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ACTIVE AND PASSIVE REMOTE SENSING OF ICE

Under the sponsorship of the ONR contract N00014-89-J-1107, we have published 26 journal and conference papers and 3 student theses.

Fully polarimetric scattering of electromagnetic waves from snow and sea ice is studied with a layered random medium model and applied to interpret experimental data obtained under laboratory controlled conditions. The snow layer is modeled as an isotropic random medium. The sea ice is described as an anisotropic random medium due to the elongated form of brine inclusions. The underlying sea water is considered as a homogeneous half-space. The scattering effects of both random media are described by three-dimensional correlation functions with variances and correlation lengths corresponding to the fluctuation strengths and the physical geometry of the inhomogeneities, respectively. The strong fluctuation theory is used to calculate the effective permittivities of the random media. The distorted Born approximation is then applied to obtain the covariance matrix which describes the fully polarimetric scattering properties of the remotely sensed media.

During the winter of 1988 and 1989, fully polarimetric microwave measurements were made of artificial sea ice at frequencies of 1.8, 5, 10, and 35 GHz and incident angles ranging from 0° to 60° at a facility located at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). A 5 m × 15 m outdoor tank was filled with sea water to a depth of 1.2 m and the time evolution of the growth cycle of the sea ice was observed over two 2-month periods. Maximum ice thickness was 20 cm. During this investigation, continuous detailed scene characterizations were made. The standard array of physical property observations (i.e. fabric analysis, salinity, density, and temperature) were assembled and supplemented by location, description, and statistical analysis of internal inhomogeneities and surface roughness. To explain polarimetric scattering from the experimentally simulated bare sea ice, the two-layer configuration is used to model sea-ice layer over sea water. The distinction on the characteristics of the media are investigated with the conventional backscattering coefficients and the complex correlation coefficient ρ between σ_{hh} and σ_{vv}. For ice-type identification, the measured covariance matrices are studied with the model to infer the physical characteristics pertaining to the different ice types. The three-layer configuration is then used to investigate the effects on fully polarimetric radar returns from snow covered sea ice.

Accurate calibration of polarimetric radar systems is essential for the polarimetric remote sensing of earth terrain. A polarimetric calibration algorithm using three arbitrary in-scene reflectors is developed. The transmitting and receiving ports of the polarimetric radar are modeled by two unknown polarization transfer matrices. These unknown matrices are determined using the the measured scattering matrices from the calibration targets. A Polarization-Basis Transformation technique is introduced to convert the scattering matrices of the calibration targets into one of the six sets of targets with simpler scattering matrices. Then, the solution to the original problem can be expressed in terms of the solution obtained using the simpler scattering matrices. The uniqueness of polarimetric calibration using three targets is addressed for all possible combinations of calibration targets. The effect of misalignment of the calibration targets and the sensitivity of the polarimetric calibration algorithm to the noise are illustrated by investigating several sets of calibration targets in detail.

In the interpretation of active and passive microwave remote sensing data from earth terrain, the random medium model has been shown to be quite successful. In the random medium model, a correlation function is used to describe the random permittivity fluctuations with associated mean and variance. In the past, the correlation functions used were either assumed to be of certain form or calculated from cross sectional pictures of scattering media. In this paper, we calculate the correlation function for a random collection of discrete scatterers imbedded in a background medium of constant permittivity. Correlation functions are first calculated for the simple cases of the uniform distribution of scatterers and the uniform distribution with the hole correction. Then, the correlation function for a more realistic case is obtained using the Percus-Yevik pair distribution function. Once the correlation function is obtained, the strong fluctuation theory is used to calculate the effective permittivities. Then, the distorted Born approximation is used to calculate the backscattering coefficients from a halfspace configuration. The theoretical results are illustrated by comparing the effective permittivities and the backscattering coefficients with the results obtained with the discrete scatterer theory.

A multivariate K-distribution is proposed to model the statistics of fully polarimetric radar returns from earth terrain. 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 coventional 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 α. In the limit the parameter α approaches infinity, the multivariate K-distribution reduces to the multivariate Gaussian distribution. With the polarimetric covariance matrix and the α 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. 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 the α parameter is being investigated for various other radar clutter.

