# Section 3 Electromagnetics

## Chapter 1 Electromagnetic Wave Theory and Applications

# Chapter 1. Electromagnetic Wave Theory and Applications

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## 1.1 ILS/MLS Frequency Management Assessment

### Sponsor

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Developed during World War II, the Instrument Landing System (ILS) is currently being used at airports worldwide as the standard precision approach guidance system to assist pilots landing during poor visibility weather conditions. It consists of three basic components: (1) a localizer to line up the airplane with the runway, (2) a glideslope for vertical glide path control, and (3) marker beacons for homing and position determination. To improve the range accuracy, Distance Measurement Equipment (DME) is often used as a replacement for the marker beacons in newer ILS.

The Microwave Landing System (MLS) was developed to overcome some of the problems and limitations associated with ILS. In order to install

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ILS, flat terrain over an extended area is required since traditional glideslope antennas use ground reflection to generate desired radiation patterns. Furthermore, the clearance requirement around an ILS site is stringent to avoid guidance error caused by multipath interference. MLS overcomes these limitations by using much higher frequencies (5030 MHz - 5090 MHz) so that very narrow beams can be formed from antennas of reasonable sizes. The narrow beams can avoid most structures near the airport, and flat terrain is not required in front of the vertical guidance part of MLS. A benefit of the higher frequency band is that the number of channels available for MLS is five times that for ILS. There are 200 channels allocated for MLS in the band between 5030 MHz and 5090 MHz, in contrast to 40 channels for ILS in the 108-112 MHz (localizer) and 329-335 MHz (glideslope) bands. In order to accommodate future growth beyond the year 2015, the International Civil Aviation Organization (ICAO) has passed a resolution to expand MLS by 120 more channels up to 5126 MHz and allowed nations to use up to 5150 MHz.

MLS has more channel capacity than ILS available to satisfy the future requirements in the National Airspace System Plan. However, the user community, particularly aircarriers in the United States, because of fear of the high cost of conversing from ILS to MLS, constantly challenges the FAA's gloomy picture of the ILS spectrum. As a result, Congress has mandated that a detailed study explore the capacity of ILS to expand in major metropolitan areas where the FAA has identified potential frequency congestion and radio interference problems.

To address the concerns of the aviation community, this project is centered around building simulation software that can:

1. predict channel capacities of ILS and MLS in congested metropolitan areas (e.g., New York, Chicago, Los Angeles and Dallas/Fort Worth), as well as many other geographical areas;

2. perform quantitative analyses of in-band (aviation band) and out-of-band electromagnetic interferences; and

3. make quantitative assessments of electromagnetic interferences within the ILS/MLS service volume.

Based upon the above requirements, we established a methodology for implementing simulation software from theoretical studies of electromagnetic interference phenomena. In brief, first we locate potential interference sources, and then we use an electromagnetic propagation model to compute desired and interfering signal strengths. Then an interference analysis based upon safety standards, which are consistent with the receiver model, is performed. Finally, the interference analysis results for various locations are combined to make a channel capacity assessment. Accordingly, the following tasks have been identified:

1. identification of radiation sources, including in-band and out-of-band sources,

2. development of propagation models to be used to calculate interference levels,

3. development of receiver models to determine the quantitative effect of interference signals,

4. verification and validation of models through testing and checking against existing data, and

5. development of graphical user interface which allows for interactive retrieval of quantitative information on the assessment.

In this project, we have developed a computer simulation tool, EMSALS, which uses the databases of navigational and commercial radiowave transmitters to calculate the strengths of desired and undesired signals and generate an EM interference assessment based on user-selected assumptions. The first part of the software EMSALS/I (for ILS) has been used to analyze the frequency congestion and electromagnetic interference problems in the continental United States given the assumptions of the current level of FAA standard interference protection. Emphasis was first placed on ten complex metropolitan areas having a density of runways. Then the less densely populated regions were analyzed to determine ILS capacity across the entire continental United States (CONUS).

Based upon the current flight standards and interference protection criteria specified by the ICAO and FAA, computer simulations across the ten metropolitan areas predict shortfalls in ILS channel capacity. For example, ILS substantially fails to meet the precision landing runway requirements in the New York-Philadelphia-Washington DC area, even with several different priority schemes to optimize the number of available channels. The limitations of the ILS spectrum are best illustrated by the fact that as assignment priorities are changed, the number of available channels for specific regions over a large geographical area also changes. Assigning additional frequencies in one region can seriously reduce the channel availability in nearby regions. Analysis of other areas such as Denver and Chicago demonstrated that the limited ILS channel capacity could significantly impede expansion plans. Analysis of the regions outside the ten metropolitan areas also showed potentially significant shortfalls because of FM interference problems. Using computer simulation, we have obtained the number of possible ILS installations at the candidate runways throughout the CONUS under the current FAA interference protection requirements. While the actual number may deviate from these because of different local conditions and equipment set-up, the over-all picture is that ILS will reach its capacity limit given the high demand for precision landing runways. The EMSALS/I software can also be used for detailed analysis of the local set-up.

