CONTINUATION PROPOSAL OF NASA GRANT NAGW-4555

DIGITAL TOPOGRAPHY FROM SAR INTERFEROMETRY: DETERMINATION OF AND CORRECTION FOR VEGETATION HEIGHT

Submitted to :
Code YS/ NRA-97-MTPE-08
Office of Mission to Planet Earth
NASA Headquarters
300 E. Street SW
Washington D.C. 20546
Attention: Dr. Diane Wickland

Submitted by:
Kamal Sarabandi (PI),
Craig Dobson (Co-I),
Radiation Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109-2122
Tel: (313) 764-0500, Fax: (313) 747-2106

Robert Treuhaft and Jakob J. van Zyl (Co-Is)
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

and
David Harding (Co-I)
NASA Goddard Space Flight Center
Geodynamics Branch
Mail Code 921
Greenbelt, MD 20720

Project Duration: March 15, 1998 to March 14, 2001

33273-1-T = RL-2458

DIGITAL TOPOGRAPHY FROM SAR INTERFEROMETRY: DETERMINATION OF AND CORRECTION FOR VEGETATION HEIGHT

Abstract

In this proposed investigation theoretical and experimental studies will be carried out to demonstrate the potential of SAR interferometry and polarimetry in determining the spatial organization and retrieving the physical parameters of vegetation canopies. During Phase I of this investigation (March 1995- present), we have focused our efforts on the development of basic understanding of the problem which includes: 1) development of simple theoretical models capable of relating vegetation parameters to the interferogram phase and correlation coefficient, 2) conducting field experiments using JPL TOPSAR over more than 30 forest stands (physical parameters of these stands and their ground surface topography are measured very accurately), 3) establishing a fundamental relationship between spatial and frequency interferometry (relationship between INSAR and Δk-radar) which is of great importance in characterizing the scattering phase center using numerical simulations or conducting experiments using wideband scatterometers, 4) development and verification of a high fidelity coherent scattering model capable of predicting the interferometric and polarimetric responses of tree canopies over a wide frequency range (P- to X-band). Simulation and experimental results show that the location of scattering phase center (canopy height measured by an INSAR) is a strong function of tree type and its structure. Extremely encouraged by the outcome of our research activities over the past two years, we propose to extend the goal of this study by incorporating radar polarimetry and radar interferometry and/or multi-frequency radar interferometry data to extract important structural and physical parameters of forest canopies. The proposed research plan for Phase II consists of three major activities. The first activity pertains to the development and validation of semi-empirical models for tree structure of interests derived from the Monte Carlo coherent scattering model. These models are amenable to inversion processes which require efficient calculation of backscattering coefficients and the scattering phase center height. Validation will be done using existing TOSAR, AIRSAR, and SIR-C data over our two well-characterized sites: the Raco Supersite and the NSF Long Term Ecological Research Site at the Kellogg Biological Station near Kalamazoo, Michigan. The second activity involves the development of a general inversion algorithm based on a Genetic Algorithm (a stochastic optimization technique) for estimation of canopy parameters from an arbitrary set of polarimetric and interferometric data. This algorithm is specifically useful for the problem at hand as it searches for the global minimum and provides a set of optimum solutions. The third activity is to implement the forest stands of BOREAS sites for which extensive ground-truth data and polarimetric and interferometric SAR data exist. In this effort we are also planning to incorporate the laser altimeter canopy height data taken by SLICER. Activities related to lidar data fusion is very much in concert with the upcoming Vegetation Canopy Lidar (VCL) mission.

Contents

1 Background and Objectives

Accurate estimation of gross forest parameters such as total vegetation biomass, total leaf area index, and tree height in global scale has long been an important goal within the remote sensing community. Over the past two decades much efforts have been devoted to the development of scattering models [1, 2, 3], for understanding of interaction of electromagnetic waves with vegetation, and to the construction and development of advanced imaging radars for acquiring test data and and examining the feasibility of the remote sensing problem [4]. In most practical situations the number of vegetation parameters influencing the radar response usually exceeds the number of radar observation parameters. For this reason the application of multi-frequency and multi-polarization radar systems was proposed and such system was flown aboard the Shuttle Endeavor in April and October 1994 [4]. Preliminary results indicate that the classification and retrieval of vegetation biophysical parameters indeed require many simultaneous radar channels, however, free-flight of such systems is not practical due to the exorbitant power requirements.

Characterization of the spatial organization of particles in a vegetation canopy is of great importance determining many ecosystem processes including energy and chemical exchanges. Traditional remote sensing instruments provide two-dimensional spatial information of the target which may contain, depending on the instrument, some information vertical particle arrangement in a convoluted fashion. Recent advancements in the field of radar interferometry have opened a new door to the radar remote sensing of vegetation. In addition to the backscattering coefficient of a distributed target, radar interferometers provide two additional parameters that contain information about the target. These parameters are the correlation coefficient and the interferogram phase [5, 6]. To interpret these parameters and to characterize their dependency to the physical parameters of the target, a thorough understanding of coherent interaction of electromagnetic waves with vegetation particles is required. The premise of this investigation with regard to retrieving vegetation parameters from INSAR data stems from the fact that the location of scattering phase center of a target is a strong function of the target structure. For example the scattering phase centers of non-vegetated terrain are located at or slightly below the surface depending upon the wavelength and the dielectric properties of the surface media. Whereas for vegetated terrain, these scattering phase centers lie at or above the surface depending upon the wavelength of the SAR and the vegetation attributes. It also must be recognized that the vegetation cover in many interferometric SAR applications where the vegetation itself is not the primary target, such as geological field mapping or surface change monitoring, acts as an interference. In these cases it is also important to identify and characterize the effect of vegetation on the topographic information obtained from the interferometric SAR.

The overall objectives of the proposed study are to:

1. Quantify the role of vegetation attributes in determining the location of the scattering phase centers as measured by SAR interferometry using theoretical and Monte Carlo based coherent electromagnetic scattering model for vegetation.

2. Examine the utility of the combination of SAR interferometry and polarimetry for estimating the vegetation and surfaces parameters.

3. Determine the significance of polarimetric SAR interferometry, using the Monte Carlo model and existing SIR-C repeat-pass data.

4. Map vegetation height and crown layer vegetation attributes, including vegetation structure, through the combined use of multi-incidence angle and/or multi-frequency SAR interferometry in conjunction with available radar backscatter coefficients.

5. Correct SAR interferometry for vegetation effects through use of an inversion algorithm based upon vegetation type and biomass. The end product is surface elevation.

6. Examine the application of ancillary data such as canopy laser altimeter for enhancement and/or for verification of vegetation parameter estimation.

7. Integrate the products derived from SAR interferometry into ecophysiological classifications and forest biophysical parameter estimations.

