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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 72 refereed journal and conference papers for the research on the remote sensing of earth terrain.

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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