The second part of the software, EMSALS/M (for MLS), was used to evaluate channel availability and to generate a frequency assignment plan given the assumptions of the current ICAO MLS channel assignment rules and interference protection standards. The channel assignments had to be carried out for ILS-to-MLS conversion sites as well as new candidates, including heliports which cannot be sited with ILS. The total number of candidate sites is over 1800.

Unlike the ILS analysis, the main concern was in-band interference because the MLS-band is currently well protected, and no proven out-of-band interference sources have been identified yet. The MLS analysis shows marked improvement in the congestion problems as compared to ILS availability. In addition to satisfying all existing and new qualified site requirements, there still remains channel capacity for future expansion.

## 1.2 Future Aircraft Landing System: Global Positioning System (GPS) and Synthetic Vision Sensors (SVS)

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### Project Staff

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Precision landing systems play an important role in continuing air travel service during adverse weather conditions. The Instrument Landing System (ILS) has been in service for the past five decades, and the Microwave Landing System (MLS) will be gradually replacing ILS within the next decade. These two systems require that ground equipment works properly; therefore, their usage is limited to locations where these setups are available. Two alternative technologies that do not require ground setups have been proposed as the future replacement for ILS and MLS: Synthetic Vision (SV) sensors and the Global Positioning System (GPS).

Specifically, it has been suggested that technologies such as Active Millimeter Wave (MMW) radar or passive Forward-looking Infrared (FLIR) could be used as approach and landing aids by aircraft for locating airport runways during approximately the last 1 nmi of flight. GPS is the newest satellite-based navigation system which distributes precision timing information on a continuous basis. With a constellation of 18 to 24 satellites in high altitude orbits, receivers at any position in the sky or on the ground can obtain signals from several satellites to derive three-dimensional positions to a very high degree of accuracy. It has also been suggested that the GPS can play a significant role during approach and landing either: (1) in conjunction with an SV sensor in which case GPS would provide sole-means guidance information until the SV sensor could be used to "see" the landing environment and then might provide supplementary guidance information; or (2) as an alternative to ILS and MLS, in which case the currently planned GPS would be augmented, for example, by ground-based differential stations at the airport.

The goals of our study are to:

1. assess the capability of present and projected future state-of-the-art active millimeter wave and passive infrared systems to serve as low-visibility approach and landing aids for civil aviation, and
2. evaluate GPS requirements and capabilities in specific areas which directly affect the feasibility of using GPS for precision approach, e.g., availability and integrity.

The approach employed for SV sensor evaluation is based on the generation of simulated images to portray the capabilities of active MMW and passive FLIR SV systems. MMW and FLIR images of the same scene for the same altitudes and visibility conditions are generated using validated computer models and software. Comparison of the visible MMW and IR images provides the assessment of the capabilities of SV sensors. Simulated FLIR images have been generated using InfraRed Modeling and Analysis (IRMA) program developed by the Air Force Armament Laboratory. This simulation has been under development for several years and is thoroughly validated. IRMA models both emission and propagation of long IR (8-12 $\mu$m), which has the best weather penetration capability.

Active MMW images are also generated using models and software from related projects. Preliminary simulation of 35 GHz sensor scene reveals the lack of depth information and resolution, but shows good weather penetration. Future work is required in the area of postprocessing in order to achieve better images.

## 1.3 Multilayer Media and Superconducting Electronics

### Sponsors

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A method for the calculation of current distribution, resistance, and inductance matrices for a system of coupled superconducting transmission lines having finite rectangular cross-section is presented. These calculations allow accurate characterization of both high-$T_c$ and low-$T_c$ superconducting strip transmission lines. For a single stripline geometry with finite ground planes, the current distribution, resistance, inductance, and kinetic inductance are calculated as a function of the penetration depth for various film thicknesses. These calculations are then used to determine the penetration depth for Nb, NbN, and $YBa_2Cu_3O_{7-x}$ superconducting thin films from the measured temperature dependence of the resonant frequency of a stripline resonator. The calculations are also used to convert measured temperature dependence of the quality factor to the intrinsic surface resistance as a function of temperature for an Nb stripline resonator.

