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REMOTE SENSING OF EARTH TERRAIN

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SEMI-ANNUAL PROGRESS REPORT

Under the sponsorship of the NASA Contract NAG5-270, the publication list includes 2 books and 85 refereed journal and conference papers for the research on the remote sensing of earth terrain.

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

Polarimetric calibration algorithms are developed to provide tools for polarimetric radar calibration. The transmission and receiving ports of the polarimetric radar are modelled by two unknown polarization transfer matrices. These two matrices are solved using three in-scene reflectors with different scattering matrices. All possible combinations of calibration targets are discussed and the solutions of each cases are presented. Thus if three scatterers with known scattering matrices, not necessarily man-made, are known to exist within a radar image, the whole image can be calibrated accordingly by using our exact solutions.

For active and passive microwave remote sensing, the correlation function used in the random medium model provides a direct link between electrical behaviors and physical properties of geophysical media. The distribution, shape, size, and orientation of embedded inhomogeneities, such as ice grains in snow and brine inclusions in sea ice, can be characterized by the functional form of the correlation function, the variance, and the correlation lengths. Based on the probability theory, analytical expressions of correlation functions for two-phase mixtures with randomly distributed inclusions of spherical and spheroidal shapes are derived. It is shown that the functional form of the correlation function is determined by the shape and orientation of inclusions while correlation lengths are related to the fractional volume of the scatterers and the total common surface area.

For remote sensing of geophysical media, the correlation function provides us the valuable information to identify feature signature. With the application of probability theory, correlation functions for isotropic and anisotropic random media with three-phase mixtures are derived. Although the two cases under consideration are idealistic, the presented approach is very useful to elucidate the microscopic textures of the random media through the obtained correlation functions. It is found that functional forms of the correlation functions depend on the geometrical shapes of embedded inclusions while the correlation lengths are related to the common surface areas and the fractional volumes of different species.

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

For active and passive microwave remote sensing of sea ice, a correlation function of exponential form is extracted from the photograph of a horizontal thin section taken from a sample of artificially grown saline ice that closely resembled Arctic congelation sea ice. It is found that the extracted correlation lengths are consistent with the published average size of brine pockets. With the application of strong fluctuation theory and the bilocal approximation, the effective permittivity tensor is derived in the low frequency limit for an unbounded uniaxial random medium with two-phase mixtures. Using the extracted correlation lengths, the effective permittivity tensor is computed as a function of fractional volume of brine inclusions and compared with in situ measurements at 4.8 and 9.5 GHz.

A general mixing formula is derived for discrete scatterers immersed in a host medium. The inclusion particles are assumed to be ellipsoidal. The electric field inside the scatterers is determined by quasistatic analysis, assuming the diameter of the inclusion particles to be much smaller than the wavelength. The results are applicable to general multiphase mixtures, and the scattering ellipsoids of the different phases can have different sizes and arbitrary ellipticity distribution and axis orientation, i.e., the mixture may be isotropic or anisotropic. The resulting mixing formula is nonlinear and implicit for the effective complex dielectric constant, because the approach in calculating the internal field of scatterers is self-consistent. Still, the form is especially suitable for iterative solution. The formula contains a quantity called the apparent permittivity, and with different choices of this quantity, the result leads to the generalized Lorentz - Lorenz formula, the generalized Polder - van Santen formula, and the generalized coherent potential - quasicrystalline approximation formula. Finally, the results are applied to calculating the complex effective permittivity of snow and sea ice.

This paper will present a mathematically rigorous and fully polarimetric radar clutter model used to evaluate the radar backscatter from various types of terrain clutter such as forested areas, vegetation canopies, snow covered terrains, or ice fields. With this model, we can calculate the radar backscattering coefficients (σ^o) for the multi-channel polarimetric radar returns, in addition to the complex cross correlation coefficients between elements of the polarimetric measurement vector. The complete polarization covariance matrix can be computed and the scattering properties of the clutter environment characterized over a broad range of incident angles and frequencies.