This study proposes to meet these objectives using a methodology that treats the problem both theoretically and experimentally. Monte Carlo simulations of the forward problem, that includes multiple scattering between vegetation elements up to second order, will be used to understand the roles of both sensor parameters (wavelength, polarization and angle of incidence) and vegetation attributes (type, quantity and dielectric properties) in determining the location of the scattering phase centers. Experimental efforts will be mounted at three well-characterized sites: the Raco Supersite used by SIR-C/X-SAR, the NSF Long Term Ecological Research Site at the Kellogg Biological Station near Kalamazoo, Michigan, and BOREAS sites. These sites represent a wide range of vegetation conditions. The Raco and BOREAS sites are largely forested and KBS is mostly agricultural. These studies utilize TOPSAR, AIRSAR, SIR-C, and SLICER data both to verify theoretical efforts and to provide for application development and testing.

2 Summary of Phase-I Accomplishments

In March, 1995, the University of Michigan, in collaboration with the Radar Science Group of Jet Propulsion Laboratory, was awarded a three-year grant by the Terrestrial Ecology Program at NASA Headquarters to characterize and quantify the role of vegetation attributes in determining the scattering phase centers as observed by interferometric SARs. For this purpose analytical, numerical, and experimental aspects of electromagnetic scattering from forest canopies have been under investigation over the past two years. We shall refer to this segment of the overall program as Phase I and to the proposed contribution as Phase II. A summary of accomplishments realized to date during phase I is given next.

2.1 Theoretical Model Development

2.1.1 Δk Radar Equivalence of an INSAR

A fundamental relationship between INSAR and Δk radar is established. This relationship is the cornerstone of analytical and numerical analysis of the problem at hand. Understanding the relationship between the tree height and the corresponding location of the scattering phase centers requires numerical simulations (Monte Carlo simulation of a fractal generated forest stand) or controlled experiments using scatterometers. The scattering phase center of a target can also be obtained using a Δk-radar assuming that the incidence angle is known. Evaluation of the scattering phase centers using frequency shift can easily be accomplished in a numerical simulation or in a controlled experiment using a wideband scatterometer. Basically by requiring the backscatter phase differences, once obtained from a small change in the aspect angle and the other one obtained from a small change in the frequency of operation, be identical for both approaches we established that

$$\Delta f = f_0 \frac{B}{2r} \sin(\theta - \alpha_0) \tag{1}$$

where Δf is the frequency shift of the equivalent *Deltak* radar, f_0 is the operating frequency, B and α_0 are, respectively, the baseline distance and angle, r is the slant range, and θ is the look angle. It is mathematically proven that this equivalence relationship is valid for multiple scattering among particles and the scattering interaction between particles and the ground plane. The details are reported in reference [7].

2.1.2 Statistical Analysis

In estimating the height of the scattering phase center of a distributed targets, random fluctuations of the calculated/measured phase due to fading was investigated. An analytical form for the p.d.f. of the interferogram phase was obtained in terms of two independent parameters: (1)ζ: mean phase and (2)α: degree of correlation, which is given by

$$\begin{aligned} f_\Phi(\phi) = & \frac{1-\alpha^2}{2\pi\left[1-\alpha^2\cos^2(\phi-\zeta)\right]} \\ & \cdot \left\{ 1 + \frac{\alpha\cos(\phi-\zeta)}{\sqrt{1-\alpha^2\cos^2(\phi-\zeta)}} \left[\frac{\pi}{2} + \tan^{-1} \frac{\alpha\cos(\phi-\zeta)}{\sqrt{1-\alpha^2\cos^2(\phi-\zeta)}} \right] \right\} \quad , \end{aligned} \tag{2}$$

ζ is proportional to the mean scattering phase center height and α is inversely proportional to the uncertainty with which ζ can be estimated. It is shown that α is directly related to the frequency correlation function (FCF) of the distributed target given by

$$\alpha = \frac{|<E_1 E_2^*>|}{<|E_1|^2>} \tag{3}$$

Using this pdf the uncertainty in estimation of ζ, or equivalently the mean height, from a single pixel can be evaluated. Figure 1 shows the phase uncertainty range for 80% and 90% confidence criteria [7]. Statistical analysis shows that the uncertainty in the height estimation of a distributed target is a function of equivalent frequency decorrelation bandwidth and is independent of the baseline distance.

2.1.3 Vegetation Model

Theoretical vegetation models capable of predicting backscattering coefficients and location of scattering phase center for simple canopy structures (homogeneous particle distribution) were developed [7, 10]. It is also shown that for a uniform closed canopy the extinction and the physical height of the canopy top can be estimated provided that the correlation coefficient (α) can be measured very accurately. For example for a dense canopy it is found that the extinction

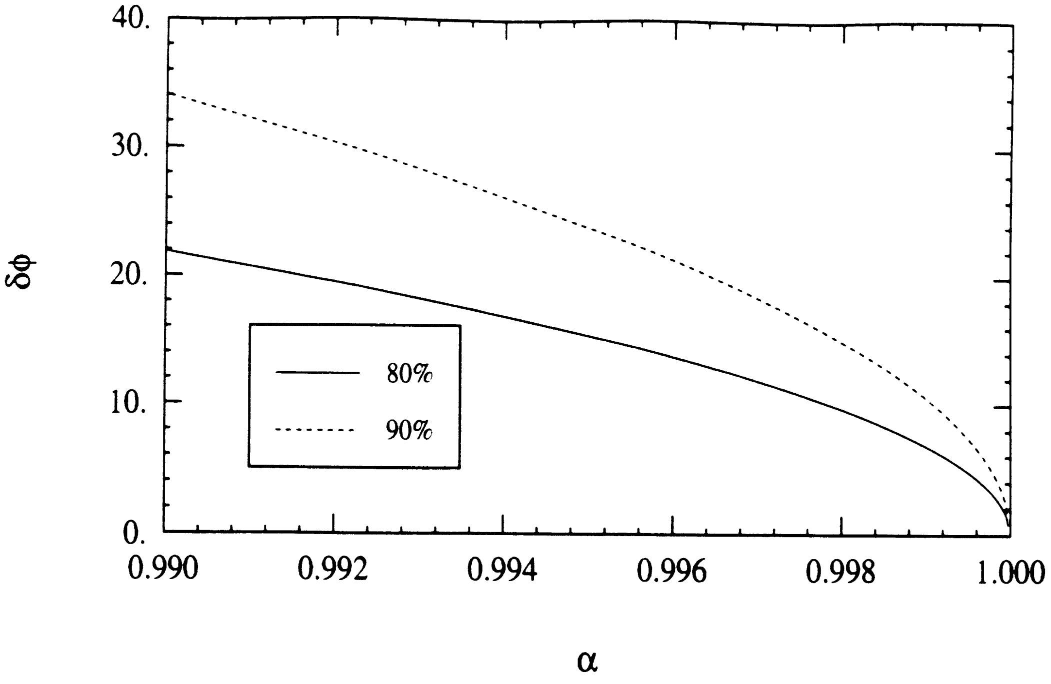


Figure 1: The phase uncertainty for 80% and 90% error probability criteria as a function of α.