The frequency-dependent resistance and inductance of uniform transmission lines are calculated with a hybrid technique that combines a cross-section coupled circuit method with a surface integral equation approach. The coupled circuit approach is most applicable for low-frequency calculations, while the integral equation approach is best for high frequencies. The low-frequency method consists in subdividing the cross section of each conductor into triangular filaments, each with an assumed uniform current distribution. The resistance and mutual inductance between the filaments are calculated, and a matrix is inverted to give the overall resistance and inductance of the conductors. The high-frequency method expresses the resistance and inductance of each conductor in terms of the current at the surface of that conductor and the derivative of that current normal to the surface. A coupled integral equation is then derived to relate these quantities through the diffusion equation inside the conductors and Laplace's equation outside. The method of moments with pulse basis functions is used to solve the integral equations. An interpolation between the results of these two methods gives very good results over the entire frequency range, even when few basis functions are used. Results for a variety of configurations are obtained and are compared with experimental data and other numerical techniques.

A spectral domain dyadic Green's function formulation defining the fields inside a multilayer chiral medium due to arbitrary distribution of sources is developed. The constitutive parameters and the chirality of each layer are assumed to be different. The fields are obtained in terms of electric and magnetic type dyadic Green's functions. The singular behavior of these dyadic Green's functions in the source region is taken into account by extracting the delta function singularities. The fields in any layer are obtained in terms of appropriately defined global reflection and transmission matrices.

In order to understand the physical meaning of rational reflection coefficients in one-dimensional inverse scattering theory for optical waveguide design, we have studied the relation between the poles of the transverse reflection coefficient and the modes in inhomogeneous dielectrics. By using a stratified medium model, it is shown that these poles of the reflection coefficient have a one-to-one correspondence to the discrete modes, which are the guided and leaky modes. The radiation modes have continuous real values of transverse wave numbers and are not represented by the poles of the reflection coefficient. Based on these results, applications of the Gel'fand-Levitan-Marchenko theory to optical waveguide synthesis with the rational function representation of the transverse reflection coefficient are discussed.

We developed an inversion algorithm referred to as the Renormalized Source-Type Integral Equation approach. The objective of this method is to overcome some of the limitations and difficulties of the iterative Born technique. It recasts the inversion, which is nonlinear in nature, in terms of the solution of a set of linear equations; however, the final inversion equation is still nonlinear. The derived inversion equation is an exact equation which sums up the iterative Neuman (or Born) series in a closed form and; thus, is a valid representation even in the case when the Born series diverges; hence, the name *Renormalized* Source-Type Integral Equation (STIE) Approach. This renormalized STIE approach has been applied to underground soil moisture inversion and formation inversion in the borehole geometry.

Several recent papers discuss techniques for reducing the parasitic circuit capacitance of millimeter-wave planar air bridge type GaAs Schottky barrier diodes by completely etching away the semi-insulating material under the active region and transferring the device to a second carrier that is better suited, both electrically and mechanically, to the intended high frequency application. This technique and a similar procedure are being explored as a means of producing a semi-integrated subharmonically pumped two-diode mixer for use in 640 GHz. For this application, a planar antiparallel diode pair is incorporated into the center of a pair of low pass microstrip filters formed on an insulating GaAs substrate. An appealing substitute for millimeter and submillimeter wavelength applications is fused quartz which has an order of magnitude lower loss tangent, one-third the dielectric constant, and is much more mechanically rigid than GaAs. Using known techniques, it is possible to thin an entire GaAs wafer to a thickness on the order of 1-3 microns and then transfer the remaining active layer onto quartz. An interesting question that arises as a result of this procedure is the effect of the ultrathin GaAs layer on the filter characteristics. A three-dimensional finite difference time domain (FD-TD) method is used to calculate the response of the filter both with and without the GaAs layer.[8] It is shown that even a very thin layer of high dielectric constant material can have a noticeable effect on the filter response. The FD-TD analysis agreed fairly well with measured response and could be used for subsequent design.

In the last few years there has been an increasing interest in the interaction of electromagnetic fields with chiral media. A chiral medium is a subset of the wider class referred to as bianisotropic. Such media are characterized by linear constitutive relations that couple the electric and magnetic field vectors by three independent scalars. A rigorous formulation deals with the problem of radiation of electric and magnetic sources embedded in a layered lossless chiral medium. The fields are obtained in terms of dyadic Green's functions of electric or magnetic type represented in two-dimensional spectral-domain form. First, the spectral domain dyadic Green's functions of electric and magnetic types for an unbounded chiral medium are derived. The singular behavior of the various dyadic Green's functions in the source region is investigated and taken into account by extracting the delta function singularities. Finally, introducing global upward and downward reflection and transmission matrices, the dyadic Green's functions in any layer of the stratified chiral medium are derived.