In the remote sensing of sea ice, there is considerable interest in identifying and classifying ice types by using polarimetric scattering data. Due to differences in structure and composition, ice of different types such as frazil, first-year, or multi-year can have different polarimetric scattering behaviors. To study the polarimetric response of sea ice, the layered random medium model is used. In this model, the sea-ice layer is described as an anisotropic random medium composed of a host medium with randomly embedded inhomogeneities, such as elongated brine inclusions, which can have preferred orientation direction. The underlying sea-water layer is considered as a homogenous half space. The scattering effect of the inhomogeneities in the sea ice are characterized by three-dimensional correlation function with variance and correlation lengths respectively corresponding to the fluctuation strength and the physical geometry of the scatterers. The effective permittivity of the sea ice is calculated with the strong fluctuation theory and the polarimetric backscattering coefficients are obtained under the distorted Born approximation. The distinction on the characteristics of different ice types are investigated with the conventional backscattering coefficients and the complex correlation coefficient ρ between

σ_{hh} and σ_{vv}. The correlation coefficient ρ contains additional information on the sea-ice structure and can be useful in the identification of the ice types. By relating to the covariance matrices, the model is used to explain the polarization signatures of different ice types. In the case of snow-covered sea ice, the snow layer is modeled as an isotropic random medium and the obtained solution accounts for the effect of snow cover on polarimetric scattering properties of sea ice.

We present an inversion algorithm based on a recently developed inversion method 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 Approach.

Tower-based measurements of EM bias in radar altimetry have been made using a 14GHz scatterometer in SAXON-CLT in 1988, and most recently using both 5GHz and 14 GHz scatterometers from a plafrom in the Gulf of Mexico. In SAXON the EM bias was found to be an increasing fraction of the significant wave height with increasing wind speed, or equivalently, decreasing radar cross section. Preliminary analysis of the simultaneous measurements at both frequencies in the Gulf show that the bias at C Band is qualitatively similar to that at Ku band in its dependence on wave height and wind speed. However, the C-band bias is approximately 20–25% greater at the higher values. These results are consistent with a two-scale model of microwave scattering from the ocean surface presented at this meeting. The implications of these results for operational radar altimetry are discussed.

As an electromagnetic wave propagates through a random scattering medium, 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. 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.

Strong permittivity fluctuation theory is used to solve the problem of scattering from a medium composed of completely randomly oriented scatterers under the low frequency limit. Based on Finkel'berg's approach [1964], Gaussian statistics is not assumed for the renormalized scattering sources. The effective permittivity is obtained under the low frequency limit and the result is shown to be isotropic due to no preferred direction in the orientation of the scatterers. Numerical results of the effective permittivity are illustrated for oblate and prolate spheroidal scatterers and compared with the results for spherical scatterers. The results derived are shown to be consistent with the discrete scatterer theory. The effective permittivity of random medium embedded with nonspherical scatterers shows a higher imaginary part than that of spherical scatterer case with equal correlation volume. Under the distorted Born approximation, the polarimetric covariance matrix for the backscattered electric field is calculated for the half-space randomly oriented scatterers. The nonspherical geometry of the scatterers shows significant effects on the cross-polarized backscattering returns σ_{hv} and the correlation coefficient ρ between HH and VV returns. The polarimetric backscattering scattering coefficients can provide useful information in distinguishing the geometry of scatterers.

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

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

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

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

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.

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

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

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

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

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

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

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

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

The normalized polarimetric classifier is proposed such that only the relative magnitudes and phases of the polarimetric data will be utilized to discriminate terrain elements. For polarimetric data with arbitrary probability density function (PDF), the distance measures of the normalized polarimetric classifier based on a general class of normalization functions are shown to be equivalent to one another. The normalized polarimetric classifier thus derived will be optimal among all normalization schemes, when the system absolute calibration factors are common to all polarimetric channels. Further assuming a multivariate complex Gaussian distribution for the un-normalized data, the distance measure of the normalized polarimetric classifier is given explicitly and turns out to be also independent of the number of scatterers. The usefulness of the normalized polarimetric classifier is demonstrated by the classification of trees and grass in the experimental data obtained from Lincoln Laboratory. The classification error is shown to be the smallest among those of magnitude ratio or phase difference classifications.

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