Chapter 1. Electromagnetic Wave Theory and Applications

Academic and Research Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Robert T. Shin, Dr. Y. Eric Yang

Visiting Scientists and Research Affiliates

Dr. Yih-min Chen,[1] Dr. Chien-Chin Chiu,[2] Dr. Akira Itoh,[3] Dr. Arthur K. Jordan,[4] Fillippo Marliani,[5] Dr. Kevin O'Neill,[6] Dr. Leung Tsang,[7] Dr. Michael Tsuk,[8] Dr. Ji Wu[9]

Graduate Students

Jerome J. Ackerson, Chi O. Ao, Siwaphong Boonsalee, Henning Braunisch, Jihwan Choi, James Ernstmeyer, Yin-Chun (Andrew) Kao, Konstantinos Konistis, Christopher D. Moss, Mark C. Roh, Shih-En Shih, Bae-Ian Wu, Yan Zhang

Technical and Support Staff

Shu-hui Su, Zhen Wu, Lu-Hui Ying

1.1 Electromagnetic Radiation, Propagation and Scattering in Complex Media and Multifunctional Radio Frequency Systems

Sponsor

U.S. Navy - Office of Naval Research
Contract N00014-92-J-4098

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Arthur K. Jordan, Kevin O'Neill, Michael Tsuk, Jerome J. Ackerson, Yin-Chun (Andrew) Kao, Shih-En Shih, Yan Zhang, Konstantinos Konistis, Christopher D. Moss, Bae-Ian Wu, Mark C. Roh

The objective of this research is to develop an electromagnetic model for analyzing complex media and multifunctional radio frequency (RF) systems. The emphasis of this project is to use available analytical techniques to complement the complex numerical simulations which are often called for in these large-scale electromagnetic analyses problems.

An FDTD formulation for transmission through thin imperfect conductors has been developed. The goal is to obtain an accurate model of electromagnetic field inside metallic enclosures for a wide frequency spectrum that encompasses resonance. This problem is nontrivial because the thickness can vary from a few skin depth to much smaller than a skin depth across the spectrum. We devised an analytical formulation suitable for finite-difference time-domain implementation. Because over a wide frequency range it can be shown that any EM wave travels inside a good conductor practically along the normal direction to the interface, a transmission line model can be used to represent the local characteristics to the thin conductor. This transmission line is loaded by free space. Using the impedance transformation formula of the transmission line theory, one can then derive the equivalent frequency-dependent surface input impedance and use it to represent the metal sheet.

The impedance, which relates the local electric field to the local magnetic field, is written in the Laplace domain and expanded as infinite products in both

1 Yuan-Tze University, Chung-Li, Taiwan.
2 Tam-Kang University, Tam-shui, Taiwan.
3 Tokyo National University of Science and Technology, Tokyo, Japan.
4 U.S. Navy, Naval Research Lab, Washington, D.C.
5 University of Florence, Florence, Italy.
6 U.S. Army, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
7 University of Washington, Seattle, Washington.
8 Digital Equipment Corporation, Tewksbury, Massachusetts.
9 Chinese Academy of Science, Beijing, China.

denominator and numerator. The rational function approximation of this impedance can be obtained by truncating the infinite products. From this approximation and the inverse transformation back to the time domain, we can show that is possible to implement the boundary condition involving past E and H fields with a recursive formulation. Both one- and two-dimensional formulations have been developed and applied to the calculation of resonator Q factor.

1.2 Study Effects of Radio Interference on ILS

Sponsor

U.S. Federal Aviation Administration
Contract 97-G-031

Project Staff

Professor Jin Au Kong, Dr. Y. Eric Yang, Igor Balk, Yan Zhang

This project expanded the scope of analysis of ILS autolanding system integrity and continuity risk under various RF interference conditions. Generic simulation models of the autoland system are developed for airline transports with varying weights and different extent of inertial smoothing in the control system. The autolanding model is combined with the ILS receiver response and wind disturbance models to simulate the final approach process. A greatly enhanced computer model enabled Monte Carlo simulations of thousands of landings to assess the total system risk. The continuity risk is defined to be the probability of CDI current exceeding 20 microamps during the final 30 seconds, a condition which normally causes the autoland system to “disconnect.” The integrity risk is defined by the probability of key system performance measures exceeding certain boundaries at the touch down point even when there is no disconnect, i.e., without detectable alarms. The key measures defining a successful landing include aircraft lateral displacement, banking angle, and sideslip rate. We found from the simulation that continuity risk appears to dominate integrity risk, and that present standard of RF interference immunity for ILS receiver provide sufficient margins to control the continuity risk. The study also confirmed that when certain conditions are met, control systems with inertial smoothing has lower integrity risk than those without.

1.3 SIR-C Polarimetric Radar Image Simulation and Interpretation

Sponsor

National Aeronautics and Space Administration
Contract JPL 958461

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Shih-En Shih, Vincent Thomassier, Li-Fang Wang, Chen-Pang Yeang, Yan Zhang

This project investigates the use of spaceborne polarimetric radar measurements for monitoring, mapping, and retrieving the aboveground vegetation biomass. Fully polarimetric radar data obtained from the SIR-C/XSAR missions over the Landes Forest in southwestern France have been analyzed in great detail. In the investigation of the application of SIR-C data to vegetated terrain classification and biomass inversion, the measured backscattering coefficients and the derived complex correlation coefficient of HH and VV polarization as well as the ratio between cross- and co-polarization ratio are fully utilized.

A validated pine forest scattering model, based on the radiative transfer theory and taking into account the specific branching structure of pine trees, is used to interpret the SIR-C/XSAR polarimetric backscattering measurements from the Landes forest. From the analysis of measured data and the model results, the cross-polarization backscattering coefficients at L-band and the correlation between HH and VV backscattering returns at both L- and C-band are found to be most useful for the biomass retrieval. Bayesian classifications using data with known ground truth and with theoretical simulation are applied to classify the forest for biomass up to 50 tons per hectare with the available data. With the use of the pine forest scattering model, biomass inversion has been shown to be feasible over a wider biomass range (up to 100 tons per hectare) for angles of incidence around 45 degrees. In addition to the analysis of SIR-C/XSAR data, we have refined our forest scattering model by taking into account the double scattering mechanism between trunk and branches. This shows more effect on the cross-polarized backscattering return.

We have developed a coherent scattering model of rice fields which takes into account the rice planting structure and the volume-surface coherent interactions. The model has been applied to interpret the temporal variations of the SAR backscatter data from test rice field sites with ground truth characteristics. The test rice-field sites were in Indonesia and Japan. These sites have been the subject of remote sensing project using ERS-1 and JERS-1 data to monitor the rice growth.