The growth of epitaxial Fe film on GaAs was first demonstrated using molecular beam epitaxy. Deposition of such films by ion-beam sputtering was reported and their application to microwave filters has previously been discussed. A theoretical analysis is performed to the analysis of a tunable band-stop filter using epitaxial Fe films on [011] GaAs, in which the Fe layer is part of a microstrip line that runs along either a [100] or a [110] direction, the easy and hard directions of magnetization of the Fe film, respectively.[9] The analysis indicates that peak attenuation should occur at the ferromagnetic resonance (FMR) frequency and be proportional to the length of the microstrip line, and inversely proportional to the substrate thickness.

A rigorous approach to the problem of radiation of electric or magnetic sources in a stratified arbitrarily magnetized linear plasma.[10] The fields are obtained in terms of dyadic Green's functions of electric or magnetic type represented in the spec-

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[8] P.H. Siegel, J.E. Oswald, R.G. Dengler, D.M. Sheen, and S.M. Ali, "Measured and Computed Performance of a Microstrip Filter Composed of Semi-Insulating GaAs on a Fused Quartz Substrate," *IEEE Microwave Guided Wave Lett.* 1(4): April (1991).

[9] V.S. Liau, T.W. Stacey, S. Ali, and E. Schloemann, "Tunable Band-Stop Filter Based on Epitaxial Fe Film on GaAs," *Proceedings of the 1991 IEEE MTT-S International Microwave Symposium,* Boston, Massachusetts, June 11-14, 1991, pp. 957-960.

[10] T.M. Habashy, S.M. Ali, J.A. Kong, and M.D. Grossi, "Dyadic Green's Functions in a Planar Stratified, Arbitrarily Magnetized Linear Plasma," *Radio Sci.* 26(3): 701-716 (1991).

tral domain. First, the dyadic Green's functions for an unbounded arbitrarily magnetized plasma is derived. The formulation is considerably simplified by using the KDB system of coordinates in conjunction with the Fourier transform. This leads to compact and explicit expressions for the dyadic Green's functions. The distributional singular behavior of the various dyadic Green's functions in the source region is investigated and taken into account by extracting the delta function singularities. Finally, the dyadic Green's function in any arbitrary layer is obtained in terms of appropriately defined global upward and downward reflection and transmission matrices. The field expressions for any arbitrary distribution of sources or linear antennas can be obtained by performing a convolution integral over the volume of the antenna weighted by the current density on the antenna.

The input impedance of a microstrip antenna consisting of two circular microstrip disks in a stacked configuration driven by a coaxial probe is investigated.[11] A rigorous analysis is performed using a dyadic Green's function formulation where the mixed boundary value problem is reduced to a set of coupled vector integral equations using the vector Hankel transform. Galerkin's method is employed in the spectral domain where two sets of disk current expansions are used. One set is based on the complete set of orthogonal modes of the magnetic cavity, and the other employs Chebyshev polynomials with the proper edge condition for disk currents. An additional term is added to the disk current expansion to properly model the current in the vicinity of the probe/disk junction. The input impedance of the stacked microstrip antenna including the probe self-impedance is calculated as a function of the layered parameters and the ratio of the two disk radii. Disk current distribution and radiation patterns are also presented. The calculated results are compared with experimental data and shown to be in good agreement.

A method for the analysis of complex frequency-dependent signal interconnections and planar circuits terminated with nonlinear load is investigated. The frequency-dependent portion of the system is first analyzed to get the scattering parameters and hence the impulse responses. Two different methods, depending on the complexity of the system, are used to get the scattering parameters: the three-dimensional finite-difference time-domain method and an analytical procedure. The nonlinear convolution equations governing the overall system are then derived and solved numerically. The transient responses of a pair of coupled dispersive microstrip lines, a corner discontinuity, and a microstrip switching circuit are presented.

We analysed three-dimensional (3-D) multichip module (MCM) interconnects. In this technology, the vertical interconnects consist of small conductor plated via holes etched by a photo lithography system. The via dimensions are in the same order as the microstrip and stripline widths to reduce the transmission line discontinuities. Two 3-D transitions are investigated: microstrip-via-stripline and microstrip-via-90 degree stripline. The finite-difference time-domain with nonuniform grid is applied to the analysis of these transitions. Electric field distribution and pulse propagation under the strip and the strip line are presented. The scattering parameters for various cases are calculated and compared. Geometrical effects such as different conductor extensions on top of the vias and different hole sizes in the reference plane are also investigated.

