equations, we studied the complex frequencies with sinusoidal basis functions and investigated the effect of the edge singularity of the patch current on the convergence. Numerical results show that the HE_{10} mode for the wraparound patch and the cylindrical-rectangular patches have narrow bandwidth; thus, they are more appropriate for resonator applications. The TE_{01} and HE_{01} modes of the wraparound and cylindrical-rectangular patches, respectively, have wide bandwidth and are efficient radiating modes.

We investigated a more realistic problem of the radiation from a cylindrical microstrip antenna excited by a probe, discussing both the cylindrical-rectangular and the wraparound elements. Using a cylindrically stratified medium approach, we rigorously formulated the current distribution on the patch, deriving a set of vector integral equations that govern it. We then solved this set of equations using Galerkin's method, which expands the patch current in terms of a complete set of basis functions that can take into account the edge singularity condition. The input impedance, together with the radiation pattern, are derived both exactly and in the small substrate thickness limit where a single mode approximation is employed. For thick substrates, hybrid modes are excited. Only in the case of axially symmetric modes ($n = 0$), is the TE_{0m} decoupled from the TM_{0m}; modes of different parity do not couple. The presence of the dielectric substrate widens the bandwidth and broadens the radiation pattern. The radiation pattern is insensitive to the substrate thickness (especially for high dielectrics). For wraparound antenna, all current modes with no axial variation tend to weakly radiate and consequently have narrow bandwidth. When the TE_{01} mode is excited, the wraparound antenna works as a good antenna. The rectangular-cylindrical patch is, generally, less radiating than the wraparound.

For microwave integrated circuit applications, the characteristics of interconnects have been investigated for the propagation modes, time response, crosstalk, coupling, delay, etc. For these analyses, we assumed that quasi-TEM modes are guided along the multiconductor transmission lines. The analysis was performed for two asymmetric transmission lines. Also, an arbitrary number of transmission lines was analyzed in which the load and the source conditions were presented in terms of the modal reflection and transmission coefficient matrices.

A quasi-TEM analysis for multiconductor transmission lines with finite strip thickness embedded in arbitrary layers of a lossy isotropic stratified medium is presented. A spectral domain scalar Green's function of a uniform line charge immersed in a lossy isotropic stratified medium is introduced. In the formulation, no side walls are introduced, the transmission structure is not truncated, and the analysis is valid for arbitrary number of dielectric layers.

Based on the scalar Green's function, a set of coupled integral equations is obtained for the charge distribution on the strip surfaces. We used Pulse basis functions and a point-matching scheme is used to numerically solve the set of integral equations for the charge distribution, and hence the capacitance matrix. The duality between electrostatic formulation and a magnetostatic one is applied to calculate the inductance matrix. The conductance matrix is obtained by using the duality between the electrostatic and current field problem. To calculate the resistance matrix, we used a perturbation method.

Finally, we derived a transmission line analysis to obtain the transfer matrix for multiconductor uniform lines, which significantly reduces the effort in treating the load and the source conditions. We obtained transient responses by using the Fourier transform and presented the results for two coupled lines.

Due to their many advantages (including low profile and light weight), conventional microstrip antennas consisting of a single perfectly conducting patch on a grounded dielectric slab have received much attention in recent years. However, due to their resonant behavior, their use is severely limited in that they radiate efficiently only over a narrow band of frequencies, with bandwidths typically only a few percent. Techniques for increasing the bandwidth have included stacking a number of microstrip patches in multilayer configurations, introducing additional resonances in the frequency range of interest, and achieving wider bandwidths.

We have considered using a microstrip antenna consisting of two microstrip disks in a stacked configuration. With the dyadic Green's function formulation, we performed a rigorous analysis of the two stacked circular microstrip disks in a layered medium. We derived a set of coupled integral equations for the current distribution on the disks using the vector Hankel transform. This coupled set is then solved using Galerkin's method. The choice of the current basis functions is based on the currents of the magnetic wall cavity. Complex resonant frequencies are calculated as a function of the layered substrate, permittivities and thicknesses, and the ratio of the two disks radii. The resonant frequencies of two different stacked configurations are studied as function of the coupling interaction. Critical coupling between the two resonators occurs at the point where the real part of the resonance curves for the two isolated resonators intersect. The splitting of the complex resonance curves at this point is a function of the strength of the coupling between the two resonators. The dual frequency or wide band operation is shown to be achieved by changing the coupling coefficient.