A general trend for the response of electromagnetic sensor at C-band has been analyzed and derived for a whole rice growth cycle. The model has also been applied to examine the effects of rice planting structure on the radar returns at L-band and to explain the large variations on SAR observations from different directions. It showed that the rice planting structure strongly affects scattering returns at L-band. With the SIR-C/XSAR's concurrent multifrequency and fully polarimetric radar measurements, we further investigated the multifrequency and multipolarization radar backscatters from different growth stages of rice. It was found that a derived quantity as the ratio of HH and VV backscattering coefficients is not sensitive to the radar looking direction or rice planting direction. In addition, the ratio (HH/VV) of rice shows strong variations with its growth stages or biomass which is quite different from other types of vegetation. It suggests that the use of the ratio of HH and VV returns can be useful in monitoring rice growth, retrieving rice biomass, and classification of rice from other vegetation areas.

1.4 Polarimetric Passive Remote Sensing

Sponsor

U.S. Navy - Office of Naval Research
Contract N00014-92-J-1616
Contract N00014-98-1-0643
Contract N00014-99-1-0175

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Yan Zhang, Jihwan Choi

The polarimetric passive emission of ocean surface has shown the capability for the retrieval of ocean surface wind speed and directions in the microwave remote sensing. However under high wind conditions, the presence of foam will significantly affect the polarimetric brightness temperatures of the open ocean surface. The thermal emissions of atmosphere also contribute to the total brightness temperature. The significance of foam on the ocean surface remote sensing has been recognized long time ago, and several subsequent experiments confirmed its importance. Previous studies of the foam contribution to the emissivity of ocean surface were mostly based on the empirical formulation derived from experimental data. Although several attempts of modeling the foam theoretically have been presented, the combination of atmospheric model and foam with rough ocean surface were left unaddressed.

We conducted a theoretical study on the polarimetric thermal emissions from foam-covered wind-driven ocean surface based on a composite volume and rough surface scattering model and solved with the radiative transfer theory. The geometry of the problem includes the atmospheric layer, foam layer and rough ocean surface. In the atmospheric layer, the absorption coefficient is calculated using the millimeter wave propagation model (MPM) and the data from the U.S. Standard Atmosphere 1976. By neglecting scattering effect, the atmospheric contribution of the brightness temperature is derived in a closed form using the radiative transfer equation. The down-going brightness temperature from the atmospheric layer is used as the input for the foam layer. In the foam layer, the water droplets are represented by dielectric spherical particles overlying the rough ocean surface. The small perturbation method (SPM) is used up to the second order to calculate the emissivity from the ocean surface. This is used as the boundary condition for the radiative transfer equation of the foam layer. Using the Kirchhoff's law, the emissivity of the rough ocean surface is calculated by integrating the bistatic scattering coefficient over the rough ocean surface. The radiative transfer equations of the foam layer with the rough interface are solved using iterative technique. The wind-driven rough ocean surface is described using Durden-Vesecky empirical power spectrum. The large-scale rough surface and the hydrodynamic effect of the up- and down-wind asymmetry are also included in this model.

1.5 Analytic and Monte Carlo Studies on Electromagnetic Interactions with Nonspherical Dense Media

Sponsor

National Science Foundation
Grant ECS 96-15799

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Arthur K. Jordan, Kevin O'Neill, James Ernstmeyer, Yin-Chun (Andrew) Kao, Henning Braunisch, Bae-Ian Wu, Chi O. Ao

In this work, we perform Monte Carlo simulations of electromagnetic waves scattering from random media with spheroidal dielectric particles. Scattering by nonspherical particles have interesting results, particularly the polarimetric dependence of scattering. The multiple scattering equations are formulated through the volume integral equation approach and solved numerically. The method of moments is used with the choice of basis functions that are appropriate for spheroids. Specifically, these basis functions are based on electrostatic solutions of spheroids, both dipole and quadrupole fields for small spheroids are considered. The Metropolis shuffling process is used to generate the positions of densely packed spheroids. Both cases of aligned orientations and random orientations have been studied.

In the course of shuffling, we have to check whether any two spheroids overlap. Such checking is facilitated by the use of contact functions. Numerical simulations have been performed for the extinction rates and the phase matrices using 2000 spheroids, and results are averaged over 50 realizations. The results show substantial difference from those of independent scattering. Salient features of numerical results indicate that (1) the extinction rates of densely packed small spheroids are smaller than those of independent scattering; (2) for aligned spheroids, the extinction rates are polarization dependent, while for completely random orientation, the extinction rates are polarization independent; and (3) the co-polarized part of the phase matrix is smaller than that of independent scattering, while the depolarized part is larger than that of independent scattering. This indicates that, while the total amount of scattering is substantially less than independent scattering, the ratio of cross-polarization to co-polarization is the opposite and the ratio can be many times larger than independent scattering. The results are important when the polarimetric dependence of scattering are important in optical scattering data analysis.

1.6 Analysis of Electromagnetic Interaction with Ships on the Ocean

Sponsor

U.S. Navy - Office of Naval Research
Contract N00014-97-1-0172

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Yan Zhang, Henning Braunisch, Chi O. Ao

We have continued the farfield analysis of electromagnetic scattering interaction between the canonical shaped bodies and rough ocean surfaces. Main progress is in finishing the development of hybrid MOM/SPM technique. A small perturbation expansion formulation is applied to decompose the full scattering equations involving discrete objects and rough surface into different orders with respect to the mean surface height. It is discovered that the equations share the same form for all orders.

These equations actually represent simpler physical configurations-scattering from discrete objects in the presence of a flat interface. Less computational effort is required to solve them because we can reformulate the integral equation using layered dyadic Green’s function and solve only unknown current distribution on the discrete conducting objects but not that on the rough surface. Furthermore, the process of matrix inversion only needs to be done once for all orders. All these factors contribute to significant time-savings compared to purely numerical schemes. Comparison of the hybrid method to the first order with standard MOM solution with sparse matrix conjugate gradient algorithm shows good agreement in numerical results. However, the standard MOM solution takes about 15 times longer to run based on a typical problem with 15 by 15 wavelength rough surface and an object of a few wavelength size.

We also discovered that the hybrid technique provides useful physical insight to the computational results. The zeroth order solution represents the response from objects in the presence of flat interface, which includes (1) specular return from the surface, and (2) multiple interactions between the objects and the flat interface from the coherent field. On the other hand, the first order solution is the result of interaction between incoherent scattering terms of rough surface and the object, which can be further decomposed into (3) first-order incoherent return in the presence of discrete object, and (4) scattering from the object due to the incoherent field generated from the rough surface.

