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Extended Ecosystem Signatures with Application to Eos Synergism Requirements

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Extended Ecosystem Signatures with Application to Eos Synergism Requirements

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1.0 Introduction

The primary objective of this study is to define the advantages of synergistically combining optical and microwave remote sensing measurements for the determination of biophysical properties important in ecosystem modeling. This objective has been approached in a stepwise fashion starting with ground-based observations of controlled agricultural and orchard canopies and progressing to airborne observations of more natural forest ecosystems. This observational program is complemented by a parallel effort to model the visible reflectance and microwave scattering properties of composite vegetation canopies. The goals of the modeling studies are to verify our basic understanding of the sensor-scene interaction physics and to provide the basis for development of inverse models optimized for retrieval of key biophysical properties. These retrieval algorithms can then be used to simulate the expected performance of various aspects of Eos including (1) the need for simultaneous SAR and HIRIS observations or justification for other (non-synchronous) relative timing constraints and (2) the frequency, polarization and angle of incidence requirements for accurate biophysical parameter extractions.

This final report covers the period of performance from June 1987 to June 1993. During this period, the following institutions received support or collaborated with the University of Michigan on this effort:

Aster Consulting
Duke University
Environmental Research Institute of Michigan
Fresno State
George Washington University
Jet Propulsion Laboratory
NASA Ames Research Center
University of California at Davis
University of Nebraska
University of Wisconsin

Support from this project has contributed to 6 PhD degrees and funded the efforts of over 40 other graduate and undergraduate research assistants. The results of this research have been distributed via 119 papers including: theses, technical reports, symposia, and journal articles. These are listed in Section 3. In addition, the MIMICS computer code for microwave scattering from vegetation has been presented at several workshops and installed, at no cost, at over 20 sites in the North America, Europe, Asia and Australia.

2.0 Synopsis of Research Results

This program completed a very successful series of truck-mounted experiments, made remarkable progress in development and validation of optical reflectance and microwave scattering models for vegetation, extended these results through airborne experimentation, expanded the scattering models to accommodate discontinuous and periodic canopies, developed inversion approaches for surface and canopy properties and disseminated these results widely through symposia and journal publications. In addition, the third generation of the computer code for the microwave scattering models has been provided to a number of other US, Canadian, Austrtalian and European investigators who are currently presenting and publishing results using the MIMICS research code.

2.1 Ground-Based Experiments

A highly successful field experiment was conducted in the summer of 1987 in a walnut orchard at the Kearney Agricultrual Field Station near Fresno, California. This experiment and follow-up studies have involved over 50 researchers from 11 institutions (The University of Michigan, the University of Nebraska, the University of California at Davis, the University of Wisconsin, Duke University, George Washington University, Fresno State, ERIM, the Jet Propulsion Laboratory, Ames Research Center and Aster Consulting). In this experiment, the orchard was monitored over a several week period in mid-summer by boom-mounted optical radiometers (Barnes MMR) and polarimetric microwave scatterometers (L-, C- and X-band range-probing, scatterometers). The observations were made in a continuous fashion over adjacent diurnal periods such that temporal changes in optical reflectance and/or radar backscattering could be correlated with temporal variations in canopy conditions. Key to the experiment was a thorough suite of observations of the canopy biophysical variates including: biomass (total and by canopy component such as trunks and branches), leaf area index, size and orientation distributions of foliage and woody components, the moisture status of vegetation components (gravimetric moisture and water potential), soil properties (surface roughness, bulk density and moisture distribution), optical reflectance and transmittance properties of the soil and vegetation components, and the microwave dielectric properties of the soil and vegetation components. This experiment has now been extensively reported in the literature in terms of the objectives, data and findings.

The walnut experiment has produced a number of significant findings. Optical reflectance is shown to vary over the day, but only in response to changes in solar zenith angle. Consequently, preferred observation times for HIRIS in the optical region are not driven, in this case, by diurnal changes in canopy properties. Thus, no case can be made for simultaneous observation of vegetated terrain by HIRIS and SAR. As a result, HIRIS timing should be linked to expected minima in local cloud-cover.

In contrast, the microwave backscattering from the orchard exhibited pronounced diurnal fluctuations in response to variations of soil and canopy water status. Tests of a novel method for nondestructive, *in situ* measurement of the microwave dielectric constant of woody components of the walnut trees demonstrated that circadian patterns of water flow and distribution are the primary causative factors leading to diurnal variation in radar backscattering of 2 dB to 3 dB. An important technical result of this study is that while the signal from the Eos SAR can be expected to be diurnally variant in response to changes in canopy and substrate moisture conditions and changes in leaf angle distributions (at high frequencies) for heliotropic plants, these variations are shown to be relatively continuous in nature with certain notable exceptions. Truck-mounted scatterometer data and polarimetric AIRSAR data (from other experiments) demonstrate that certain meteorologic events (i.e., rain) and anthropogenic activities (i.e., tillage and harvest) induce an immediate change in radar backscattering.