A method for calculation of the current distribution, resistance, inductance matrices for a system of coupled superconducting transmission lines having finite rectangular cross section is developed.[12] These calculations allow accurate characterization of both high-$T_c$ and low-$T_c$ superconducting transmission lines. For a single stripline geometry with finite ground planes, the current distribution, resistance, and kinetic inductance are calculated as a function of the penetration depth for various film thicknesses. These calculations are then used to determine the penetration depth for Nb, NbN, and $YBa_2Cu_3O_{7-x}$ superconducting thin films from the measured temperature dependance of the resonant frequency of a stripline resonator. The calculations are also used to convert measured temperature dependance of the quality factor to the intrinsic surface resistance as a function of temperature for an Nb stripline resonator.

The calculations of resistance and inductance are used for the determination of surface impedance of

11 A.N. Tulintseff, S.M. Ali, and J.A. Kong, "Input Impedance of a Probe-Fed Stacked Circular Microstrip Antenna," *IEEE Trans. Antennas Propag.* 39(3): 381-390 (1991).

12 D.M. Sheen, S.M. Ali, D.E. Oates, R.S. Withers, and J.A. Kong, "Current Distribution, Resistance, and Inductance for Superconducting Strip Transmission Lines," *IEEE Trans. Appl. Superconduct.* 1(2): 108-115 (1991); D.M. Sheen, S.M. Ali, D.E. Oates, R.S. Withers, and J.A. Kong, "Current Distribution in Superconducting Strip Transmission Lines," Proceedings of the 1991 IEEE MTT-S International Microwave Symposium, pp. 161-164, Boston, Massachusetts, June 11-14, 1991.

$YBa_2Cu_3O_{7-x}$ thin films using a stripline resonator.[13] The surface impedance as a function of frequency from 1.5 to 20 GHz, as function of temperature from 4K to the transition temperature (90 K), and as a function of the RF magnetic field from zero to 300 Oe, is obtained. At low temperatures the surface resistance of the films shows a very week dependance on the magnetic field up to 225 to 250 Oe. At 77 K, the surface resistance is proportional to the square of the field. The penetration depth shows a much weaker dependence on the field than does the surface resistance.

The Ginzburg-Landau (GL) theory is used to predict the nonlinear behavior in a superconducting stripline resonator as a function of input. A method for calculating the nonlinear inductance and the fractional change in the resonant frequency of a stripline resonator is presented. By solving the GL equations inside the superconducting strip, the spatial variation of the number density of superconducting electrons, and hence the spatial variation of the magnetic penetration depth are obtained for different values of input current. First, an infinite parallel plate transmission line is considered where the one-dimensional GL equations are solved. The two-dimensional case of stripline is then considered. Nonlinear inductances are calculated as functions of input current for different superconducting strip lines. Comparisons of the calculated resonance frequency shift with measurements for $YBa_2Cu_3O_{7-x}$ stripline resonators show excellent agreement.

A full-wave numerical analysis is applied to accurately characterize superconducting transmission lines embedded in a layered media. An integral equation formulation is developed by using a spectral domain Green's function for stratified media. Galerkin's method with roof top basis functions for the electric field distribution inside the superconductor is then employed to solve for the complex propagation constant. The thickness of the superconducting film is arbitrary in this analysis, and the formulation rigorously accounts for the anisotropy of the superconducting film. The propagation characteristics of a superconducting microstrip transmission line with a thin dielectric buffer layer are investigated. A superconducting stripline configuration with an air gap is also studied.

A full-wave analysis is applied to accurately characterize normal and superconducting coplanar strip lines (CPS) and coplanar waveguides (CPW). A volume integral equation formulation which rigorously considers the finite thickness, conductivity, and anisotropy of the strips, is developed. The phase and attenuation constants for copper CPS and CPW at 77 K and room temperatures are calculated and compared to experimental results obtained by short-pulse propagation measurements.

## 1.4 Remote Sensing of Earth Terrain

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A branching model is proposed for the remote sensing of vegetation. The frequency and angular response of a two-scale cylinder cluster are calculated to demonstrate the significance of vegetation architecture. The results indicate that it is necessary for theoretical remote sensing models to take into account the architecture of vegetation which plays an important role in determining the observed coherent effects. A two-scale branching model is implemented for soybeans with its internal structure and the resulting clustering effects considered. Furthermore, at the scale of soybean fields, the relative locations of soybean plants is described by a pair distribution function. The polarimetric backscattering coefficients are obtained in terms of the scattering properties of soybean plants and their pair distribution. Theoretical backscattering coefficients are evaluated using a hole-corrected pair distribution function. Backscattering coefficients calculated are in good agreement with extensive data collected from soybean fields. It is found that the hole-correction approximation, which prevents two soybean plants from overlaying each other, greatly improves the agreement between the model and these three data sets near normal incidence, by introducing destructive interference at small angles of incidence.