coefficient can be directly obtained from α. Also the location of scattering phase center (from the canopy top) is given by the following simple relationship:

$$\Delta d = \frac{\cos\theta}{2\kappa}. \tag{4}$$

However, for finite canopies, estimation of extinction and scattering phase center is not straitforward. Using the model developed in [10], the estimation of tree height and surface topography was attempted. It was shown that measurements of interferometric phase and amplitude were not enough to estimate the three relevant parameters, which are the tree height, ground-surface altitude, and extinction coefficient, if only volume scattering (from the leaf-branch-trunk canopy) is considered. The first demonstration was therefore supplemented with *in situ* extinction coefficient measurements and the dual-baseline estimates were based on INSAR data alone [26]. The results of the dual-baseline demonstration are shown in Figures 2 and 3. Figure 2 shows the tree heights derived from dual-baseline INSAR alone versus ground-truth tree height. While there are some outliers, there is generally good agreement within the error bars. Figure 3 shows the topographic altitudes derived from the INSAR phase in the absence of the modeling which produced Fig. 2. The actual topography of the region has been largely removed, so the trend with tree height should be flat. Because trees cause an error of the order of their heights, there is an upward trend for the uncorrected altitudes as a function of tree height. When the altitudes derived from phase are corrected by modeling the multi-baseline data to determine tree height, the scatter about zero (rms in the figure) drops from 12.6 m to 6.3 m. Thus the modeling approach to multi-baseline INSAR data has dramatically improved the accuracy of the surface topographic measurement. For the single-baseline demonstration in [10], slightly worse results were achieved with biases in tree height at about the 5-m level.

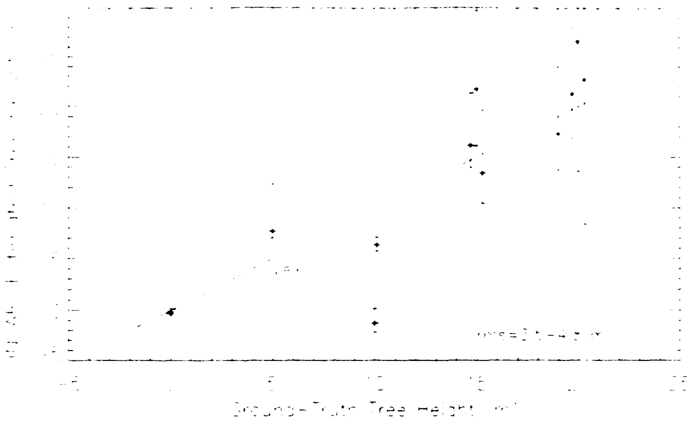


Figure 2: Tree heights derived from dual-baseline INSAR alone versus ground-truth tree height.

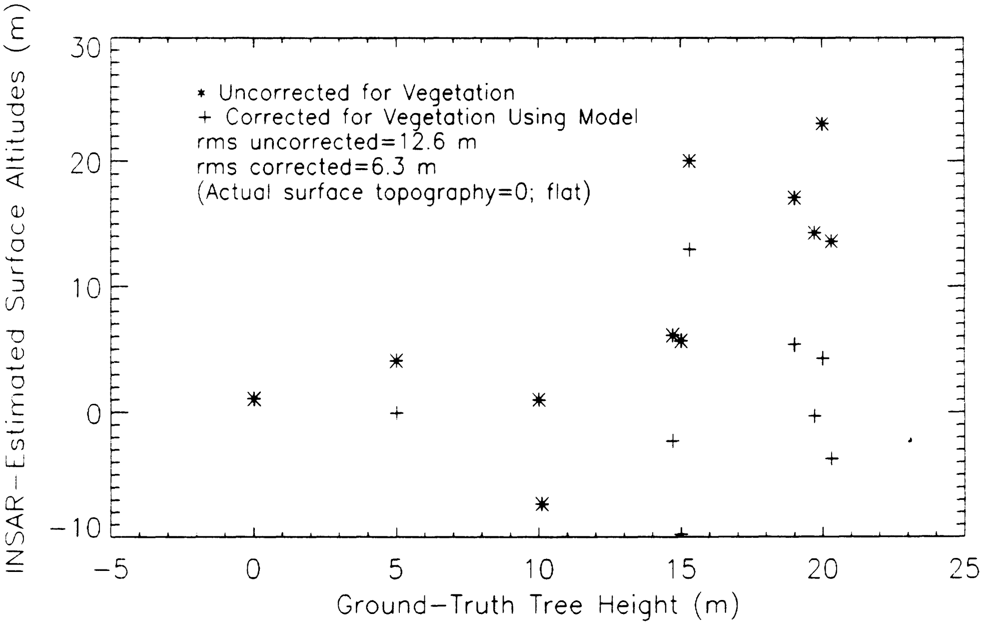
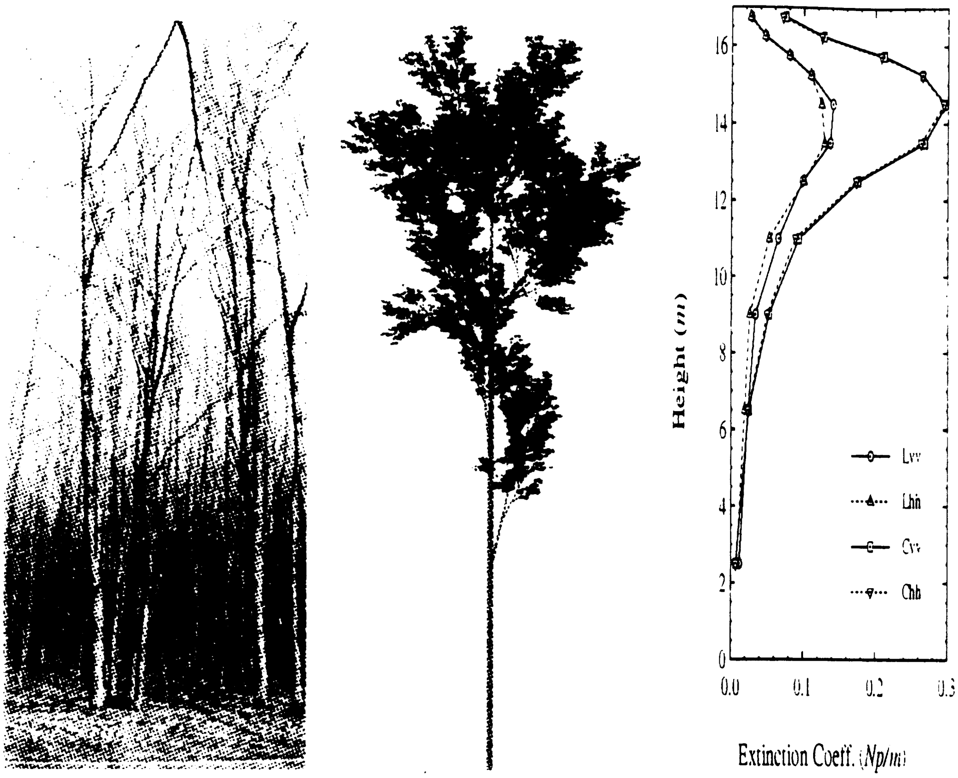


Figure 3: The topographic altitudes derived from the INSAR phase.