2.2 Model Development and Validation

In addition, great progress has been made in the development and validation of models to predict radar backscatter and optical reflectance on the basis of measurable biophysical attributes. The one-dimensional Cupid model predicts bidirectional reflectance functions which agree very closely with the MMR measurements of the walnut orchard. In the microwave region, MIMICS I, a first-order, vector radiative transfer model, is found to predict the observed L-band backscattering coefficient to within better than 1 dB and closely matches the observed diurnal variations at all polarizations. Despite this excellent agreement at L-band, some of the model assumptions begin to break down at higher frequencies (X-band); and it is apparent that single-scattering theory is insufficient to explain X-band cross-polarized backscattering in particular.

2.3 Airborne Experiments

In an effort to extend the preceding findings from an "engineered" orchard to conditions more representative of a natural forest ecosystem, a multidate airborne SAR experiment was undertaken in July through September of 1989 using the JPL AIRSAR. Approximately 20 researchers from the University of Michigan, ERIM, Duke University, JPL and the University of California at Davis collected extensive ground-level observations from 60 forest stands at the Duke University Research Forest. These even-aged stands of primarily loblolly pine are distributed over two soil types and ranged in age from seedlings to about 80 years. Microwave dielectric measurements made *in situ* in living loblolly trunks were used to investigate the variation in the dielectric constant as a function of depth into the trunk tissue, as a function of height and as a function of time over several diurnal periods. These measurements, made at P-, L-, C- and X-bands, show diurnal variations which are highly correlated with tree physiologic properties such as stem water-potential and transpiration which, in turn, are linked to cloud-cover and incident solar radiation.

In early September, the JPL AIRSAR overflew the Duke Research Forest with 12 identical passes 20 minutes apart from noon until about 4:00 pm and again the next morning with 3 passes from 8:00 am to 9:00 am. Radar backscatter simulations with MIMICS I using the measured tree structural and dielectric properties over the experimental period show a diurnal variation of generally less than 1 dB at P-, L- and C-bands for the forest stands of loblolly pine. These model expectations are congruent with externally calibrated AIRSAR observations. Since the uncertainties in mean radar backscattering coefficient related to coherent fading and calibration accuracy are both on the order of +/- 1 dB, the observed temporal variation in radar backscattering from these forest stands is not very significant. While the humid loblolly pine forest of North Carolina did not exhibit significant diurnal variation in radar backscattering coefficient, this forest was clearly not moisture-stressed. Hence, care must be taken in extrapolating these results to other forest environments. However, it is clear from the dielectric and radar evidence collected to date that, for studies seeking to maximize sensitivity to circadian patterns in plant water status, Eos SAR passes close to (or shortly after) solar noon and again pre-dawn would be the preferred times.

Recent comparisons of calibrated backscattering coefficients extracted from AIRSAR data for the Duke forest loblolly pines with similar data for maritime pines of the Landes Forest near Bordeaux, France show very strong correlations with aboveground biomass at P- and L-bands, especially for H-polarized terms. The power-law relationship between backscattering and biomass is found to be identical for both species for all polarizations except at C-band (where one specie is offset by 1dB to 2 dB relative to the other). The long wavelength response is the same for both species because the trunk and branch architectures of the two species are similar. The differences at C-band are attributable to inter-specie differences in the size, orietation and density of needles. Importantly, this power-law relationship at long wavelengths is predicted by MIMICS.

2.4 Extension of MIMICS to Open Canopies

The MIMICS I model assumes a vegetation canopy to be comprised of three statistically homogeneous random layers. The scattering elements in the crown and trunk layers are uniformly distributed over a dielectric half-space with a rough surface. As a consequence, the model is only applicable to "closed-canopy" conditions meaning there are no gaps in the crown. The crown constituents, foliage and branches, are modeled as dielectric discs or needles and smooth dielectric cylinders, respectively. The trunk layer is assumed to consist of a size distribution of homogeneous dielectric cylinders. The air-crown and crown-trunk interfaces are treated as diffuse boundaries. Since the relative volume fraction of canopy elements is low (<<1%), the phase and extinction matrices in the radiative transfer formulation are derived using the single scattering approximation.