[13] D.E. Oates, C. Anderson, D.M. Sheen, and S.M. Ali, "Stripline Resonator Measurements of $Z_sVSH_{rf}$ in $YBa_2Cu_3O_{7-x}$ Thin Films," *IEEE Trans. Microwave Theory Tech.* 39: 1522-1529 (1991).

In the past, when radiative transfer theory was applied to the modeling of vegetation, the average phase matrix of vegetation layer was approximated by an incoherent sum of the phase matrices of individual vegetation elements. In this research,[14] radiative transfer theory is applied to vegetation with clustered structures. To take into account vegetation structure in the radiative transfer theory, the phase matrix of a vegetation cluster is calculated by incorporating the phase interference of scattered fields from every component. Subsequently, the resulting phase matrix is used in the radiative transfer equations to evaluate the polarimetric backscattering coefficients from a layer of medium embedded with vegetation clusters. Theoretical results are illustrated for various kinds of vegetation clusters. It is found that the simulated polarization, frequency, and angular responses carry significant information regarding the structure of vegetation clusters and also agree with the signatures observed in measured multifrequency polarimetric synthetic aperture radar images.

We have also formulated the vector radiative transfer equation for passive microwave remote sensing of a vegetation canopy overlying a soil half-space and study the calculated brightness temperatures resulting from microwave thermal emission based on the first order iterative solution. A randomly distributed stem-leave model is employed to construct the phase matrix such that we can properly account for the effects of coherence and multiscale vegetation cluster.

For polarimetric remote sensing, geophysical media are modeled as layers containing randomly embedded scatterers. In media such as snow, ice, and vegetation canopy, scatterers can have various shapes, sizes, and permittivities that are significantly distinct from the background medium. The model studied in our research considers each type of the scatterers as a species which can takes on a shape, size, and complex permittivity different from other species. The effective permittivity of the random medium is derived under the strong permittivity fluctuation theory and polarimetric scattering coefficients are calculated for the layer configuration with the distorted Born approximation in the analytical wave theory which preserves the phase information. The multiple species in the random medium are considered as randomly oriented ellipsoids and described by multiple three-dimensional ellipsoidal correlation functions. The variances and correlation lengths of the correlation functions characterize the fluctuation strengths and the physical geometry of the scatterers, respectively. The result for the cross-polarized return $\sigma_{hv}$ is non-zero even in the first order approximation. Due to the non-spherical shape and the random orientation of the scatterers, the correlation coefficient between the HH and VV returns has a magnitude different from unity and a small phase. The scattering coefficients are also used to calculate the Mueller matrix for synthesis of polarization signatures. The copolarized signature of the random medium has a rather straight distortion track and a recognizable pedestal.

The concept of polarimetry in active remote sensing has been extended to passive remote sensing.[15] The potential use of the third and fourth Stokes parameters $U$ and $V$, which play an important role in polarimetric active remote sensing, is demonstrated for passive remote sensing. It is shown that by the use of the reciprocity principle the polarimetric parameters of passive remote sensing can be obtained through the solution of the associated direct scattering problem. These ideas are applied to study polarimetric passive remote sensing of periodic surfaces. The solution of the direct scattering problem is obtained by an integral equation formulation which involves evaluation of periodic Green's functions and normal derivative of those on the surface. Rapid evaluation of the slowly convergent series associated with these functions is observed to be critical for the feasibility of the method. New formulas, which are rapidly convergent, are derived for the calculation of these series. The study has shown that the brightness temperature of the Stokes parameter $U$ can be significant in passive remote sensing. Values as high as 50 K are observed for certain configurations.

To verify our theory, a triangular corrugation pattern with height $h$ = 2.5 cm and period $p$ = 5 cm is made on the sandy soil surface covering 23 periods by length $l$ = 160 cm and thickness $d$ = 12.7 cm. A radiometer of 15° beam width oper-

[14] C.C. Hsu, S.H. Yueh, H.C. Han, R.T. Shin, and J.A. Kong, "Radiative Transfer Modeling of Vegetation Clusters," *Proceedings of the Progress in Electromagnetics Research Symposium,* p. 609, Boston, Massachusetts, July 1-5, 1991.