2.2 Development of a Monte Carlo Coherent Scattering Model for Tree Canopies Based on Fractal Theory

Although there are a number of EM scattering models for vegetation canopies [1, 2], they are of little use with regard to INSAR applications due to the models inability to predict the absolute phase of the scattered field. The absolute phase of the scattered field is the fundamental quantity from which the interferogram images are constructed. As mentioned earlier in order to simulate the response of an INSAR system a coherent scattering model capable of preserving the absolute phase of the scattered field is needed. Traditional scattering models for forest canopy such as radiative transfer and distorted Born approximation are incapable of providing the phase of the backscatter and do not preserve the effect of coherence caused by the relative position of scatterers within a tree. We have completed the task of developing a coherent scattering model for forest canopies. This model is based on a Monte Carlo scattering simulation which preserves the exact structure of desired trees [11, 12]. In this model first random generation of tree architectures is implemented by employing the Lindenmayer systems (L-systems). The L-systems is a convenient tool for creating fractal patterns of botanical structures. After generating a tree structure, the electromagnetic scattering problem is then solved by invoking the single scattering theory. In this solution scattering from individual tree components when illuminated by the mean field is computed and then added coherently. This model was examined thoroughly and its validity was tested using SIR-C data. We used our test site (Hiawatha National Forest) in Michigan's Upper peninsula for which we collected extensive ground-truth data during SIR-C overflight. Figure 4 shows a photo of a red maple stand, computer simulated tree structure of the same stand, and the exact extinction profile derived from the Monte Carlo simulation. Figures 5a and 5b show the comparison between the model prediction and SIR-C polarimetric backscattering coefficients at L- and C-band respectively. The three angular measurement points correspond to three different orbits of the October 94 mission. To our knowledge this model is the most accurate and sophisticated scattering model for forest canopies to date. The model preserves the exact structure of the trees, it can simulate a forest over a hilly terrain, it can simulate both coniferous and deciduous trees, it can also incorporate radially inhomogeneous dielectric profile for branches and tree trunk. The details of this model is reported in [12].

We have also used the Monte Carlo coherent model in simulating the location of scattering phase center of different forest stands. As mentioned in the summary of the theoretical activities, the equivalence relationship can be invoked to find the location of the scattering phase center of a tree. This is basically done by evaluating the backscatter from a forest stand at two slightly different frequencies and calculating the phase difference of the backscattered. The difference in frequency is directly proportional to the base-line distance and is also a function of the center frequency and the incidence angle. In April 1995 JPL TOPSAR flew over one of our test sites in the Michigan's Upper peninsula. For this site extensive ground truth data for vegetation including tree heights, type, number density, dielectric constant and for the ground surface including soil moisture and surface elevation were collected. We have recently received the processed data from JPL and were able to compare the result of our model with the actual measurement of TOPSAR at C-band. Figure 6 shows a photo of a red pine stand, and a computer generated red pine. Figures 7 and 8 respectively show the TOPSAR image of the test stand and the measured (at two incidence angles) and estimated height of the scattering phase centers of this stand. Finally Fig. 9 shows the measured and calculated backscattering coefficients. In Figs. 8 and 9



(a) Stand 31 (b) Fractal Tree (c) Extinction Profile

Figure 4: The generated fractal tree (b), based on the forest Stand 31 (a), and the calculated extinction profile (c).

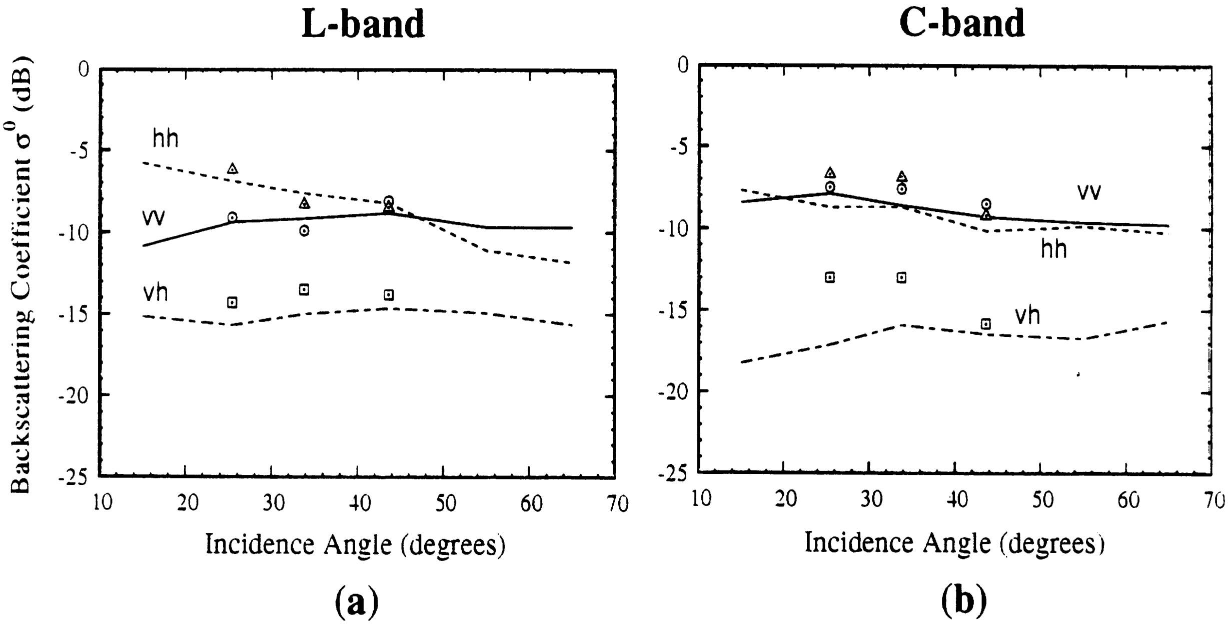
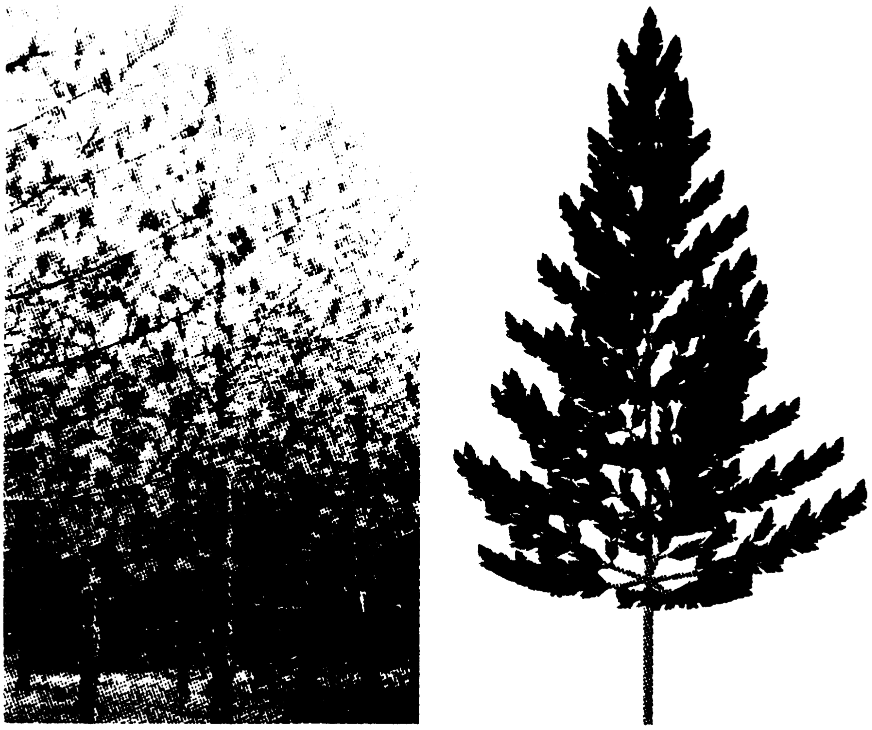