Earth terrain media, such as vegetation, forest, snow, and ice exhibit strong volume scattering effects. To study polarimetric radar backscatter of earth terrains from the point of view of electromagnetic wave theory, we use a layered random medium model to characterize the terrain clutter. The random medium is described by a background permittivity with a fluctuating component; the randomness of the fluctuation is characterized by a three-dimensional correlation function with a variance and horizontal and vertical correlation lengths. The variance corresponds to the strength of the fluctuation, whereas the correlation lengths coincide with the geometrical size of the basic scattering elements. The polarimetric backscattering coefficients can be obtained from the electromagnetic wave theory by calculating the covariance matrix of the polarimetric measurement vector.

The problem of scattering by a layer of random medium (e.g. snow field, meadow, etc.) can be solved with a number of different techniques. In this paper, we shall develop a wave approach by applying the Born approximation. An integral equation is formulated for the electric field by using the unperturbed Green's function for a layered random medium in the absence of permittivity fluctuations. The random fluctuations are treated as induced scattering sources in the integral equation, which will then be solved by iteration to obtain a Neumann series. To include the depolarization effects, the Born approximation is carried out to the second order. Physically, the Born first-order and second-order approximations account, respectively, for a single and double scattering process. The calculated covariance matrix for a layered isotropic random medium has four of its elements equal to zero, indicating absence of correlation between the HV and HH terms and HV and VV terms. The theoretical results are shown to be consistent with measurement data obtained from the MIT Lincoln Laboratory.

With the same approach, the polarimetric scattering effects from a layer of anisotropic random medium (e.g. sea ice) or from a layer of isotropic random medium on top of another layer of anisotropic random medium (e.g. tree canopy, snow-covered sea ice, etc.) are investigated and the complete covariance matrices with nine non-zero elements are computed. Theoretically calculated covariance matrices will be compared with experimental polarimetric HH, HV, and VV clutter data collected from the various terrains. Physical interpretations will be illustrated along with the other properties of the covariance matrix elements.

The evaluation of clutter backscatter coefficients for HH, HV and VV polarimetric returns is useful in the design and analysis of optimal radar target detection, discrimination and classification schemes. Another important application is the generation of random clutter returns for Monte-Carlo simulations. The application of the fully polarimetric clutter model in the terrain classification will be illustrated. The optimal (Bayes) fully polarimetric and normalized polarimetric classifiers as well as simpler polarimetric discriminants will also be presented. In addition, the optimal polarimetric matched filter will be introduced as a means of enhancing the contrast between two areas within radar polarimetry. Fully polarimetric synthetic aperture radar images, obtained from the Jet Propulsion Laboratory, will be used to demonstrate various terrain classification schemes and the contrast enhancement obtained using the polarization matched filter.

Fully polarimetric scattering of electromagnetic waves from earth terrain media are studied with three-layer configuration. The inhomogeneous layers are modeled as random media and characterized with three-dimensional correlation functions. The strong fluctuation theory and the distorted Born approximation are used to calculate the covariance matrix which describes the polarimetric radar scattering from the remotely sensed media. Theoretical results are first obtained for two-layer cases and then used to compare with results for three-layer cases to identify the effects on polarimetric wave scattering due to the top layer. A covering dry-snow layer can give rise to the enhancement of radar returns from first-year sea ice and also the oscillation in the real and imaginary parts of the correlation coefficient ρ between the VV and HH returns as a function of incident angle. The magnitude of ρ, however, does not show the oscillation and clearly retains the similar characteristics as observed directly from bare sea ice. When the covering layer is thick or lossy, some polarimetric information from the sea-ice layer is masked out.