[15] S.V. Nghiem, M.E. Veysoglu, J.A. Kong, R.T. Shin, K. O'Neill, and A.W. Lohanick, "Polarimetric Passive Remote Sensing of a Periodic Soil Surface: Microwave Measurements and Analysis," *J. Electromag. Waves Appl.* 5(9): 997-1005 (1991); M.E. Veysoglu, H.A. Yueh, R.T. Shin, and J.A. Kong, "Polarimetric Passive Remote Sensing of Periodic Surfaces," *J. Electromag. Waves Appl.* 5(3): 267-280 (1991).

ating at 10 GHz is used in the experiment. The radiometer is mounted on a tripod at an elevation of 1.8 m height and directed toward the soil surface along the look direction determined by azimuthal angle $\phi$ and polar angle $\theta$. Polarimetric brightness temperatures $T_{Bh}$, $T_{Bv}$, and $T_{Bp}$ are measured respectively with horizontal, vertical, and 45° polarization orientations for $\theta = 20°, 30°$ and $\phi$ from 0° to 90°. From the measured temperatures, the third Stokes brightness temperatures $U_B$ are obtained. Absolute values as high as 30-40 K of the third Stokes brightness temperatures are observed. A theoretical analysis of the data indicates that the high values of $U_B$ are caused by the azimuthal asymmetry on the remotely sensed soil surface. It is also observed from the experiment that as $T_{Bh}$ decreases, $T_{Bv}$ increases, $T_{Bp}$ decreases to a minimum at $\phi = 45°$ and then increases as $\phi$ takes on the increased values. For $U_B$, the trend is similar to that of $T_{Bp}$. These general trends are supported by our theoretical predictions of the polarimetric brightness temperatures.

In most of the scattering models, volume scattering and surface scattering effects have been investigated separately. We have studied the first order iterative solution to the vector radiative transfer equations for a two-layer medium with a diffuse top boundary and an irregular bottom boundary of Gaussian roughness.[16] The geometrical optics approach with shadowing correction are used in formulating the boundary conditions. We applied our formula with a phase matrix for randomly oriented spheroidal discrete scatterers to calculate the backscattering coefficients from soybean field in different growing stages and compare the results with the experimental measurements. Good agreement has been achieved for both the co-polarized and the cross-polarized data. It is observed that the presence of the rough surface can significantly enhance the backscattering at small incident angles and the levels of the cross-polarized return.

As an electromagnetic wave propagates through a random scattering medium, such as a forest, its energy is attenuated, and random phase fluctuations are induced. The magnitude of the random phase fluctuations induced is important in estimating how well a Synthetic Aperture Radar (SAR) can image objects within the scattering medium. The two-layer random medium model, consisting of a scattering layer between free space and ground, is used to calculate the variance of the phase fluctuations induced between a transmitter located above the random medium and a receiver located below the random medium.[17] The scattering properties of the random medium are 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 large permittivity fluctuations of the scatterers. The distorted Born approximation is used to calculate the first-order scattered field. A perturbation series for the phase of the received field is then introduced, and the variance of the phase fluctuations is solved to first order in the permittivity fluctuations. The variance of the phase fluctuations is also calculated assuming that the transmitter and receiver are in the paraxial limit of the random medium, which allows an analytic solution to be obtained. The effects studied are the dependence of the variance of the phase fluctuations on receiver location in lossy and lossless regions, medium thickness, correlation length and fractional volume of scatterers, depolarization of the incident wave, ground layer permittivity, angle of incidence, and polarization.

## 1.5 SAR Image Interpretation and Simulation

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[16] H.C. Han, J.A. Kong, S.V. Nghiem, and T. Le Toan, "Analytical Solution of the Vector Radiative Transfer Equation with Rough Surface Boundary Condition," *Proceedings of Progress in Electromagnetics Research Symposium,* p. 536, Boston, Massachusetts, July 1-5 (1991).

[17] J. Fleischman, S. Ayasli, R.T. Shin, N.C. Chu, H.A. Yueh, and S.V. Nghiem, "Covariance of Phase and Amplitude Fluctuations of Electromagnetic Waves Propagating Through a Random Medium," *Proceedings of the Progress in Electromagnetics Research Symposium,* p. 617, Boston, Massachusetts, July 1-5 (1991).

Classification of terrain cover using polarimetric radar is an area of considerable current interest and research. A number of methods have been developed to classify ground terrain types from fully polarimetric synthetic aperture radar (SAR) images, and these techniques are often grouped into supervised and unsupervised approaches. Supervised methods, including both conventional Maximum Likelihood (ML) and more recent Multilayer Perceptron classifiers, have yielded higher accuracy than unsupervised techniques, but suffer from the need for human interaction to predetermine classes and training regions. In contrast, unsupervised methods determine classes automatically, but generally show limited ability to accurately divide terrain into natural classes. In this research, a new terrain classification technique is introduced, utilizing unsupervised neural networks to provide automatic classification, but employing an iterative algorithm which overcomes the poor accuracy of other unsupervised techniques.