We investigated the input impedance of a microstrip antenna consisting of two circular microstrip disks in a stacked configuration driven by a coaxial probe and performed a rigorous analysis using a dyadic Green's function formulation where the mixed boundary value problem is reduced to a set of coupled vector integral equations. Galerkin's method is employed in the spectral domain with an additional term used in the disk current expansion (1) to account for the singular nature of the current in the vicinity of the probe, (2) to ensure continuity of the current, and (3) to speed up convergence of the solution. To confirm the validity of the uniform probe current assumption with the use of the attachment mode, we compared the input impedance results of a single disk on both a thin and thick substrate with published data. The input impedance of the stacked microstrip antenna is calculated as a function of the layered parameters and the ratio of the two disks. We showed that the results of the stacked microstrip configuration are in good agreement with experimental data.

Many authors have studied microstrip discontinuities, such as open end, gap and step in width. There are different methods for analyzing microstrip discontinuities, such as quasi-static approach, planar waveguide model, and integral equation formulation. As the frequency increases, the quasi-static assumption is not valid. In the planar waveguide model analyses, the thickness of the substrate is assumed to be much smaller than the wavelength, so that we can apply a two-dimensional model. In this case, the effect of radiation and surface waves are not considered. We applied the integral equation method to study the open end and gap dicontinuities on isotropic substrates. In applying the integral equation method, we introduced various approximation in the computation procedure. More recently, we used finite element expansion currents to formulate a full-wave analysis of micristrip discontinuities on isotropic substrate.

We rigorously analyzed the open end, gap, and step in width discontinuities placed on anisotropic substrates. Both uniaxial and tilted uniaxial anisotropy are considered. The materials are assumed to be lossless and the metal strips to be infinitely thin. A dyadic Green's function for layered anisotropic media is used to formulate a set of vector integral equations for the current distribution. The fundamental hybrid mode is assumed to be propagating on the input and output of microstrip lines. In solving the set of vector integral equations, we employed the method of moment. The basis functions for the current on the metal strip consider the edge effect. Both longitudinal and transverse currents are considered in the calculation. First, the propagation constant for the infinitely long uniform microstrip line is calculated. Then, the propagation constant of the fundamental mode is used to formulate the excitation of the discontinuity problem. At the discontinuity, local basis functions are used to simulate the local currents near the discontinuity. The scattering matrix can then be obtained, and an equivalent circuit model can be proposed. We investigated the effect of the anisotropyand discussed the results.

We investigated wave propagation along microstrip lines on uniaxially anisotropic substrates, in which the width is periodically modulated, by dividing the structure into consecutive uniform sections. We derived a rigorous formulation for calculating the capacitance matrix of uniform lines. We then used a quasi-TEM approximation to obtain the circuit parameters for each section. To obtain the dispersion relation of the periodic structures, the transfer matrix is applied. The effects of the anisotropy of substrate material and the strip line geometry on the stopband characteristics are exploited. We also investigated the properties of two coupled width-modulated lines.

Most of the published work on the input impedance and other parameters of a probe-fed microstrip antenna employ an approximation to the probe feed by assuming thin dielectric substrates; the probe current can be modeled by an idealized uniform current ribbon of the same dimensions as the probe. To ensure the proper variation of the patch current near the probe and to enforce the continuity of current at the probe-patch junction, an attachment current mode has been incorporated in the patch current expansion. This leads to acceptable numerical results for the computation of the radiation pattern by the patch and for the mutual impedance between the probe and the patch. However, this approximation is not sufficiently accurate to solve for the current distribution on the patch nor for the computation of the self impedance at the terminals of the probe. Furthermore, in millimeter wave applications and for wideband operation where thick substrates or stacked structures are used, the thin substrate approximation is not valid. Recently, an alternative approach for the computation of the input impedance was developed. In this formulation, an approximate solution satisfying the boundary condition on the metallic probe was obtained in the framework of the magnetic cavity model. The fringing of the field at the edges of the patch and the radiation and surface wave losses were artificially considered by using an edge extension formula and an effective loss tangent.