A radar clutter model is used to simulate fully polarimetric returns for a stepped frequency radar. The purpose is to create synthetic site dependent clutter signatures that can be utilized in a hardware-in-the-loop test system. The fully polarimetric, multi-frequency, multi-incident angle random medium model is employed to generate normalized backscatter coefficients of terrain clutter. This model is used to generate the polarimetric terrain clutter covariance matrices for each of N high resolution range bins, at each of the M discrete frequencies. The random medium model allows us to include the effect of the terrain local incident angle on the clutter covariance matrix elements. In the simulation, we assume that there is a single clutter class within each of the N range bins, although the depression angle may vary from bin to bin. The covariance matrices are decomposed and multiplied by complex Gaussian noise in order to generate the normalized electric fields in the backscattering direction for each of the N range bins, at each of the M discrete frequencies. These fields are then coherently added, taking into account the effects of both terrain elevation and range. This yields a single frequency polarimetric return that a radar would measure from the specified terrain. The radar return for each of the other discrete frequencies is calculated in a similar manner. The result is the clutter's low resolution range polarimetric profile, i.e., the backscattered signal response within the beam footprint of the radar antenna. Each discrete frequency is simulated and the effects of shadowing and overlay are taken into account. The simulation produces coherent phase-history clutter returns which can be coherently superimposed on the target phase-history returns. The combined (or clutter only) returns are processed to obtain either (1) the coherent, high resolution range profile or (2) the noncoherent, autocorrelation range profile.

A systematic approach for the identification of terrain media such as vegetation canopy, forest, and snow-covered fields is developed using the optimum polarimetric classifier. The covariance matrices for the various terrain cover are computed from theoretical models of random medium by evaluating the full polarimetric scattering matrix elements. The optimal classification scheme makes use of a quadratic distance measure and is applied to classify a vegetation canopy consisting of both trees and grass. Experimentally measured data are used to validate the classification scheme. Theoretical probability of classification error using the full polarimetric matrix are compared with classification based on single features including the phase difference between the VV and HH polarization returns. It is shown that the full polarimetric results are optimal and provide better classification performance than single feature measurements.

There is a considerable interest in determining the optimal polarizations that achieve maximum contrast between two scattering classes in radar polarimetric images for the purpose of terrain discrimination. In this paper, we present a systematic approach for obtaining the optimal polarimetric matched filter which produces maximum contrast between two scattering classes, each represented by its respective covariance matrix.

To accomplish this, we derive a linear weighting vector that maximizes the expected power return ratio, i.e., the contrast ratio between the two scattering classes. The maximization procedure involves solving an eigenvalue problem where the eigenvector yielding this maxima will correspond to the optimal polarimetric matched filter. Then, through use of polarization synthesis, it is demonstrated that when this weighting vector is utilized to process fully polarimetric radar images, the maximum contrast between the two respective classes results. The suboptimal problem of a fixed transmitting polarization is also considered. In this case, the received polarization is optimized such that a maxima in the contrast ratio is obtained under this constraint. To exhibit the physical significance of this filter, we transform it into its associated transmitting and receiving polarizations, in terms of their horizontal and vertical vector components.

This technique is then applied to radar polarimetry obtained from the Jet Propulsion Laboratory. It is shown, both numerically and through the use of radar imagery, that maximum image contrast can be realized when data is processed with the optimal polarimetric matched filter.

Supervised and unsupervised classification procedures are developed and applied to synthetic aperture radar (SAR) polarimetric images in order to identify its various earth terrain components. For the supervised classification processing, the Bayes technique is utilized to classify fully polarimetric and normalized polarimetric SAR data. Simpler polarimetric discriminates, such as the unnormalized and normalized magnitude response of the individual receiver channel returns, in addition to the phase difference between the receiver channels are also considered. Covariance matrices are computed for each terrain class from selected portions within the image where ground truth is available, under the assumption that the polarimetric data has a multivariate Gaussian distribution. These matrices are used to train the optimal classifier, which in turn is used to classify the entire image. In this case, classification is based on determining the *distances* between the training classes and the observed feature vector, then assigning the feature vector to belong to that training class for which the distance was minimum. Another processing algorithm based on comparing general properties of the Stokes parameters of the scattered wave to that of simple scattering models is also discussed. This algorithm, which is an unsupervised technique, classifies terrain elements based on the relationship between the orientation angle and handedness, or ellipticity, of the transmitted and received polarization state. These classification procedures will be applied to San Francisco Bay and Traverse City SAR imagery, supplied by the Jet Propulsion Laboratory. It is shown that fully polarimetric classification yields the best overall performance. Also, in some selected areas where the observed amplitudes of the returns are quite different than that of the training data, classification techniques not based on the absolute amplitudes of the returns, e.g., the normalized polarimetric classifier, produced a more consistent result with respect to the ground truth data.