Figure 5: Comparison between the model predictions (lines) and SIR-C data (symbols) at (a) L-band and (b) C-band.



(a) Stand 22 (b) Fractal Tree

Figure 6: The red pine forest stand (a), the generated fractal tree (b).

excellent agreements between the measured and calculated results are shown. The details of this simulation and some sensitivity analysis can be found in [13].

2.3 Experimental Activities

Our experimental activities so far have been focused over two well-characterized sites: 1) Hiawatha National Forest (HNF) in Michigan's Upper peninsula, and 2) the Kellogg Biological Station (KBS) near Kalamazoo, Michigan. Nearly 25 different forest stands were chosen in the NHF test site which included varieties of tree types, tree height and density, and surface topography . For these stands, extensive ground truth data were collected. The ground truth for vegetation includes tree heights, type and structure, number density, and dielectric constant and for the ground surface includes soil moisture and surface elevation. In April 1995 JPL TOPSAR flew over this site and interferometric images were collected at two incidence angles. Figure 2.3 shows the map of HNF site and the location of some of the forest test stands. The grey level indicates the surface elevation as measured by TOPSAR at incidence angle 31°. An important and most difficult-to-characterized ground truth parameter was the forest floor surface elevation data which is required to extract the scattering phase center height from INSAR images. To accomplish this, differential GPS technique was used to characterize the elevation map of the forest floor of each stand with a resolution of the order of $\pm 5cm$. Figure 10 shows a typical surface elevation map of a stand generated from the differential GPS measurements.

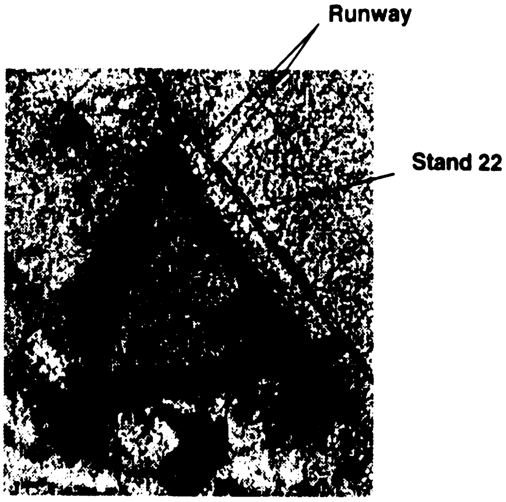


Figure 7: C-band image (σ_{vv}^{0}) of Stand 22 in Raco, Michigan.

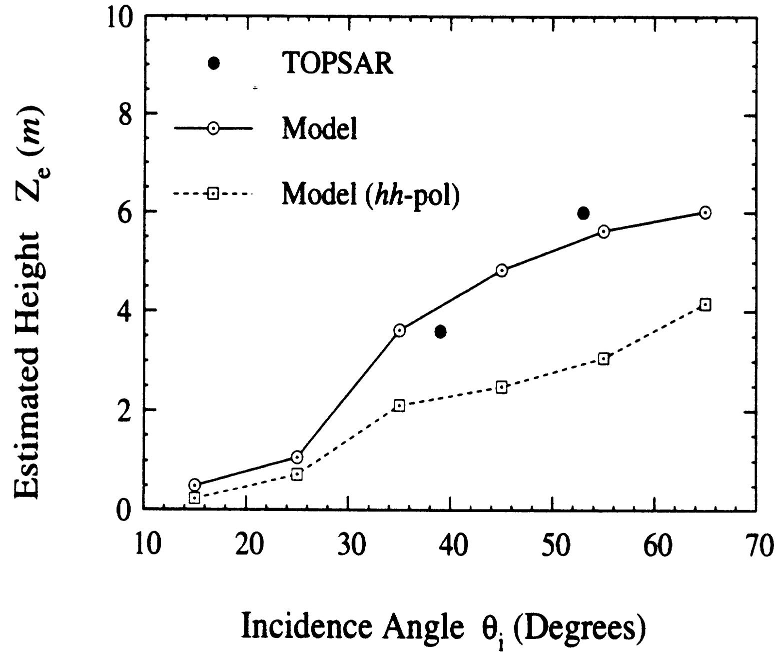


Figure 8: The estimated height of scattering phase center of Stand 22, compared with the interferometric data from JPL TOPSAR.