We rigorously analyzed the problem of a circular microstrip disk on a thick dielectric substrate, fed by an eccentric probe. We formulated the problem in terms of a Vector Weber Transform which allows us to develop the Green's function of the layered medium with the eccentric probe and the microstrip patch as part of the medium. Using the Vector Weber Transform automatically enforces the boundary conditions on the probe and the patch. This allows us to cast the problem as the solution of a set of two coupled vector integral equations governing the tangential components of the electric field across the aperture of the coaxial line feed and those across the interface where the patch lies. This set is then solved using the method of moments where the magnetic frill current across the aperture of the coaxial line is represented by a Vector Weber Series expansion. From the computed electric field across the aperture of the coaxial line feed, the reflection coefficient for the TEM mode is obtained which allows us to compute the input impedance at the terminals of the probe. Numerical results for the input impedance are presented.

Publications

Ali, S.M., T.M. Habashy, J.F. Kiang, and J.A. Kong. "Resonance in Cylindrical-Rectangular and Wraparound Microstrip Structures." *IEEE Trans. Microwave Theory Tech.* 37 (11):1773-1783 (1989).

Ali, S.M., T.M. Habashy, and J.A. Kong. "Input Impedance of a Circular Microstrip Antenna Fed by an Eccentric Probe." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Habashy, T.M., S.M. Ali, and J.A. Kong. "Impedance Parameters and Radiation Pattern of Cylinderical-Rectangular and Wraparound Microstrip Antennas." *IEEE Trans. Antennas Propag.* Forthcoming.

Kiang, J.F., S.M. Ali, and J.A. Kong. "Modeling of Lossy Microstrip Lines with Finite Thickness." *J. Electromag. Waves Appl.* Forthcoming.

Tulintseff, A.N., S.M. Ali, and J.A. Kong. "Input Impedance and Radiation Fields of a Probe-Fed Stacked Circular Microstrip Antenna." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Xia, J., S.M. Ali, and J.A. Kong. "Analysis of Microstrip Discontinuities on Anisotropic Substrates." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

1.6 High-Speed Integrated Circuit Interconnects

Sponsor

Digital Equipment Corporation
International Business Machines Corporation

Project Staff

Professor Jin Au Kong, Dr. Sami M. Ali, Dr. Tarek M. Habashy, Dr. Soon Y. Poh, Dr. Ying-Ching E. Yang, Ann N. Tulintseff, Jean-F. Kiang, Check-Fu Lee, Michael J. Tsuk, Cheung-Wei Lam, David M. Sheen

We developed a new method for analyzing frequency-dependent transmission line systems with nonlinear terminations by using the generalized scattering matrix formulation for the time domain iteration scheme. Previous works have employed either the admittance matrix, which results in extended impulse responses, or introduced artificial matching networks, which could render the solution unstable. In contrast, the generalized scattering matrix approach is most closely tied to the concept of waves. Therefore, it can achieve a shorter impulse response that leads to smaller computer memory requirement and faster computation time.

We have carried out the detailed procedure for solving this kind of nonlinear transient problem for a microstrip transmission line with linear source resistance. The diode-like terminal characteristics has been considered, and the speed of convergence is quite satisfactory.