Polarimetric radar backscatter data have been used extensively to classify terrain cover. Since it is difficult to calibrate out the effects of amplitude and phase errors induced by atmospheric effects, path loss, etc., absolute amplitude and phase of radar returns are not reliable features for terrain classification purposes. The use of normalized polarimetric data is proposed such that only the relative magnitudes and phases will be utilized to discriminate different terrain elements. It is shown that the Bayes classification error does not depend on the form of the normalization function if the unknown radar system calibration factor is modeled as a multiplicative term in the received signal. Assuming a multivariate Gaussian distribution for the un-normalized polarimetric data, the probability density function (PDF) of the normalized data and the corresponding Bayes classifier distance measure for the normalized data are derived. Furthermore, by assuming a specific form of the covariance matrix for the polarimetric data, exact PDFs are given for HH, HV, VV and span type normalization schemes. Corresponding classification errors are evaluated to verify their independence from all normalization functions.

A two-layer random medium model has been successfully applied to polarimetric remote sensing of earth terrain such as vegetation, meadow, and ice layer. The results obtained with the three-layer configuration have the capability of accounting for polarimetric scattering from earth terrain under the effects of weather, seasonal variation, and atmospheric conditions such as forest under mist, meadow under fog, and ice under snow. The effects on polarimetric wave scattering due to the top layer are identified by comparing the three-layer model results with those obtained from the two-layer model. The enhancement of the radar returns due to dry-snow cover on top of first-year sea ice observed in the experimental data can be explained using the three-layer random medium model. The theoretical results are illustrated by comparing the calculated covariance matrices with the polarimetric measurement data.

A three-layer random medium model is developed to study the fully polarimetric scattering properties of earth terrain. The top layer is modeled as an isotropic random medium, the middle layer as an anisotropic random medium, and the bottom layer as a homogeneous half-space. Volume scattering effects of both random media are characterized by correlation functions in which variances and correlation lengths describe strengths of permittivity fluctuations and physical sizes of embedded inhomogeneities, respectively. The anisotropic effect of the middle layer is attributed to specific structure and alignment of the scatterers. With the strong fluctuation theory, the mean fields in the random media are derived under the bilocal approximation with singularities of the dyadic Green's functions properly taken into consideration. With the discrete scatterer concept, effective permittivities of the random media are calculated by two-phase mixing formulas. Then, the distorted Born approximation is used to calculate the covariance matrix which describes the fully polarimetric scattering properties of the terrain and is used in radar image simulation and earth terrain identification and classification.

The scattering of electromagnetic waves from a randomly perturbed periodic surface is formulated by the Extended Boundary Condition (EBC) method and solved by the small perturbation method (SPM). The scattering from periodic surface is solved exactly and this solution is used in the SPM to solve for the surface currents and scattered fields up to the second order. The random perturbation is modeled as a Gaussian random process. The theoretical results are illustrated by calculating the bistatic and backscattering coefficients. It is shown that as the correlation length of the random roughness increases, the bistatic scattering pattern of the scattered fields show several beams associated with each Bragg diffraction direction of the periodic surface. When the correlation length becomes smaller, then the shape of the beams become broader. The results obtained using the EBC/SPM method is also compared with the results obtained using the Kirchhoff approximation. It is shown that the Kirchhoff approximation results show quite a good agreement with EBC/SPM method results for the hh and vv polarized backscattering coefficients for small angles of incidence. However, the Kirchhoff approximation does not give depolarized returns in the backscattering direction whereas the results obtained using the EBC/SPM method give significiant depolarized returns when the incident direction is not perpendicular to the row direction of the periodic surface.

We modeled earth terrain covers as random media characterized by different dielectric constants and correlation functions. In order to model sea ice with brine inclusions and vegetation with row structures, the random medium is assumed to be anisotropic. A three-layer model will be used to simulate a vegetation field or a snow-covered ice field with the top layer being snow or leaves, the middle layer being ice or trunks, and the bottom layer being sea water or ground.