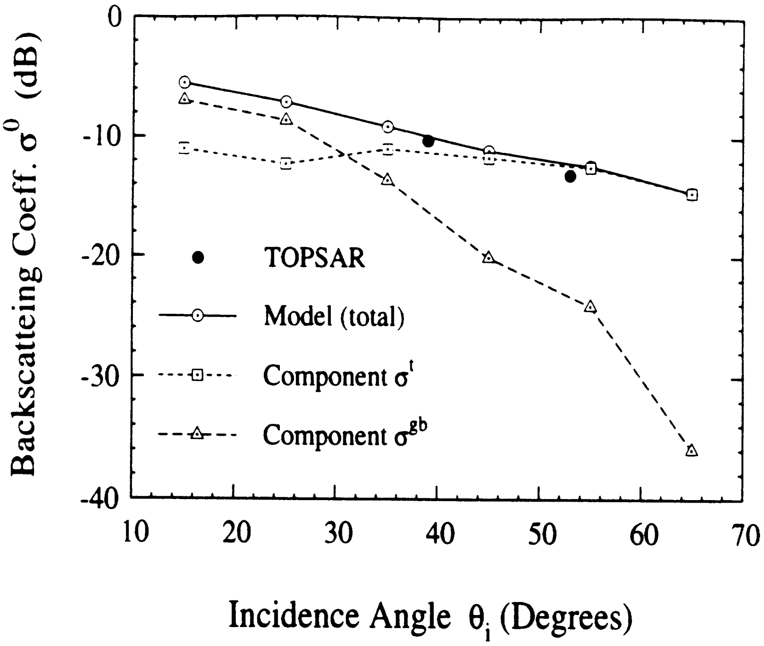


Figure 9: The simulated backscattering coefficient of Stand 22, compared with the measured data from JPL TOPSAR.

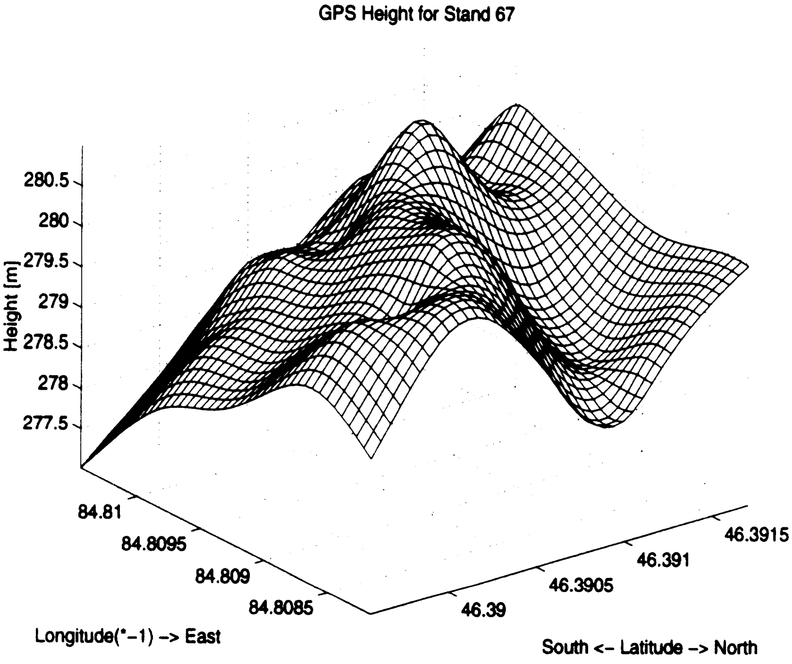


Figure 10: Surface elevation map of Stand 67 at HNF as measured by differential GPS.

We also conducted an experiment at the KBS site mainly to characterize the role of short vegetation on the phase and amplitude of interferograms. TOPSAR and polarimetric L- and C-band AIRSAR data were collected for this site. Different test fields with different vegetation type including wheat, alfalfa, corn, and native grass were considered. Ground truth data for each test field were also collected. We have also conducted an extensive polarimetric wideband backscatter measurements of these fields using The University of Michigan L- and C-band scatterometers. The intent of this experiment was to simulate the response of INSARs according to the procedure outlined in [7, 9]. Basically by invoking the equivalence relationship the location of the scattering phase center and correlation coefficient can be computed directly from a scatterometer. For example Fig. 11 shows the measured and modeled (developed in [9]) frequency correlation function (FCF) of a native grass with physical height 1.2 m at incidence angle $20°$. Using the phase of FCF the location of scattering phase center, from the vegetation top, is computed from [7]

$$h = \frac{-1}{2\cos(\theta)}\ \frac{\phi}{\Delta k} = 0.461\ m \tag{5}$$

Currently we are post processing the rest of data which will be compared with INSAR measurements in Phase II of this investigation.

3 PROPOSED PLAN

3.1 Enhancement of The Coherent Monte Carlo Scattering Model

The coherent Monte Carlo model, as it stands now, is capable of predicting the backscattering coefficients and the location of scattering phase center as well as the correlation coefficient, fully polarimetricly over a frequency range extending from P-band to X-band. The calculations are based on single scattering theory. We are planing to enhance the model by including the multiple scattering among vegetation particles. Theoretical models that can evaluate scattering up to second order have already been developed [14, 15, 16]. We will incorporate these into the coherent model in an efficient manner by examining the significance of the second order terms prior to their numerical calculations. It is expected that the second order scattering terms would improve the cross-polarized response.

Another enhancement to the existing model is the inclusion of forest understory. Most forest stands have underlying layers of vegetation including smaller trees and short vegetation. Depending on the frequency, the underlying layer influences the SAR/INSAR responses to some extent. In order to examine the effect and importance of the forest understories, an relatively unstructured layer of vegetation will be added to the existing forest model. The scattering and attenuation caused by this layer will be taken in to account in a coherent fashion.

3.2 INSAR Response To Short vegetation

As part of our Phase I activities, we will complete the experimental aspects of studying the effects of short vegetation on the phase and magnitude of interferogram. We have conducted experiments with TOSAR and polarimetric wideband scatterometers at KBS site. Analysis and data interpretation will be performed during the Phase II of this project. We will also develop