Dispersion characteristics of canonical objects, including infinitely thin vertical plate, long rectangular cylinder, finite circular cylinders, long finite cylinder with trapezoidal cross section and wedged end-cap have been studied from the zeroth order responses in the hybrid MoM/SPM method, which is equivalent to scattering in the presence of flat interface. A composite model consisting of these shapes has also been tested. For known shapes, the frequency/azimuth angle profile can easily provide information such as the length of the cylinder. For example, given scattering profiles in terms of frequency/wavenumber space for a horizontal circular cylinder, we are able to derive a simple formula for estimating the length from the spacing between nulls.

1.7 Research on a Synthetic Aperture Radar Simulation Model

Sponsor

Mitsubishi Corporation

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Shih-En Shih, Fillippo Marliani

In spaceborne synthetic aperture radar (SAR) interferometry, the terrain elevation information is obtained from the phase difference of two SAR images gathered by the same sensor in repeated passes. In order to compare various processing methods systematically, we developed a simulation model called EMSARS based on physical principle of electromagnetic scattering. GIS database-including DEM (digital elevation map) and feature map is used to create synthesized SAR images. The real SAR simulation involves calculation of received field for each time step and frequency component, a very time consuming process. We choose instead to start from the simulated range compressed data, in which the scattered field for each azimuthal step is calculated by summing up scattering field from individual cells that are within the specified azimuthal beamwidth and range resolution. K-distribution statistics is used to simulate the speckle inherent to the radar data. The scattering fields obtained from two repeat passes are combined to form the interferogram. The Doppler part of the commonly used range-Doppler algorithm is used to synthesize images under various mis-alignment conditions.

1.8 Research on SAR Interferometry

Sponsor

Mitsubishi Corporation

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Jerome J. Ackerson, Bae-Ian Wu, Fillippo Marliani

In spaceborne synthetic aperture radar (SAR) interferometry, the terrain elevation information is obtained from the phase difference of two SAR images gathered by the same sensor in repeated passes. Among the factors crucial to the accuracy of altitude mapping are the registration of complex SAR images and the phase unwrapping processes. In the processing of interferometric SAR (InSAR) data, a number of experiences have been reported in the literature and various methods about the interferometric SAR image registration and phase unwrapping are available. A phase unwrapping study on both simulated and real SAR image data is conducted. Both the hybrid weighted least squares and the optimum branch cut methods offered essentially the same error performance when applied to both simulated SAR interferograms with additive noise and real ERS-1 interferograms. These methods consistently showed improvement over the straight least squares and coherence weighted least squares methods.

The global optimum branch cut method is appropriate when there are not many residues; however, the local optimum provide near identical results in far less time. The branch cut method is more likely to produce local errors as shown by the symmetrical error histograms. The hybrid weighted least squares method produces a fairly symmetrical histogram especially when compared to the straight least squares and coherence weighted least squares methods. In other words, using a weighting scheme greatly reduces the global error introduced by the least squares method. In fact, the residue mask most closely approaches the desirable local error distribution of the branch cut method. The results show that the residue weighting scheme (or hybrid method) offers superior performance in comparison with the coherence and +12‘nd modified coherence weighting schemes.

1.9 Inverse Scattering Models for Recognition of Target Under Foliage

Sponsor

MIT Lincoln Laboratory
Agreement BX-6807

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Shih-En Shih, Christopher D. Moss

Target recognition based on microwave sensor response is inherently a challenging problem. Recent advances in synthetic aperture radar (SAR) technology has made it possible to achieve high resolution and increase the likelihood of accurate identification of targets. For ground targets, the scattering and absorption of radio wave by foliage can create some problems. This is because the formation of synthetic aperture is a coherent process, which requires integration of the received fields along the pass of antenna, and the random phase fluctuation and attenuation caused by the foliage will deteriorate the ability to image the targets. In the past, there have been efforts to quantify the effect of foliage on radar signal processing. For example, MIT Lincoln Laboratory has conducted a foliage penetration (FOPEN) experiment to study the variations of the attenuation and the phase fluctuation with respect to polarization, frequency, depression angle, and the synthetic aperture length. To some degree, these studies addressed the issue of how foliage affect the performance of microwave sensors. However, overall investigation of how they affect the recognition algorithms as well as how to develop inverse scattering algorithms to combat the foliage effects has been missing in the literature. It is therefore the objective of the current study to fill this void in theoretical models.

The objective of the proposed program is to study inverse scattering models for target recognition, taking into account radio wave propagation model in the foliage environment. The key effort is to integrate the remote sensing model of clutters with deterministic target (forward and inverse) scattering model. Both active and passive models or the combination of them will be considered.

1.10 Land Mine and Unexploded Ordnance Detection Based on Enhanced Signatures Using Angular Correlation Function

Sponsor

MIT Lincoln Laboratory
Agreement BX-6841

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Leung Tsang, Dr. Y. Eric Yang, Henning Braunisch, Chi O. Ao

The motivation for this project is to clear minefields in post-war zones and to clear military proving grounds from unexploded ordnance (UXO). A novel technique based on the angular correlation function (ACF) has been recently proposed for the detection of buried objects. By choosing an appropriate set of incidence and observation angles, theoretical simulation has shown that the ACF of scattered radiation from a random rough surface buried with a deterministic object can be 10 dB higher than that of the rough surface clutter. In the proposed research, we will investigate the ACF of scattered radiation from targets to assess (1) the possibility of using this correlation function as signatures for the target detection; (2) to explore the use of angular correlation function to suppress both surface and volume clutter; and (3) to employ this technique to enhance radar images.

An airborne ground penetrating radar (GPR) measurement geometry is considered in this study. We will develop an electromagnetic scattering model which uses the method of moments technique to calculate the scattering of electromagnetic waves from a three-dimensional model scenario consisting of a two-dimensional dielectric rough surface with randomly distributed dielectric scatterers and metal targets which are shallowly or partially buried or above the rough surface. The time-domain fields will be synthesized via the Fourier transform. The ACF of scattered fields observed at two or more angles will be calculated based on realization or frequency averaging. We will investigate the magnitude and phase of ACF in relation to the target size and location. Model results both with and without targets will be compared and examined to formulate an optimal measurement configuration for target detection. By employing field measurements, the technique based on angular correlation function will be tested to assess its ability of suppressing clutter, enhancing the image quality, and detecting mines and UXOs.