The strong fluctuation theory with the distorted Born approximation is applied to the solution of the radar backscattering coefficients. In order to take into account the polarimetric information, we relate the backscattered Stokes vector to the incident Stokes vector by the Mueller matrix, which completely describes the scattering (in amplitude, phase, frequency, and polarization) from the three-layer anisotropic random medium. The Mueller matrix properties, as well as the covariance matrix issues, relevant to the radar backscattering will be examined. It is shown that for an isotropic medium, eight of the sixteen elements of the Mueller matrix are identically zero. However, the tilted anisotropic permittivity of the middle layer (sea ice or trunks) generates a full nonzero Mueller matrix.

The Mueller matrix and polarization covariance matrix are studied for polarimetric radar systems. The clutter is modelled by a layer of random permittivity, described by a three-dimensional correlation function, with variance, and horizontal and vertical correlation lengths. This model is applied, using the wave theory with Born approximations carried to the second order, to find the backscattering elements of the polarimetric matrices. It is found that 8 out of 16 elements of the Mueller matrix are identically zero, corresponding to a covariance matrix with four zero elements. Theoretical predictions are matched with experimental data for vegetation fields.

The volume scattering effects of snow-covered sea ice are studied with a three-layer random medium model for microwave remote sensing. The strong fluctuation theory and the bilocal approximation are applied to calculate the effective permittivities for snow and sea ice. The wave scattering theory in conjunction with the distorted Born approximation is then used to compute bistatic coefficients and backscattering cross sections. Theoretical results are illustrated by matching experimental data for dry snow-covered thick first-year sea ice at Point Barrow. The radar backscattering cross sections are seen to increase with snow cover for snow-covered sea ice, due to the increased scattering effects in the snow layer. The results derived can also be applied to the passive remote sensing by calculating the emissivity from the bistatic scattering coefficients.

A general mixing formula is derived for discrete scatterers immersed in a host medium. The inclusion particles are assumed to be ellipsoidal. The electric field inside the scatterers is determined by quasistatic analysis, assuming the diameter of the inclusion particles to be much smaller than the wavelength. The results are applicable to general multiphase mixtures, and the scattering ellipsoids of the different phases can have different sizes and arbitrary ellipticity distribution and axis orientation, i.e., the mixture may be isotropic or anisotropic. The resulting mixing formula is nonlinear and implicit for the effective complex dielectric constant, because the approach in calculating the internal field of scatterers is self-consistent. Still, the form is especially suitable for iterative solution. The formula contains a quantity called the apparent permittivity, and with different choices of this quantity, the result leads to the generalized Lorentz - Lorenz formula, the generalized Polder - van Santen formula, and the generalized coherent potential - quasicrystalline approximation formula. Finally, the results are applied to calculating the complex effective permittivity of snow and sea ice.

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

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

The Feynman diagrammatic technique is used to derive the Dyson equation for the mean field and the Bethe-Salpeter equation for the correlation or the covariance of the field for electromagnetic wave propagation and scattering in an anisotropic random medium. With the random permittivity expressed in a general form, the bilocal and the nonlinear approximations are employed to solve the Dyson equation and the ladder approximation to the Bethe-Salpeter equation. The mean dyadic Green's function for a two-layer anisotropic random medium with arbitrary three-dimensional correlation functions has been investigated with the zeroth-order solutions to the Dyson equation under the nonlinear approximation. The effective propagation constants are calculated for the four characteristic waves associated with the coherent vector fields propagating in an anisotropic random medium layer, which are the ordinary and extraordinary waves with upward and downward propagating vectors.

The vegetation canopy and snow-covered ice field have been studied with a three-layer model, an isotropic random medium layer overlying an anisotropic random medium. We have calculated the dyadic Green's functions of the three-layer medium and the scattered electromagnetic intensities with Born approximation. The backscattering cross sections are evaluated for active microwave remote sensing. The theoretical approach can be extended to derive the bistatic scattering coefficients. After integrating the bistatic scattering coefficients over the upper hemisphere and substracting from unity, we can also compute the radiometric brightness temperatures for passive microwave remote sensing by invoking the principle of reciprocity.

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K-distribution and polarimetric terrain radar clutter (H. A. Yueh, J. A. Kong, J. K. Jao, R. T. Shin, and L. M. Novak), submitted for publication in *Journal of Electromagnetic Waves and Applications,* 1988.

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