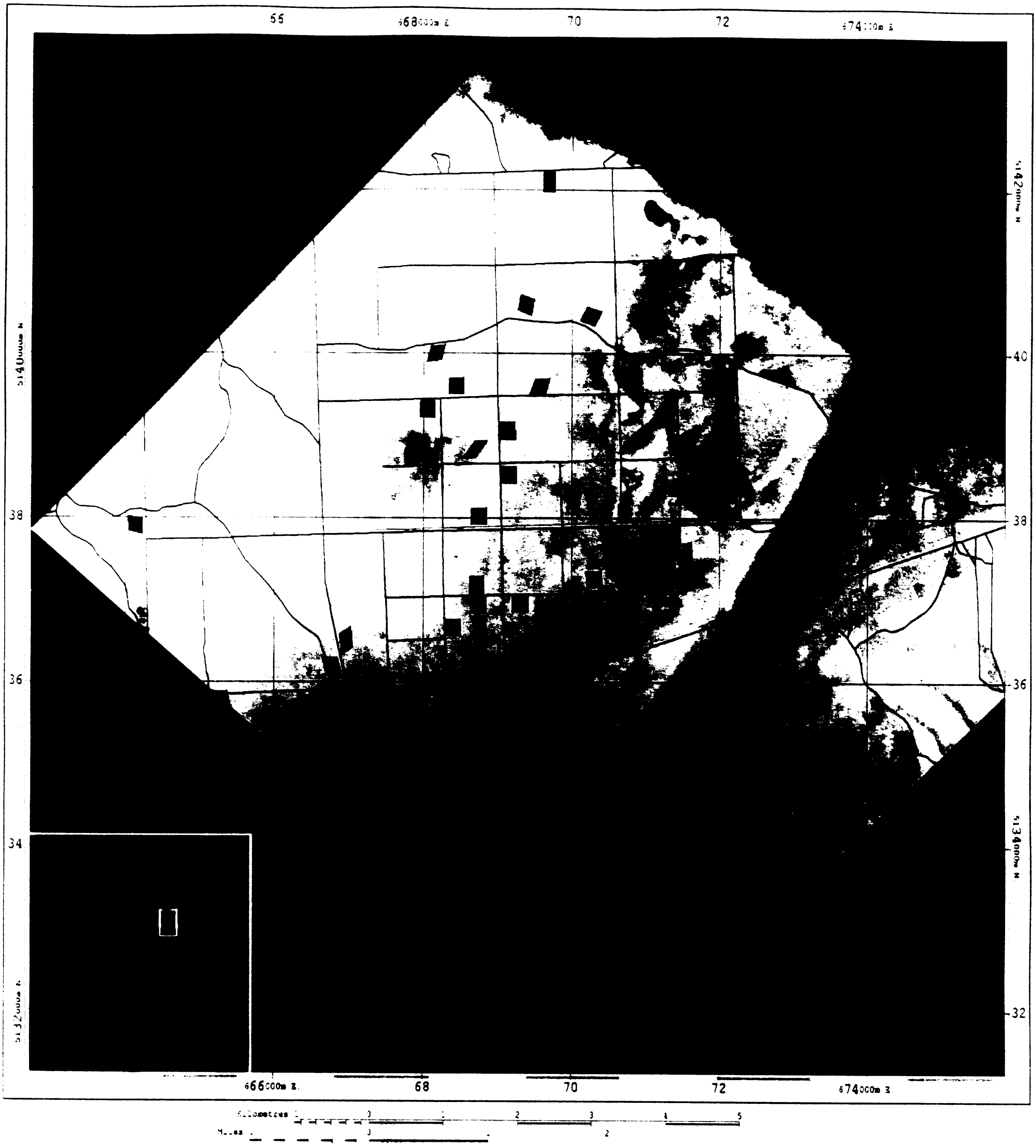


Figure 11: The surface elevation map (measured by TOPSAR) and road map of the HNF site and the location of some of the forest test stands.

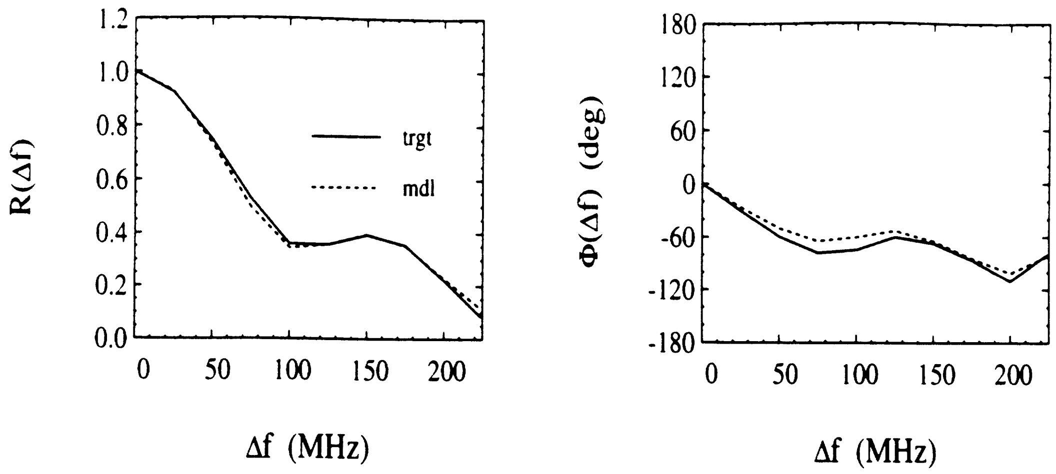


Figure 11: The measured and predicted magnitude and phase of the frequency correlation function of native grass from which the location of scattering phase center can be evaluated.

analytical models to explain the data. Of particular interest in this study is the behavior of correlation coefficient. Ideally, the measured correlation coefficient is a function of two independent components: 1) system parameters such as incidence angle and system point spread function, and 2) target attributes [7]. If the system dependent component of the correlation coefficient can be estimated accurately, the target dependent component can be evaluated which can be used in inversion algorithms. One way of estimating the system component is a direct measurements of correlation coefficient of clear-cut areas. Clear-cut areas are usually covered with short vegetation, and therefore it is important to investigate their effect on the correlation coefficient.

3.3 Investigation on the Utility of Multi-Polarization INSAR

As mentioned earlier, the number of parameters of a forest canopy that influence its backscatter response is large and therefore parameter retrieval using a single-frequency, single-polarization INSAR is practically very difficult, if not impossible. In this study we propose to investigate the enhancement achievable by utilizing the polarimetric interferometry for a canopy retrieval algorithm. Initially the coherent Monte Carlo scattering model will be used to examine the response of a polarimetric SAR interferometer to a variety different forest structures. This can be accomplished as the coherent Monte Carlo model is fully polarimetric which preserves the absolute phase of the backscatter.