The ACF has been theoretically studied for finding scattered waves from a buried metallic object under a one-dimensional rough surface without or with random scatterers. It is found that the ACF can be used to distinguish scattering from volume scatterers, random rough surface, and a deterministic buried object. We expect that the simulation technique and the signal processing algorithm based on ACF developed in this research will be directly applicable to the mine and UXO detection problem.

1.11 Computational Technique for Electromagnetic Propagation in Three-Dimensional Periodic Structures

Sponsor

MIT Lincoln Laboratory
Agreement CX-27584

Project Staff

Professor Jin Au Kong, Dr. Y. Eric Yang, Bae-Ian Wu, Christopher D. Moss

In recent years, there have been increasing interests in multilayer three-dimensional periodic structures. This is because three-dimensional metallodielectric photonic crystals have been shown to provide good stop-band properties over a broad range of incidence angles, providing many useful applications. While they have been experimentally demonstrated, efficient computational algorithms were not available. This makes it difficult to conduct theoretical simulations before actual fabrication of new structures.

Practical analysis of wide bandgap exhibited experimentally in three-dimensional structures can be carried out using the finite-difference time-domain (FDTD) technique. In this work, the periodic boundary condition required for running FDTD code on EM propagation of three-dimensional metallodielectric photonic crystals will be developed. Using this formulation, various proposed periodic structures will be tested against experimental results. The final goal of this project is to create a versatile simulation tool to facilitate the development of new devices.

1.12 Publications

1.12.1 Journal Articles

Golden, K.M., M. Cheney, K.H. Ding, A.K. Fung, T.C. Grenfell, D. Issacson, J.A. Kong, S.V. Nghiem, J. Sylvester, and D.P. Weinbrenner. "Forward Electromagnetic Scattering Models For Sea Ice." *IEEE Trans. Geo. Rem. Sens.* 36(5): 1655-74 (1998).

Golden, K.M., D. Borup, M. Cheney, E. Cherkaeva, M.S. Dawson, K.H. Ding, A.K. Fung, D. Issacson, S.A. Johnson, A.K. Jordan, J.A. Kong, R. Kwok, S.V. Nghiem, R.G. Onstott, J. Sylvester, D.P. Weinbrenner, and I.H. Zabel. "Inverse Electromagnetic Scattering Models For Sea Ice." *IEEE Trans. Geo. Rem. Sens.* 36(5): 1675-1704 (1998).

Johnson, J.T., J.A. Kong, K. Pak, R.T. Shin, and L. Tsang. "Numerical Study of the Composite Surface Model for Ocean Backscattering." *IEEE Trans. Geo. Rem. Sens*. 36(1): (1998).

Nghiem, S.V., K.H. Ding, A.J. Gow, T.C. Grenfell, C.C. Hsu, J.A. Kong, R. Kwok, D.K. Perovich, and S. Yueh. "Diurnal Thermal Cycling Effects on Microwave Signatures of Thin Sea Ice." *IEEE Trans. Geo. Rem. Sens.* 36(1): 111-24 (1998).

Shih, S.E., K.H. Ding, A.K. Jordan, J.A. Kong, and S.V. Nghiem. "Saline Ice Thickness Retrieval under Diurnal Thermal Cycling Conditions." *IEEE Trans. Geo. Rem. Sens.* 36(5): 1731-42 (1998).

Shih, S.E., K.H. Ding, C.C. Hsu, A.K. Jordan, J.A. Kong, and S.V. Nghiem. "Thin Saline Ice Thickness Retrieval Using Time-Series C-Band Polarimetric Radar Measurements." *IEEE Trans. Geo. Rem. Sens.* 36(5): 1589-98 (1998).

Tsang, L., K.H. Ding, J.A. Kong, and S.E. Shih. "Scattering of Electromagnetic Waves from Dense Distributions of Spheroidal Particles Based on Monte Carlo Simulations." *J. Opt. Soc. Am. A*. Forthcoming.

Zhang, Y., A.K. Jordan, and J.A. Kong. "Inversion of Arbitrary Electromagnetic Scattering Data to Reconstruct the Scattering Potential of A Plasma Medium." *Microwave Opt. Tech. Lett.* 17(2): 97-101(1998).

1.12.2 Chapter in a Book

Zhang, Y., H. Braunisch, J.A. Kong, and Y.E. Yang. "Electromagnetic Wave Interaction of Conducting Object with Rough Surface by Hybrid SPM/MoM Technique-summary." In *Progress in Electromagnetic Research.* New York: Elsevier. Forthcoming.

1.12.3 Meeting Papers

Hara, Y., J.J. Akerson, J.A. Kong, C. Satoh, and Y.E. Yang. "A Weighted Least Squares Phase Unwrapping Technique Using Residues for SAR Interferometry." International Symposium on Noise Reduction for Imaging and Communication Systems, Tokyo, Japan, November 10-12, 1998.

Shih, S.E., K.H. Ding, J.A. Kong, and Y. Zhang. "Subsurface Detection Based on Enhanced SAR Signatures Using Angular Correlation Function." IEEE IGARSS, Seattle, Washington, July 6-9, 1998.

Shih, S.E., K.H. Ding, A.K. Jordan, J.A. Kong, and S.V. Nghiem. "Saline Ice Thickness Retrieval under Diurnal Thermal Cycling Conditions." IEEE IGARSS, Seattle, Washington, July 6-9, 1998.

Yang, Y.E., H. Braunisch, J.A. Kong, and Y. Zhang. "Electromagnetic Wave Scattering From Conducting Objects Partially Buried under a Randomly Rough Surface." Progress in Electromagnetics Symposium, Taipei, Taiwan, March 22-26, 1999.

Yang, Y.E., J. A. Kong, and Y. Zhang. "Investigation of Polarimetric Thermal Emission of Foam-covered Wind-driven Ocean Surface Using the Radiative Transfer Theory." URSI General Assembly, Toronto, Canada, August 13-21, 1999.

Zhang, Y., H. Braunisch, Y.E. Yang, and J.A. Kong. "Electromagnetic Wave Interaction of Conducting Object with Rough Surface by Hybrid SPM/MoM Technique." Progress in Electromagnetic Symposium, Taipei, Taiwan, March 22-26, 1999.