The "closed-canopy" assumption of MIMICS I is often violated in natural ecosystems where there may be gaps in the crown due to mortality and uneven seedling establishment or due to a mix of plant species with very different growth habit. In order to generalize MIMICS, we have developed MIMICS II which treats the case of a discontinuous crown layer. MIMICS II considers two sets of random variables: (1) tree-level random variables which characterize the scattering elements within the crown section of individual trees and (2) canopy-level random variables which characterize the variability among trees (such as the heights of trees, the sizes and shapes of crown sections for each tree, and the locational distribution of trees). Tests of MIMICS II show that, for forest stands characterized by a crown layer with low particle density (that is few branches and leaves), the model yields results not significantly different than those of MIMICS I. As the particle density within individual crowns increases, the two models diverge especially at high frequencies. At low frequencies (such as P-band) and incidence angles away from nadir, even trees with well-developed crowns yield nearly identical model predictions using the continuous or discontinuous canopy formulation. Since MIMICS II is much more computationally intensive, it is important to know that the MIMICS I assumption of a "closed-canopy" is adequate at low frequencies.

Both MIMICS I and II assume that individual plants are randomly distributed. In many agricultural crops, orchards and tree plantations, the locations of individual plants are not randomized, rather there is a periodic organization in at least one lateral dimension. MIMICS III has been developed to treat these cases. It has been successfully tested against data obtained from corn fields by the University of Michigan's truck-mounted POLARSCAT during the summer of 1990.

The MIMICS models have shown remarkable success in predicting the radar response of vegetation canopies, particularly at L-band. Despite its success, MIMICS has a number of inherent limitations and deficiencies.

2.5 MIMICS Augmentations

Extension to Second Order

Whereas at L-band the backscattering contributions of the leaves and branches in the crown layer are secondary in importance in comparison to the contributions to net backscattering by the trunk and ground layers, the leaves and branches become equally important, and sometimes dominant contributors, at higher frequencies (X-band). Hence, at L-band it is sufficient to account for only first-order scattering by the leaves and branches, but this is not the case at X-band, particularly for the cross-polarized component of the backscattering coefficient. This is evidenced by the poor agreement between the MIMICS I predictions of the cross-polarized response and experimental data for the walnut orchard at X-band. In part, this is a consequence of the size distributions of the foliage and branches becoming comparable to or greater than wavelength. Moreover, even at low frequencies (P- and L-band), the inclusion of second-order interactions between the trunks and the ground surface (trunk-trunk-ground, trunk-ground-trunk, and ground-trunk-trunk contributions) are found to improve the accuracy of MIMICS.

Improvement of Constituent Scattering Models

In MIMICS, as well as in all other available vegetation scattering models, the leaves are treated as flat disks and the branches as straight, smooth cylinders or ellipsoids at low frequencies. In reality, leaves are not flat, and the needles may be comparable to or longer than wavelength over the desired frequency range. Models have been developed for both curved leaves and long needles. Results show the reduction in radar cross section is a function of the radius of curvature relative to wavelength.

A model has also been developed for scattering by a multi-layered rough dielectric cylinder which is a more realistic representation of the dielectrically non-homogeneous bark and inner core of trunks and major branches. For the cases tested to date, the use of a two-layer corrugated cylinder model leads to a reduction in radar cross-section.

In many cases, dihedral-like multiple specular scattering mechanisms (such as ground-trunk) dominate the net backscatter from the forest. This is particularly true at long wavelengths. Laboratory based scatterometer measurements verify the importance of the roughness of the surface layer in controlling specular scattering. This roughness dependence is modeled and incorporated into MIMICS.

Derivation of Phase Statistics from Canopy Models

Since phase data is available directly from the output of polarimetric SARs, the information contained in the relative phase differences between polarization states can be used to infer information about the canopy. Because scattering models based upon radiative transfer do not provide phase information directly, it has not been possible to compare distributions of phase data to theoretical expectations. A technique has been developed that provides the phase difference statistics completely from the averaged Mueller matrix produced by the scattering model. Examination of the phase difference statistics obtained from the canopy models based on this technique compare favorably with scatterometer and AirSAR observations.

2.6 Model Inversions

Since canopy models, such as MIMICS, are usually complicated and highly non-linear functions of the desired biophysical parameters, direct inversion of these models are not straightforward. A standard approach for inversion of such models is an optimization technique that starts with an initial estimate of scene parameters and searches for convergence upon an acceptable solution via an iterative process. Such optimization techniques require calculation of the direct scattering problem many times before converging upon the solution. Because of the complexity of the vegetation scattering models, this is a computationally inefficient process. Three alternative approaches have been investigated: (1) artificial neural networks, (2) an empirical iterative approach and (3) a semi-empirical approach. The first two of these approaches use MIMICS to simulate a data sets over a ranges of scene conditions which are impractical to collect by airborne experimentation. These simulated data sets contain subsets which cover the available airborne SAR observations.