Several types of unsupervised neural networks are first applied to the classification of SAR images,[18] and the results are compared with those of more conventional unsupervised methods. Neural network approaches include Adaptive Resonance Theory (ART), Learning Vector Quantization (LVQ), and Kohonen's self-organizing feature map. Conventional classifiers utilized are the migrating means clustering algorithm and the K-means clustering method. With both neural network and conventional classifiers, preprocessing is performed to reduce speckle noise and to stabilize the training process. Results show that LVQ is the best of the neural network techniques and that this method outperforms all of the conventional unsupervised classifiers. The accuracy of even the LVQ technique, however, is seen to remain below that of supervised methods.

To overcome this poor accuracy, an iterative algorithm is proposed in which the SAR image is reclassified using a Maximum Likelihood (ML) classifier. Training of the ML classifier is performed using a training data set first classified by the above unsupervised method, thus requiring no human intervention and preserving the unsupervised nature of the overall classification scheme. The process is then repeated iteratively, training a second ML classifier using data classified by the first. It is shown that this algorithm converges rapidly and significantly improves classification accuracy. Performance after convergence is seen to be comparable to that obtained with a supervised ML classifier, while maintaining the advantages of an unsupervised technique.

The new unsupervised and iterative algorithm developed in this research is applied to polarimetric SAR images of San Francisco and Beaufort sea ice acquired by the Jet Propulsion Laboratory. The results obtained for this imagery using the new algorithm are compared with the results obtained with other techniques and also with those obtained with single-feature classification. It is found in each case that the new fully polarimetric unsupervised algorithm yields classified images which compare closely with those obtained from optimally chosen, supervised algorithms.

A multivariate K-distribution is proposed to model the statistics of fully polarimetric radar returns from earth terrain.[19] Numerous experimental data have shown that the terrain radar clutter statistics is non-Gaussian, and an accurate statistical model for the polarimetric radar clutter is needed for various applications. In the terrain cover classification using the synthetic aperture radar (SAR) images, the application of the K-distribution model will provide better performance than the conventional Gaussian classifier. In the multivariate K-distribution model, the correlated polarizations of backscattered radar returns are characterized by a covariance matrix, and the clustering behavior of terrain scatterers is described by a parameter $\alpha$. In the limit the parameter $\alpha$ approaches infinity, the multivariate K-distribution reduces to the multivariate Gaussian distribution. With the polarimetric covariance matrix and the $\alpha$ parameter extracted from the measurements, it is shown that the multivariate K-distribution model is well supported by the simultaneously measured C-, L- and P-band polarimetric SAR images provided by the Jet Propulsion Laboratory. It is also found that the $\alpha$ parameter appears to decrease from C- to P-band for forests, clear-cut areas in forests, and desert areas. The polarimetric covariance matrices of the various earth terrain media can be interpreted with the theoretical models for model validation and development of other classification algorithms. Also, the frequency-dependence of

[18] R. Kwok, Y. Hara, R.G. Atkins, S.H. Yueh, R.T. Shin, and J.A. Kong, "Application of Neural Networks to Sea Ice Classification Using Polarimetric SAR Images," International Geoscience and Remote Sensing Symposium (IGARSS '91), Helsinki University of Technology, Espoo, Finland, June 3-6, 1991.

[19] H.A. Yueh, J.A. Kong, J.K. Jao, R.T. Shin, H.A. Zebker, and T. Le Toan, "K-Distribution and Multi-Frequency Polarimetric Terrain Radar Clutter," *J. Electromag. Waves Appl.* 5(1): 1-15 (1991).

the $\alpha$ parameter is being investigated for various other radar clutter.

Polarimetric calibration algorithms using combinations of point targets and reciprocal distributed targets are developed.[20] From the reciprocity relations of distributed targets, an equivalent point target response is derived. Then the problem of polarimetric calibration using two-point targets and one distributed target reduces to that using three-point targets, which has been solved before. For calibration using one-point target and one reciprocal distributed target, two cases are analyzed with the point target being a trihedral reflector or a polarimetric active radar calibrator (PARC). For both cases, the general solutions of the system distortion matrices are written as a product of a particular solution and a matrix with one free parameter. For the trihedral-reflector case, this free parameter is determined by assuming azimuthal symmetry for the distributed target. For the PARC case, knowledge of one ratio of two covariance matrix elements of the distributed target is required to solve for the free parameter. Numerical results are simulated to demonstrate the usefulness of the algorithms developed.

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[20] H.A. Yueh, J.A. Kong, and R.T. Shin, "External Calibration of Polarimetric Radars Using Point and Distributed Targets," *Proceedings of the Third Airborne Synthetic Aperture Radar (AIRSAR) Workshop,* Jet Propulsion Laboratory, Pasadena, California, May 23-24, 1991.

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