Zhang, Y., H. Braunisch, J.A. Kong, and Y.E. Yang. "Electromagnetic Scattering From Conducting Objects Above a Randomly Rough Surface." National Radio Science Meeting Boulder, Colorado, January 4-7, 1999

Chapter 1. Electromagnetic Wave Theory and Applications

Academic and Research Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Robert T. Shin, Dr. Y. Eric Yang

Visiting Scientists and Research Affiliates

Dr. Yih-min Chen,[1] Dr. Chien-Chin Chiu,[2] Dr. Akira Itoh,[3] Dr. Arthur K. Jordan,[4] Fillippo Marliani,[5] Dr. Kevin O'Neill,[6] Dr. Leung Tsang,[7] Dr. Michael Tsuk,[8] Dr. Ji Wu[9]

Graduate Students

Jerome J. Ackerson, Chi O. Ao, Siwaphong Boonsalee, Henning Braunisch, Jihwan Choi, James Ernstmeyer, Yin-Chun (Andrew) Kao, Konstantinos Konistis, Christopher D. Moss, Mark C. Roh, Shih-En Shih, Bae-Ian Wu, Yan Zhang

Technical and Support Staff

Shu-hui Su, Zhen Wu, Lu-Hui Ying

1.1 Electromagnetic Radiation, Propagation and Scattering in Complex Media and Multifunctional Radio Frequency Systems

Sponsor

U.S. Navy - Office of Naval Research
Contract N00014-92-J-4098

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Arthur K. Jordan, Kevin O'Neill, Michael Tsuk, Jerome J. Ackerson, Yin-Chun (Andrew) Kao, Shih-En Shih, Yan Zhang, Konstantinos Konistis, Christopher D. Moss, Bae-Ian Wu, Mark C. Roh

The objective of this research is to develop an electromagnetic model for analyzing complex media and multifunctional radio frequency (RF) systems. The emphasis of this project is to use available analytical techniques to complement the complex numerical simulations which are often called for in these large-scale electromagnetic analyses problems.

An FDTD formulation for transmission through thin imperfect conductors has been developed. The goal is to obtain an accurate model of electromagnetic field inside metallic enclosures for a wide frequency spectrum that encompasses resonance. This problem is nontrivial because the thickness can vary from a few skin depth to much smaller than a skin depth across the spectrum. We devised an analytical formulation suitable for finite-difference time-domain implementation. Because over a wide frequency range it can be shown that any EM wave travels inside a good conductor practically along the normal direction to the interface, a transmission line model can be used to represent the local characteristics to the thin conductor. This transmission line is loaded by free space. Using the impedance transformation formula of the transmission line theory, one can then derive the equivalent frequency-dependent surface input impedance and use it to represent the metal sheet.

The impedance, which relates the local electric field to the local magnetic field, is written in the Laplace domain and expanded as infinite products in both

1 Yuan-Tze University, Chung-Li, Taiwan.
2 Tam-Kang University, Tam-shui, Taiwan.
3 Tokyo National University of Science and Technology, Tokyo, Japan.
4 U.S. Navy, Naval Research Lab, Washington, D.C.
5 University of Florence, Florence, Italy.
6 U.S. Army, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
7 University of Washington, Seattle, Washington.
8 Digital Equipment Corporation, Tewksbury, Massachusetts.
9 Chinese Academy of Science, Beijing, China.

denominator and numerator. The rational function approximation of this impedance can be obtained by truncating the infinite products. From this approximation and the inverse transformation back to the time domain, we can show that is possible to implement the boundary condition involving past E and H fields with a recursive formulation. Both one- and two-dimensional formulations have been developed and applied to the calculation of resonator Q factor.

1.2 Study Effects of Radio Interference on ILS

Sponsor

U.S. Federal Aviation Administration
Contract 97-G-031

Project Staff

Professor Jin Au Kong, Dr. Y. Eric Yang, Igor Balk, Yan Zhang

This project expanded the scope of analysis of ILS autolanding system integrity and continuity risk under various RF interference conditions. Generic simulation models of the autoland system are developed for airline transports with varying weights and different extent of inertial smoothing in the control system. The autolanding model is combined with the ILS receiver response and wind disturbance models to simulate the final approach process. A greatly enhanced computer model enabled Monte Carlo simulations of thousands of landings to assess the total system risk. The continuity risk is defined to be the probability of CDI current exceeding 20 microamps during the final 30 seconds, a condition which normally causes the autoland system to “disconnect.” The integrity risk is defined by the probability of key system performance measures exceeding certain boundaries at the touch down point even when there is no disconnect, i.e., without detectable alarms. The key measures defining a successful landing include aircraft lateral displacement, banking angle, and sideslip rate. We found from the simulation that continuity risk appears to dominate integrity risk, and that present standard of RF interference immunity for ILS receiver provide sufficient margins to control the continuity risk. The study also confirmed that when certain conditions are met, control systems with inertial smoothing has lower integrity risk than those without.

1.3 SIR-C Polarimetric Radar Image Simulation and Interpretation

Sponsor

National Aeronautics and Space Administration
Contract JPL 958461

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Shih-En Shih, Vincent Thomassier, Li-Fang Wang, Chen-Pang Yeang, Yan Zhang

This project investigates the use of spaceborne polarimetric radar measurements for monitoring, mapping, and retrieving the aboveground vegetation biomass. Fully polarimetric radar data obtained from the SIR-C/XSAR missions over the Landes Forest in southwestern France have been analyzed in great detail. In the investigation of the application of SIR-C data to vegetated terrain classification and biomass inversion, the measured backscattering coefficients and the derived complex correlation coefficient of HH and VV polarization as well as the ratio between cross- and co-polarization ratio are fully utilized.

A validated pine forest scattering model, based on the radiative transfer theory and taking into account the specific branching structure of pine trees, is used to interpret the SIR-C/XSAR polarimetric backscattering measurements from the Landes forest. From the analysis of measured data and the model results, the cross-polarization backscattering coefficients at L-band and the correlation between HH and VV backscattering returns at both L- and C-band are found to be most useful for the biomass retrieval. Bayesian classifications using data with known ground truth and with theoretical simulation are applied to classify the forest for biomass up to 50 tons per hectare with the available data. With the use of the pine forest scattering model, biomass inversion has been shown to be feasible over a wider biomass range (up to 100 tons per hectare) for angles of incidence around 45 degrees. In addition to the analysis of SIR-C/XSAR data, we have refined our forest scattering model by taking into account the double scattering mechanism between trunk and branches. This shows more effect on the cross-polarized backscattering return.

We have developed a coherent scattering model of rice fields which takes into account the rice planting structure and the volume-surface coherent interactions. The model has been applied to interpret the temporal variations of the SAR backscatter data from test rice field sites with ground truth characteristics. The test rice-field sites were in Indonesia and Japan. These sites have been the subject of remote sensing project using ERS-1 and JERS-1 data to monitor the rice growth.

