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REMOTE SENSING OF EARTH TERRAIN

Under the sponsorship of the NASA Contract NAGW-1617, the publication list includes 34 refereed journal and conference papers for the research on remote sensing of earth terrain.

The layered random medium model is used to investigate the fully polarimetric scattering of electromagnetic waves from vegetation. The vegetation canopy is modeled as an anisotropic random medium containing nonspherical scatterers with preferred alignment. The underlying medium is considered as a homogeneous half space. The scattering effect of the vegetation canopy are characterized by three-dimensional correlation functions with variances and correlation lengths respectively corresponding to the fluctuation strengths and the physical geometries of the scatterers. The strong fluctuation theory is used to calculate the anisotropic effective permittivity tensor of the random medium and the distorted Born approximation is then applied to obtain the covariance matrix which describes the fully polarimetric scattering properties of the vegetation field. This model accounts for all the interaction processes between the boundaries and the scatterers and includes all the coherent effects due to wave propagation in different directions such as the constructive and destructive interferences. For a vegetation canopy with low attenuation, the boundary between the vegetation and the underlying medium can give rise to significant coherent effects.

The model is used to interpret the measured data for vegetation field such as rice, wheat, or soybean over water or soil. The temporal variation of σ_{hh} and σ_{vv} of the X-band SAR data of rice fields shows a wide range of responses at different growth stages. From the data of wheat, recognizable changes of the angular and polarization behaviour of the backscattering coefficients are observed at X-band before and after the heading of the wheat. For soybean, the data collected during the growing season shows similar results

for both h- and v-polarizations. The observed effects on backscattering coefficients of the vegetation structural and moisture conditions at different growth stages can be explained by analyzing the different interaction processes pointed out by the model.

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. 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 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 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. It is also found that the α parameter appears to decrease from C- to P- band for forest, clear-cut area in the forest, and the desert area. 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 effects 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 is 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 co-variance 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.

Tower-based measurements of sea-state bias were made using a 14GHz scatteromter (Ku-Band) and a colocated IR wave gage during SAXON-CLT. The measured bias was found to be an increasing fraction of the significant wave height with increasing wind speed. The measurements are consistent with a two-scale model of the EM scattering from the ocean surface. The implications of the measurements for the improvement of sea-state bias algorithms are discussed. Preliminary results of a more recent series of tower-based measurements in the Gulf of Mexico at both Ku and C bands are presented.

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 also developed and applied to synthetic aperture radar polarimetric images in order to identify their various earth terrain components for more than two classes. For supervised classification processing, the Bayes technique is used to classify fully polarimetric and normalized polarimetric SAR data. Simpler polarimetric discriminates, such as the absolute and normalized magnitude response of the individual receiver channel returns, in addition to the phase difference between the receiver channels, are also considered. 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 of the transmitting and receiving polarization states. These classification procedures have been applied to San Francisco Bay and Traverse City SAR images, supplied by the Jet Propulsion Laboratory. It is shown that supervised classification yields the best overall performance when accurate classifier training data is used, whereas unsupervised classification is applicable when training data is not available.

Conventional classification techniques for identification of vehicle types from their range profiles, or pulse responses, have been shown to be limited in their practical ability to distinguish targets of interest. These limitations arise from the need for large signature libraries and time consuming processing for profile matching algorithms, and from the assumptions made toward the statistics of extracted features for parametric methods. To overcome the practical constraints of existing techniques, a new method of target recognition is examined which utilizes neural nets. The effectiveness of this neural net classifier is demonstrated with synthetically generated range profiles for two sets of geometries, as produced using RCS prediction techniques. The first set consists of three simple canonical geometries for which RCS predictions can be done directly. For these targets, two neural net configurations are compared, and the effects of varied aspect sampling density for the training profiles and noise corruption in the test profiles are demonstrated. Comparisons are made between the neural net classifier and several conventional techniques to determine the relative performance and cost of each algorithm. A similar set of comparisons is performed for the second group of targets consisting of more realistic air vehicle models, each composed from a collection of canonical shapes. In both cases, the neural net classifier is shown to match or exceed the performance of conventional algorithms while offering a more computationally efficient implementation.

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, 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.

A multivariate K-distribution, well supported by experimental data, is proposed to model the statistics of fully polarimetric radar clutter of earth terrain. In this approach, correlated polarizations of backscattered radar returns are characterized by a covariance matrix and homogeneity of terrain scatterers is characterized by a parameter α. As compared with C-, L- and P-band polarimetric SAR image data, simultaneous measured by Jet Propulsion Laboratory (JPL). α appears to decrease from C- to P- band for the forest, burned forest, and desert areas.