Artificial Neural Network Approach

In the past few years, the artificial neural network has been applied to several types of remote sensing problems. Neural networks offer three major advantaged over other inversion approaches. The first is the massive parallelism used in neural networks which provides higher computational rates than can be provided by serial computation. The second advantage is that the algorithms for hte neural network are very general and cna be used as a "black box" for any desired model or sets of input-output data. The third advantage is that neural network software is widely available.

Initial attempts to train a neural network using actual SAR data for the Duke Forest data set met with only limited success. We suspect that this is in part due to the narrow range of scene conditions present within that data set. As a consequence, we trained the neural network using data simulated by MIMICS over a much broader range of conditions using the backpropagation learning algorithm. The qualitative and quantitative performance of the network is found to yield promising results for the determination of forest biophysical properties such as biomass, stem density, basal are and height.

Empirical Iterative Approach

A canopy model can be viewed as a mult-valued, nonlinear continuous vector function. The choice of the output vector, and therefore the function itself, is at the discretion of the system designer, while the variables of the function and their domain is specified by the canopy configuration. The quantities measured by a polarimetric SAR are the amplitude and phase of the two co-polarized and two cross-polarized channels for any desired number of frequencies and incidence angles. Frequency and incidence angle must be selected such that the scattering model shows the maximum sensitivity to the parameters of interest. If the function is one-to-one over the desired domain of he input parameters, then invertibility and uniqueness of the inverse solution are guaranteed. The canopy models are not, in general, one-to-one functions; however, they are usually very smooth functions of the input parameters and do not show any strong resonance behavior. Consequently, the parameter space may be divided into some finite subspaces for which the function is one-to-one. Another difficulty in finding the inverse function is that the function is nonlinear in most cases. A linear system of equations is the only vector function that can be inverted exactly and systematically. It would then be desirable to find some transformation of the system response into a region over which the behavior is approximately linear. This forms the basis of the iterative inversion algorithm which works with the piecewise linear function.

For polarimetric SAR data available over a range of incidence angles, the data may be represented in terms of a Fourier series in the restricted angular range. The behavior of the Fourier coefficients as a function of the canopy parameters provide a convenient measure of the system response that is independent of incidence angle. Since the angular dependency of radar backscatter away from nadir is smooth, only the first few terms in the Fourier series are needed to represent the function. If the behavior of each Fourier component is known in terms of the canopy parameters, then we have an empirical model that describes the the scene behavior in detail. The functional form of the Fourier coefficients might be nonlinear which can be piecewise linearized over nested subdomains in the parameter space. The resulting sets of linear equations are directly invertible; and by means of a iterative process that successively converges on smaller domains, a solution set can be found.

Results obtained with this approach on a simple canopy model indicates that the algorithm is very efficient and fast, once the subdomains and linear functions are obtained. The advantage of this method over the neural network approach is that here a set of measurables can be chosen for inversion for which the maximum sensitivity to the desired parameters exist.

Semi-Empirical Model for Retrieval of Soil Properties

A third approach uses a semi-empirical model to estimate near-surface soil moisture and surface roughness from multi-polarized radar backscatter. The model is based upon backscatter data obtained from bare soil surfaces by truck-mounted polarimetric scatterometers. The approach uses polarization ratios in a semi-empirical formulation to yield estimates of soil dielectric properties and RMS roughness of the air/soil interface. Soil moisture is inferred from the estimate of the relative dielectric constant. The model performs very well for scatterometer data and is in the process of being validated for airborne SAR data acquired in Michigan, Oklahoma and California in collaboration with NASA Goddard Space Flight Center and the Jet Propulsion Laboratory.

2.7 User Friendly MIMICS Code

MIMICS has been distributed *gratis* to a large number of research institutions including: the Jet Propulsion Laboratory, the Canadian Center for Remote Sensing, the University of Guelph, Laval University, Goddard Space Flight Center, the Environmental Research

Institute of Michigan, Paul Sabatier University, Stanford University, the Joint Research Center of the EC at Ispra, and the University of Stuttgart among others. As initially distributed, MIMICS is a research code which contains a library of numeric computational modules describing the various scattering models for surfaces and vegetation. However, as a research code, these numeric modules are somewhat incompatible and not at all "user-friendly". The modules do not take advantage of recent developments in parallel computation, computer network technology, or artificial intelligence. As a result, it was felt that many potential academic researchers could not take full advantage of MIMICS (I to III).

A portable, integrated user interface and analysis package was developed for the MIMICS models. This package is now available for wider distribution to other institutions interested in incorporating the software into their educational or research acitivities. This package is highly portable to all UNIX-based platforms, and employs a variety of software components for analysis, inference and visualization of data.

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