We have applied the Time-Domain Finite-Difference modeling to obtain propagation characteristics of microstrip structures. Maxwell equations are expressed in finite-difference form, and the substrates are considered to be anisotropic in general. By positioning the components of the electric and magnetic fields at different positions and evaluating them dat alternate time steps, we obtain the components of Maxwell's equations. Boundary condition implementation in this method is an important issue. Electric and magnetic walls can be implemented simply by setting the appropriate field components to zero. Open-end termination is simulated by using the open-circuit, short-circuit technique, to cancel out the reflected waves. We have used this method to illustrate graphically the field propagation along an open microstrip line. Field components are plotted in both space and time domains. The dispersive behavior of the wave propagation can be observed. It is should be noted that this method can be conveniently applied to obtain frequency-dependent characteristics of various microstrip structures such as effective permittivity, characteristic impedance, scattering matrix elements, and equivalent circuit components. An improved source plane implementation using magnetic wall is applied for better modeling of the matched source. This method is very powerful in obtaining both the time-domain and the frequency-domain characteristics of microstrip lines, discontinuities and coupled lines.

We have developed general purpose finite difference time domain (FDTD) algorithms to solve electromagnetic wave propagation in integrated circuit problems, in particular the discontinuities such as bends and corners. The geometry is read from a file which assigns dielectric constants, permeability, and conductivity to each discrete mesh point. To limit the domain of computation, we have implemented an absorbing boundary condition which simulates an outward propagating wave at the faces of the mesh, thus eliminating reflection from these faces. Specific problems simulated so far include two-dimensional propagation from a point source to demonstrate the effectiveness of the absorbing boundary condition and three-dimensional propagation around a 90 degree microstrip corner.

We have developed a new perturbation series, coupled integral equation approach for calculating the frequency dependent circuit parameters for quasi-TEM transmission lines with lossy conductors. The method considers the addition of loss and dispersion to be perturbations on the lossless TEM case, and therefore the difference between the propagation constant and the wavenumber in free space is a small parameter. We obtain the lowest order term of the perturbation series by solving two quasistatic problems; the electrostatic problem to get the capacitance, and the magnetoquasistatic problem, with the distribution of current inside the wire considered, which gives the frequency-dependent inductance and resistance. Both of these problems are solved using one-dimensional integral equations for quantities on the surface of the conductor; this represents a significant improvement in efficiency over previous methods. For most cases of practical interest, the lowest order term of the series will suffice. If, however, the change in the propagation constant from the lossless case, due to the altered inductance and the addition of resistance, is significant, additional terms in the perturbation series can be calculated.

The method has been applied to the case of one or more wires embedded in a uniform dielectric. In the original magnetoquasistatic problem, the current is directed entirely along the axis of propagation and satisfies the frequency-domain diffusion equation. Outside the wire, the magnetic vector potential is in the same direction, and obeys Laplace's equation. The boundary conditions are the continuity of tangential and normal magnetic field at the interface, which can be expressed in terms of the current density and vector potential and their derivatives. Since we can express the ratio of the frequency-dependent resistance to the DC resistance in terms of the values of the volume current and its normal derivative on the surface of the wire only, we can use a pair of coupled integral equations to solve for these quantities alone, which we can solve by Galerkin's method or other finite element methods.

In microelectronic packaging, a problem of practical interest is the study of propagation characteristics of a shielded microstrip line in the presence of crossing strips in a multilayered structure. We have investigated the dispersion characteristics of strip lines crossed by metallic strips and embedded in the same isotropic layer and bounded by two conducting planes. We used a rigorous dyadic Green's function formulation in the spectral domain and derived a set of coupled vector integral equations for the current distribution on the conductors. We then applied Galerkin's method to derive the matrix eigenvalue equation for the propagation constant. We studied the dispersion properties of the signal lines for both cases of finite and infinite length crossing strips.

We analyzed the effects of the structure dimensions on the passband and stopband characteristics. For crossing strips of finite length, the stopband is mainly affected by the period, the crossing strip length, and the separation between the signal and the crossing strips. For crossing strips of infinite length carrying travelling waves, attenuation along the signal line exists over the whole frequency range of operation.

Publications

Gu, Q., Y.E. Yang, and J.A. Kong. "Transient Analysis of Frequency-Dependent Transmission Line Systems Terminated with Nonlinear Loads." *J. Electromag. Waves Appl.* 3 (3):183-197 (1989).

Kiang, J.F., S.M. Ali, and J.A. Kong. "Propagation Properties of Strip Lines Periodically Loaded with Crossing Strips." *IEEE Trans. Microwave Theory Tech.* 37 (4):776-786 (1989).