A general trend for the response of electromagnetic sensor at C-band has been analyzed and derived for a whole rice growth cycle. The model has also been applied to examine the effects of rice planting structure on the radar returns at L-band and to explain the large variations on SAR observations from different directions. It showed that the rice planting structure strongly affects scattering returns at L-band. With the SIR-C/XSAR's concurrent multifrequency and fully polarimetric radar measurements, we further investigated the multifrequency and multipolarization radar backscatters from different growth stages of rice. It was found that a derived quantity as the ratio of HH and VV backscattering coefficients is not sensitive to the radar looking direction or rice planting direction. In addition, the ratio (HH/VV) of rice shows strong variations with its growth stages or biomass which is quite different from other types of vegetation. It suggests that the use of the ratio of HH and VV returns can be useful in monitoring rice growth, retrieving rice biomass, and classification of rice from other vegetation areas.

1.4 Polarimetric Passive Remote Sensing

Sponsor

U.S. Navy - Office of Naval Research
Contract N00014-92-J-1616
Contract N00014-98-1-0643
Contract N00014-99-1-0175

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Yan Zhang, Jihwan Choi

The polarimetric passive emission of ocean surface has shown the capability for the retrieval of ocean surface wind speed and directions in the microwave remote sensing. However under high wind conditions, the presence of foam will significantly affect the polarimetric brightness temperatures of the open ocean surface. The thermal emissions of atmosphere also contribute to the total brightness temperature. The significance of foam on the ocean surface remote sensing has been recognized long time ago, and several subsequent experiments confirmed its importance. Previous studies of the foam contribution to the emissivity of ocean surface were mostly based on the empirical formulation derived from experimental data. Although several attempts of modeling the foam theoretically have been presented, the combination of atmospheric model and foam with rough ocean surface were left unaddressed.

We conducted a theoretical study on the polarimetric thermal emissions from foam-covered wind-driven ocean surface based on a composite volume and rough surface scattering model and solved with the radiative transfer theory. The geometry of the problem includes the atmospheric layer, foam layer and rough ocean surface. In the atmospheric layer, the absorption coefficient is calculated using the millimeter wave propagation model (MPM) and the data from the U.S. Standard Atmosphere 1976. By neglecting scattering effect, the atmospheric contribution of the brightness temperature is derived in a closed form using the radiative transfer equation. The down-going brightness temperature from the atmospheric layer is used as the input for the foam layer. In the foam layer, the water droplets are represented by dielectric spherical particles overlying the rough ocean surface. The small perturbation method (SPM) is used up to the second order to calculate the emissivity from the ocean surface. This is used as the boundary condition for the radiative transfer equation of the foam layer. Using the Kirchhoff's law, the emissivity of the rough ocean surface is calculated by integrating the bistatic scattering coefficient over the rough ocean surface. The radiative transfer equations of the foam layer with the rough interface are solved using iterative technique. The wind-driven rough ocean surface is described using Durden-Vesecky empirical power spectrum. The large-scale rough surface and the hydrodynamic effect of the up- and down-wind asymmetry are also included in this model.

1.5 Analytic and Monte Carlo Studies on Electromagnetic Interactions with Nonspherical Dense Media

Sponsor

National Science Foundation
Grant ECS 96-15799

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Arthur K. Jordan, Kevin O'Neill, James Ernstmeyer, Yin-Chun (Andrew) Kao, Henning Braunisch, Bae-Ian Wu, Chi O. Ao

In this work, we perform Monte Carlo simulations of electromagnetic waves scattering from random media with spheroidal dielectric particles. Scattering by nonspherical particles have interesting results, particularly the polarimetric dependence of scattering. The multiple scattering equations are formulated through the volume integral equation approach and solved numerically. The method of moments is used with the choice of basis functions that are appropriate for spheroids. Specifically, these basis functions are based on electrostatic solutions of spheroids, both dipole and quadrupole fields for small spheroids are considered. The Metropolis shuffling process is used to generate the positions of densely packed spheroids. Both cases of aligned orientations and random orientations have been studied.

In the course of shuffling, we have to check whether any two spheroids overlap. Such checking is facilitated by the use of contact functions. Numerical simulations have been performed for the extinction rates and the phase matrices using 2000 spheroids, and results are averaged over 50 realizations. The results show substantial difference from those of independent scattering. Salient features of numerical results indicate that (1) the extinction rates of densely packed small spheroids are smaller than those of independent scattering; (2) for aligned spheroids, the extinction rates are polarization dependent, while for completely random orientation, the extinction rates are polarization independent; and (3) the co-polarized part of the phase matrix is smaller than that of independent scattering, while the depolarized part is larger than that of independent scattering. This indicates that, while the total amount of scattering is substantially less than independent scattering, the ratio of cross-polarization to co-polarization is the opposite and the ratio can be many times larger than independent scattering. The results are important when the polarimetric dependence of scattering are important in optical scattering data analysis.

1.6 Analysis of Electromagnetic Interaction with Ships on the Ocean

Sponsor

U.S. Navy - Office of Naval Research
Contract N00014-97-1-0172

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Yan Zhang, Henning Braunisch, Chi O. Ao

We have continued the farfield analysis of electromagnetic scattering interaction between the canonical shaped bodies and rough ocean surfaces. Main progress is in finishing the development of hybrid MOM/SPM technique. A small perturbation expansion formulation is applied to decompose the full scattering equations involving discrete objects and rough surface into different orders with respect to the mean surface height. It is discovered that the equations share the same form for all orders.

These equations actually represent simpler physical configurations-scattering from discrete objects in the presence of a flat interface. Less computational effort is required to solve them because we can reformulate the integral equation using layered dyadic Green's function and solve only unknown current distribution on the discrete conducting objects but not that on the rough surface. Furthermore, the process of matrix inversion only needs to be done once for all orders. All these factors contribute to significant time-savings compared to purely numerical schemes. Comparison of the hybrid method to the first order with standard MOM solution with sparse matrix conjugate gradient algorithm shows good agreement in numerical results. However, the standard MOM solution takes about 15 times longer to run based on a typical problem with 15 by 15 wavelength rough surface and an object of a few wavelength size.

We also discovered that the hybrid technique provides useful physical insight to the computational results. The zeroth order solution represents the response from objects in the presence of flat interface, which includes (1) specular return from the surface, and (2) multiple interactions between the objects and the flat interface from the coherent field. On the other hand, the first order solution is the result of interaction between incoherent scattering terms of rough surface and the object, which can be further decomposed into (3) first-order incoherent return in the presence of discrete object, and (4) scattering from the object due to the incoherent field generated from the rough surface.