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 scatterer sizes and the permittivity fluctuation strengths. Based on the wave theory with Born approximations carried to the second order, this model is utilized 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 phase fluctuations of electromagnetic waves propagating through a scattering medium, such as a forest, is studied with the random medium model. Determination of the effectiveness of the synthetic aperture radar (SAR) in detecting and imaging objects within the scattering medium is of many practical interest. As an electromagnetic wave propagates through the scattering medium, its energy is attenuated and a random phase fluctuation is introduced. The magnitude of the random phase fluctuation introduced is important in estimating the effectiveness of SAR imaging techniques for objects within the scattering medium. The phase degradation of the one-way problem, i.e, transmitter outside the scattering medium and receiver inside the scattering medium, is investigated.

The two-layer random medium model, consisting of a scattering layer between free space and ground, is used to calculate the phase fluctuations introduced between a transmitter located above the random medium and a receiver located within the random medium. The random medium's scattering property is 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 the large permittivity fluctuations of the scatterers. The distorted Born approximation is then used in the past to calculate the backscattering coefficients. In calculating the phase fluctuations of the received field, a perturbation series for the phase of the received field is introduced and solved to first order in permittivity fluctuations.

Phase fluctuations are first calculated for the case of the transmitter located directly over the receiver, which corresponds to the normal incidence case. The first-order scattered field normalized to the zeroth-order transmitted field is calculated using the Green's function for the unbounded medium (thereby neglecting boundary effects). The variance of the normalized scattered field at the receiver is computed, which can be directly related to the magnitude of the phase fluctuations. The results obtained under these approximations are then compared to the results obtained using the paraxial approximation. The results are then extended to account for the effects of boundaries by using the two-layer Dyadic Green's function. Extension of the results to oblique angles of incidence and multilayer random media will also be discussed. The theoretical results will be illustrated by comparing the calculated phase fluctuations and attenuation of the electromagnetic waves propagating through the random medium to the available experimental data over forested areas.

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.

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.

Polarimetric radar backscatter data observed with satellite and airborne synthetic aperture radars (SAR) have demonstrated potential applications in geologic mapping and terrain cover classification. Accurate calibration of such polarimetric radar systems is essential for polarimetric remote sensing of earth terrain. A polarimetric calibration algorithm using three in-scene reflectors is developed which will be a useful tool in the radar image interpretation. The transmitting and receiving ports of the polarimetric radar are modeled by two unknown polarization transfer matrices. The measured scattering matrix is equal to the product of the transfer matrix of the receiving port, scattering matrix of the illuminated target, the transfer matrix of the transmitting port, and a common phase factor. The objective of polarimetric radar calibration is to determine these two unknown

polarization transfer matrices using measurements from targets with known scattering matrices. The transfer matrices for the transmitting and receiving ports are solved in terms of measurements from three in-scene reflectors with arbitrary known scattering matrices. The solutions for several sets of calibration targets with simple scattering matrices are first presented. Then, the polarimetric calibration using three targets with general arbitrary scattering matrices is derived using the method of simultaneous diagonalization of two matrices. A transformation matrix is found to convert the general scattering matrices into the simple cases, and the problem is solved in the transformed domain. The solutions to the original problem then can be expressed in terms of the solutions obtained for the simple 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 are known to exist within a radar image, then the whole image can be calibrated using the exact solution presented. The effects of misalignment of calibration targets and of receiver noise are also illustrated for several sets of calibration targets.

Polarimetric terrain backscatter data observed with satellite and airborne synthetic aperture radars (SAR) have demonstrated potential applications in geologic mapping and terrain cover classification. In previous publications on this subject, Gaussian statistics have been frequently assumed for the radar return signals to build the Bayes terrain classifier. However, abundant experimental evidence shows that the terrain radar clutter is non-Gaussian, i.e., non-Rayleigh in amplitude distribution. Among many non-Gaussian statistics, the K-distribution has proven to be useful in characterizing the amplitude distribution of electromagnetic echoes from various objects, including diverse ground surfaces, sea surface and wave propagation through atmospheric turbulence.

A multivariate K-distribution is proposed to model the statistics of fully polarimetric radar 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. The results are illustrated by comparing the higher-order normalized intensity moments and cumulative density functions (CDF) of the experimental data with theoretical results of the K-distribution.

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Measurements of sea-state bias at Ku and C bands (W. K. Melville, R. H. Stewart, J. A. Kong, W. C. Keller, D. Arnold, A. T. Jessup, and E. Lamarre), OCEANS'90.

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