Lam, C.W., S.M. Ali, and J.A. Kong. "A New Finite-Difference Time-Domain Grid Model for Microstrip Problems in Anisotropic Media." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

Tsuk, M.J., and J.A. Kong. "The Frequency-Dependent Resistance of Conductors with Arbitrary Cross-Section." *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-26, 1989.

1.7 ILS/MLS Frequency Management Assessment

Sponsor

U.S. Department of Transportation
Contract DTRS-57-88-C-00078

Project Staff

Professor Jin Au Kong, Dr. Robert T. Shin, Dr. Ying-Ching E. Yang, Qizheng Gu, Mohammad A. Tassoudji, Murat A. Veysoglu, Khurram K. Afridi, Li-Fang Wang

Because of the rapid expansion of air traffic in the United States and around the world, precision landing systems play an important role in both increasing airport capacity and safety. Both the traditional instrument landing system (ILS) and the newer microwave landing system (MLS) have established international standards.

In this research project, we develop simulation tools for evaluating (from the spectrum management aspect) the growth potential of ILS and MLS in metropolitan areas. Suitable electromagnetic propagation models will be established with all possible electromagnetic radiation sources within the ILS/MLS operating bands considered in our study of electromagnetic interference level. We can then use this interference level to judge whether the capacity can be met by adding a certain type of precision landing system without causing any problems.

Our technical approach included the following tasks:

1. Identification of radiation sources,
2. Development of propagation models,
3. Development of receiver models,
4. Construction of computer simulation tool,
5. Verification and validation of the simulation software, and
6. Generation of metropolitan channel capacity projection database.

The major deliverable of this project is a simulation software named EMSALS (Electromagnetic Modeling and Simulation Applied to Landing Systems). It will be subdivided into EMSALS/I (for ILS) and EMSALS/M (for MLS). Because ILS has been in use for more than forty years and its operation characteristics and interference sources are better known, our initial emphasis will be on ILS assessment. The MLS assessment will build upon the experience with ILS simulation and be implemented in a more gradual manner.

For a greater degree of feedback on our research, we decided to carry out the project in a progressive manner by dividing it into five self-contained phases. Each phase is marked by different combinations of theoretical models. An exhaustive analysis encompassing all six tasks listed above will be done during each phase. Thus, we can obtain intermediate results at any time, and can use existing data to check the degree of accuracy of the theoretical models.

The first two phases of ILS studies are devoted to automating FAA spectrum engineering procedure on 386-based PCs. We spent the past few months developing the computation model and user interface for such procedure, implementing the free-space and the IF-77 propagation models and a minimum performance standard (MOPS) compliant receiver model. At the conclusion of Phase 1, coding of the procedure is completed. Our software takes as much input as possible from site-specific information such as antenna type and radiated power, with runway headings achieving maximum degree of accuracy. We stored a digitized map of the United States, accurate to one hundredth of a degree, to be displayed with the assessment. Besides the menu feature, we also added the capability to zoom in and out at various magnification levels with a mouse or with keyboard control. Site-specific data such as antenna type and power are taken into the computation module. The next step, verification of the simulation code, will involve examining and comparing the manual analysis results with the computer output. This verification will be done on a larger scale, including several metropolitan areas. Meanwhile, we continued with building modules for the cell display simulation. The modules, originally written in Turbo Pascal, have been converted to Turbo C codes. The user interface has also been improved. On the first screen, the user can specify the name of signal strength database, which has been precalculated. On the second screen, the user specifies the models and computational parameters, on the display screen, where assessment is being made. Here "cell" refers to an area of one nautical mile by one nautical mile at the designated altitude. The cells are color coded according to the seriousness of interference. The user will be able to zoom in and out, to inquire the signal and interference strength with the mouse, and to turn on and off, or change the power of the transmitting antenna. Thus, the cell display will provide abundant information and will be an invaluable tool for FAA Spectrum Engineering Division personnel to pinpoint where the problem is and to what extent the simulation tool is eventually released.