Dispersion characteristics of canonical objects, including infinitely thin vertical plate, long rectangular cylinder, finite circular cylinders, long finite cylinder with trapezoidal cross section and wedged end-cap have been studied from the zeroth order responses in the hybrid MoM/SPM method, which is equivalent to scattering in the presence of flat interface. A composite model consisting of these shapes has also been tested. For known shapes, the frequency/azimuth angle profile can easily provide information such as the length of the cylinder. For example, given scattering profiles in terms of frequency/wavenumber space for a horizontal circular cylinder, we are able to derive a simple formula for estimating the length from the spacing between nulls.

1.7 Research on a Synthetic Aperture Radar Simulation Model

Sponsor

Mitsubishi Corporation

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Shih-En Shih, Fillippo Marliani

In spaceborne synthetic aperture radar (SAR) interferometry, the terrain elevation information is obtained from the phase difference of two SAR images gathered by the same sensor in repeated passes. In order to compare various processing methods systematically, we developed a simulation model called EMSARS based on physical principle of electromagnetic scattering. GIS database-including DEM (digital elevation map) and feature map is used to create synthesized SAR images. The real SAR simulation involves calculation of received field for each time step and frequency component, a very time consuming process. We choose instead to start from the simulated range compressed data, in which the scattered field for each azimuthal step is calculated by summing up scattering field from individual cells that are within the specified azimuthal beamwidth and range resolution. K-distribution statistics is used to simulate the speckle inherent to the radar data. The scattering fields obtained from two repeat passes are combined to form the interferogram. The Doppler part of the commonly used range-Doppler algorithm is used to synthesize images under various mis-alignment conditions.

1.8 Research on SAR Interferometry

Sponsor

Mitsubishi Corporation

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Jerome J. Ackerson, Bae-Ian Wu, Fillippo Marliani

In spaceborne synthetic aperture radar (SAR) interferometry, the terrain elevation information is obtained from the phase difference of two SAR images gathered by the same sensor in repeated passes. Among the factors crucial to the accuracy of altitude mapping are the registration of complex SAR images and the phase unwrapping processes. In the processing of interferometric SAR (InSAR) data, a number of experiences have been reported in the literature and various methods about the interferometric SAR image registration and phase unwrapping are available. A phase unwrapping study on both simulated and real SAR image data is conducted. Both the hybrid weighted least squares and the optimum branch cut methods offered essentially the same error performance when applied to both simulated SAR interferograms with additive noise and real ERS-1 interferograms. These methods consistently showed improvement over the straight least squares and coherence weighted least squares methods.

The global optimum branch cut method is appropriate when there are not many residues; however, the local optimum provide near identical results in far less time. The branch cut method is more likely to produce local errors as shown by the symmetrical error histograms. The hybrid weighted least squares method produces a fairly symmetrical histogram especially when compared to the straight least squares and coherence weighted least squares methods. In other words, using a weighting scheme greatly reduces the global error introduced by the least squares method. In fact, the residue mask most closely approaches the desirable local error distribution of the branch cut method. The results show that the residue weighting scheme (or hybrid method) offers superior performance in comparison with the coherence and +12‘nd modified coherence weighting schemes.

1.9 Inverse Scattering Models for Recognition of Target Under Foliage

Sponsor

MIT Lincoln Laboratory
Agreement BX-6807

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Y. Eric Yang, Shih-En Shih, Christopher D. Moss

Target recognition based on microwave sensor response is inherently a challenging problem. Recent advances in synthetic aperture radar (SAR) technology has made it possible to achieve high resolution and increase the likelihood of accurate identification of targets. For ground targets, the scattering and absorption of radio wave by foliage can create some problems. This is because the formation of synthetic aperture is a coherent process, which requires integration of the received fields along the pass of antenna, and the random phase fluctuation and attenuation caused by the foliage will deteriorate the ability to image the targets. In the past, there have been efforts to quantify the effect of foliage on radar signal processing. For example, MIT Lincoln Laboratory has conducted a foliage penetration (FOPEN) experiment to study the variations of the attenuation and the phase fluctuation with respect to polarization, frequency, depression angle, and the synthetic aperture length. To some degree, these studies addressed the issue of how foliage affect the performance of microwave sensors. However, overall investigation of how they affect the recognition algorithms as well as how to develop inverse scattering algorithms to combat the foliage effects has been missing in the literature. It is therefore the objective of the current study to fill this void in theoretical models.

The objective of the proposed program is to study inverse scattering models for target recognition, taking into account radio wave propagation model in the foliage environment. The key effort is to integrate the remote sensing model of clutters with deterministic target (forward and inverse) scattering model. Both active and passive models or the combination of them will be considered.

1.10 Land Mine and Unexploded Ordnance Detection Based on Enhanced Signatures Using Angular Correlation Function

Sponsor

MIT Lincoln Laboratory
Agreement BX-6841

Project Staff

Professor Jin Au Kong, Dr. Kung Hau Ding, Dr. Leung Tsang, Dr. Y. Eric Yang, Henning Braunisch, Chi O. Ao

The motivation for this project is to clear minefields in post-war zones and to clear military proving grounds from unexploded ordnance (UXO). A novel technique based on the angular correlation function (ACF) has been recently proposed for the detection of buried objects. By choosing an appropriate set of incidence and observation angles, theoretical simulation has shown that the ACF of scattered radiation from a random rough surface buried with a deterministic object can be 10 dB higher than that of the rough surface clutter. In the proposed research, we will investigate the ACF of scattered radiation from targets to assess (1) the possibility of using this correlation function as signatures for the target detection; (2) to explore the use of angular correlation function to suppress both surface and volume clutter; and (3) to employ this technique to enhance radar images.

An airborne ground penetrating radar (GPR) measurement geometry is considered in this study. We will develop an electromagnetic scattering model which uses the method of moments technique to calculate the scattering of electromagnetic waves from a three-dimensional model scenario consisting of a two-dimensional dielectric rough surface with randomly distributed dielectric scatterers and metal targets which are shallowly or partially buried or above the rough surface. The time-domain fields will be synthesized via the Fourier transform. The ACF of scattered fields observed at two or more angles will be calculated based on realization or frequency averaging. We will investigate the magnitude and phase of ACF in relation to the target size and location. Model results both with and without targets will be compared and examined to formulate an optimal measurement configuration for target detection. By employing field measurements, the technique based on angular correlation function will be tested to assess its ability of suppressing clutter, enhancing the image quality, and detecting mines and UXOs.

The ACF has been theoretically studied for finding scattered waves from a buried metallic object under a one-dimensional rough surface without or with random scatterers. It is found that the ACF can be used to distinguish scattering from volume scatterers, random rough surface, and a deterministic buried object. We expect that the simulation technique and the signal processing algorithm based on ACF developed in this research will be directly applicable to the mine and UXO detection problem.

1.11 Computational Technique for Electromagnetic Propagation in Three-Dimensional Periodic Structures

Sponsor

MIT Lincoln Laboratory
Agreement CX-27584

Project Staff

Professor Jin Au Kong, Dr. Y. Eric Yang, Bae-Ian Wu, Christopher D. Moss

In recent years, there have been increasing interests in multilayer three-dimensional periodic structures. This is because three-dimensional metallodielectric photonic crystals have been shown to provide good stop-band properties over a broad range of incidence angles, providing many useful applications. While they have been experimentally demonstrated, efficient computational algorithms were not available. This makes it difficult to conduct theoretical simulations before actual fabrication of new structures.

Practical analysis of wide bandgap exhibited experimentally in three-dimensional structures can be carried out using the finite-difference time-domain (FDTD) technique. In this work, the periodic boundary condition required for running FDTD code on EM propagation of three-dimensional metallodielectric photonic crystals will be developed. Using this formulation, various proposed periodic structures will be tested against experimental results. The final goal of this project is to create a versatile simulation tool to facilitate the development of new devices.

1.12 Publications

1.12.1 Journal Articles

Golden, K.M., M. Cheney, K.H. Ding, A.K. Fung, T.C. Grenfell, D. Issacson, J.A. Kong, S.V. Nghiem, J. Sylvester, and D.P. Weinbrenner. “Forward Electromagnetic Scattering Models For Sea Ice.” *IEEE Trans. Geo. Rem. Sens.* 36(5): 1655-74 (1998).

Golden, K.M., D. Borup, M. Cheney, E. Cherkaeva, M.S. Dawson, K.H. Ding, A.K. Fung, D. Issacson, S.A. Johnson, A.K. Jordan, J.A. Kong, R. Kwok, S.V. Nghiem, R.G. Onstott, J. Sylvester, D.P. Weinbrenner, and I.H. Zabel. “Inverse Electromagnetic Scattering Models For Sea Ice.” *IEEE Trans. Geo. Rem. Sens.* 36(5): 1675-1704 (1998).

Johnson, J.T., J.A. Kong, K. Pak, R.T. Shin, and L. Tsang. “Numerical Study of the Composite Surface Model for Ocean Backscattering.” *IEEE Trans. Geo. Rem. Sens*. 36(1): (1998).

Nghiem, S.V., K.H. Ding, A.J. Gow, T.C. Grenfell, C.C. Hsu, J.A. Kong, R. Kwok, D.K. Perovich, and S. Yueh. “Diurnal Thermal Cycling Effects on Microwave Signatures of Thin Sea Ice.” *IEEE Trans. Geo. Rem. Sens.* 36(1): 111-24 (1998).

Shih, S.E., K.H. Ding, A.K. Jordan, J.A. Kong, and S.V. Nghiem. “Saline Ice Thickness Retrieval under Diurnal Thermal Cycling Conditions.” *IEEE Trans. Geo. Rem. Sens.* 36(5): 1731-42 (1998).

Shih, S.E., K.H. Ding, C.C. Hsu, A.K. Jordan, J.A. Kong, and S.V. Nghiem. “Thin Saline Ice Thickness Retrieval Using Time-Series C-Band Polarimetric Radar Measurements.” *IEEE Trans. Geo. Rem. Sens.* 36(5): 1589-98 (1998).

Tsang, L., K.H. Ding, J.A. Kong, and S.E. Shih. “Scattering of Electromagnetic Waves from Dense Distributions of Spheroidal Particles Based on Monte Carlo Simulations.” *J. Opt. Soc. Am. A*. Forthcoming.

Zhang, Y., A.K. Jordan, and J.A. Kong. “Inversion of Arbitrary Electromagnetic Scattering Data to Reconstruct the Scattering Potential of A Plasma Medium.” *Microwave Opt. Tech. Lett.* 17(2): 97-101(1998).

1.12.2 Chapter in a Book

Zhang, Y., H. Braunisch, J.A. Kong, and Y.E. Yang. "Electromagnetic Wave Interaction of Conducting Object with Rough Surface by Hybrid SPM/MoM Technique-summary." In *Progress in Electromagnetic Research.* New York: Elsevier. Forthcoming.

1.12.3 Meeting Papers

Hara, Y., J.J. Akerson, J.A. Kong, C. Satoh, and Y.E. Yang. "A Weighted Least Squares Phase Unwrapping Technique Using Residues for SAR Interferometry." International Symposium on Noise Reduction for Imaging and Communication Systems, Tokyo, Japan, November 10-12, 1998.

Shih, S.E., K.H. Ding, J.A. Kong, and Y. Zhang. "Subsurface Detection Based on Enhanced SAR Signatures Using Angular Correlation Function." IEEE IGARSS, Seattle, Washington, July 6-9, 1998.

Shih, S.E., K.H. Ding, A.K. Jordan, J.A. Kong, and S.V. Nghiem. "Saline Ice Thickness Retrieval under Diurnal Thermal Cycling Conditions." IEEE IGARSS, Seattle, Washington, July 6-9, 1998.

Yang, Y.E., H. Braunisch, J.A. Kong, and Y. Zhang. "Electromagnetic Wave Scattering From Conducting Objects Partially Buried under a Randomly Rough Surface." Progress in Electromagnetics Symposium, Taipei, Taiwan, March 22-26, 1999.

Yang, Y.E., J. A. Kong, and Y. Zhang. "Investigation of Polarimetric Thermal Emission of Foam-covered Wind-driven Ocean Surface Using the Radiative Transfer Theory." URSI General Assembly, Toronto, Canada, August 13-21, 1999.

Zhang, Y., H. Braunisch, Y.E. Yang, and J.A. Kong. "Electromagnetic Wave Interaction of Conducting Object with Rough Surface by Hybrid SPM/MoM Technique." Progress in Electromagnetic Symposium, Taipei, Taiwan, March 22-26, 1999.

Zhang, Y., H. Braunisch, J.A. Kong, and Y.E. Yang. "Electromagnetic Scattering From Conducting Objects Above a Randomly Rough Surface." National Radio Science Meeting Boulder, Colorado, January 4-7, 1999