To demonstrate the significance of such approach we carried out a simulation for a red maple stand, denoted by Stand 31, at HNF. A fractal generated red maple tree and a picture of the stand are shown in Figure ??. The simulations for estimating the scattering phase center height are performed fully-polarimetricly at L-band and C-band. Figure 12 shows the variation of the apparent height of Stand 31 as a function of the incidence angles for co- and cross-polarized L- and C-band INSAR configurations. Simulation results at C-band show that except at very low angles of incidence, the scattering phase center is near the top of the canopy. In this case the backscatter in all three polarizations is dominated by the direct backscatter components of particles near the canopy top. The same is true for L_{vv} and L_{vh} configurations; however, since

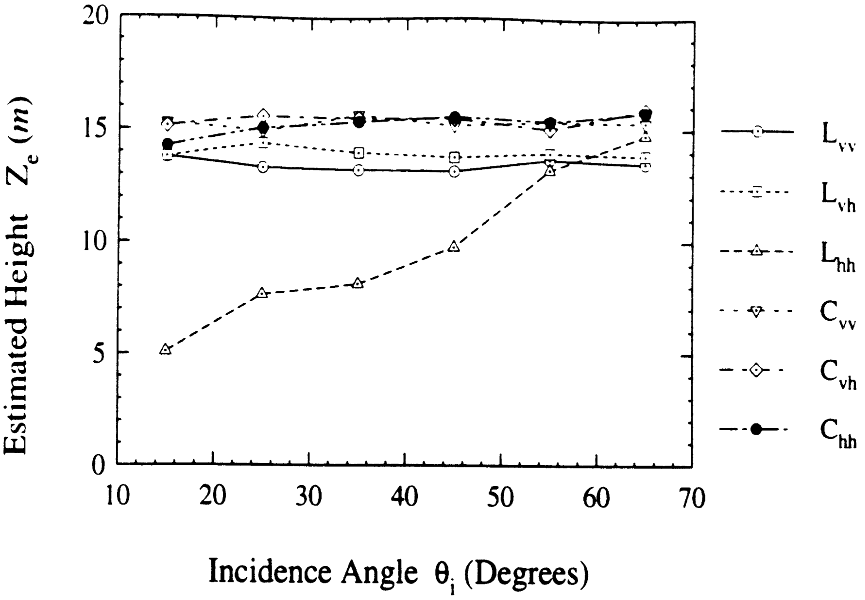


Figure 12: The estimated scattering phase center height of Stand 31 as a function of incidence angle, with fully-polarimetric L- and C-and response.

penetration depth at L-band is higher than C-band, the location of the scattering phase center appears about 1–3 m below the apparent height at C-band. The scattering phase center height for L_{hh} configuration, on the other hand, is a strong function of the incidence angle where it appears near the ground surface at low incidence angles and increases to a saturation point near grazing angles. Close examination of this figure indicates that a pair of C_{vv} (or L_{vv}) and L_{hh} INSAR data at low incidence angles can be used **to estimate the tree height of deciduous forest stands** with closed canopies.

At C-band foliated canopy behaves as a semi-infinite medium and as shown in [9] the knowledge of extinction would reveal the distance between the location of the scattering phase center and the canopy top (Δd) using $\Delta d = \cos\theta/(2\kappa)$. If an average extinction coefficient (κ) of $0.2N_p/m$ is used in the above equation, a distance $\Delta d = 1.77m$ is obtained at $\theta = 45°$. However, a simple relation for evaluating the apparent height for L_{hh} does not exist yet. Using the coherent model, empirical relationships for relating the location of scattering phase center (for each polarization and frequency) to the canopy parameters for different types of canopy will be established.

Multipolarization interferometric data will be generated using the existing SIR-C data. Following the procedures outlined in the literature repeat-pass polarimetric interferograms will be generated [17, 18, 19]. We have requested repeat-pass SIR-C data over HNF site which were acquired towards the end of SIR-C mission in October 1995. In order to estimate the baseline distance and angle, very accurate coordinates of ground control points (GCP) are required. We have already acquired coordinates of numerous GCPs within the test area of Raco, Michigan using the differential GPS method. We will focus on L-band interferometry as the temporal decorrelation will not allow meaningful C-band interferometry. Polarimetric backscattering coefficients together with the location of scattering phase centers at different polarizations will be used for estimation of height and other canopy parameters. Similar procedure will be extended to the BOREAS stands.

3.4 Inversion Algorithm Based on Multi-incidence Angle and/or Multi-frequency SAR/INSAR

The overall goal of this investigation is to obtain canopy parameters and structure from an available set of SAR and INSAR data. The inversion algorithm has to be versatile enough so that any combination of multi-frequency, multi-incidence angle, and/or multi-polarization SAR and/or INSAR data set can be used as the input to the algorithm. Sensitivity analysis will be carried out for determining the most influential canopy parameters on the SAR/INSAR responses. The result of this analysis would also reveal the most sensitive SAR/INSAR channels to the changes in the canopy parameters. These sensitive channels will be recommended for the inversion process.

Since the Monte Carlo coherent model is computationally intensive, its direct application would significantly slowdown the inversion process. To rectify this deficiency while maintaining the high fidelity of the model, simple empirical models based on the Monte Carlo model for different tree types will be developed first. Since the quantities of interest are ensemble average quantities, such as backscattering coefficients and the location of scattering phase center, it is expected that the dependence of these quantiles on the canopy parameters be very gentle. Therefore it is possible to obtain simple algebraic expressions for these quantities in terms of canopy parameters. For example for a given frequency and polarization, Taylor series expansion can be used to relate radar measured quantities to the canopy parameters at a specific incidence angle. Then by repeating this process for many incidence angles, the Taylor expansion coefficients will be fitted to an algebraic equation in terms of incidence angle. To demonstrate feasibility of such process we have developed an empirical model for red pine stands. Figure 13 shows a comparison between the empirical model and the Monte Carlo model at C-band over a wide range parameters including the incidence angular range 25° – 70°, and 40% variation on truck diameter (dbh), tree height, tree density, branch angle, branch moisture, and soil moisture. The top tree graphs show the height of the scattering phase center at the three principal polarizations and the lower three graphs show the backscattering coefficients.

Once comprehensive (multi-frequency and multi-polarization) easily calculable scattering and interferometric models for all tree types of interest are developed, inversion for any available combination of INSAR and/or SAR data can be attempted by searching for an optimum set of canopy parameters which would minimize the difference between the model prediction and measured quantities. It is expected that the objective function be highly non-linear and complex containing many local minima. In these situations gradient-based optimization methods usually converge to a weak local minimum. Stochastic algorithms such as simulated annealing [20] and genetic algorithms [21, 22] offer an alternative for the traditional gradient-based optimization methods where the dimension of parameter space is large and/or the objective function is non-differentiable. In recent years, applications of genetic algorithms to a variety of optimization problems in electromagnetics have been successfully demonstrated [23, 24, 25]. The fundamental concept of genetic algorithms (GA) is based on natural selection in the evolution process which is accomplished by genetic recombination and mutation. In this approach the entire parameter space is discretized and using a Monte Carlo simulation of the evolution process on a randomly selected subset of the discretized parameter space, the desired objective function is optimized. Genetic algorithms offer certain advantages over the traditional gradient-based (TGB) optimization algorithms. The most important feature of GAs is that the optimization is accomplished globally, that is, the probability of converging to a weak local minimum is very low unlike the

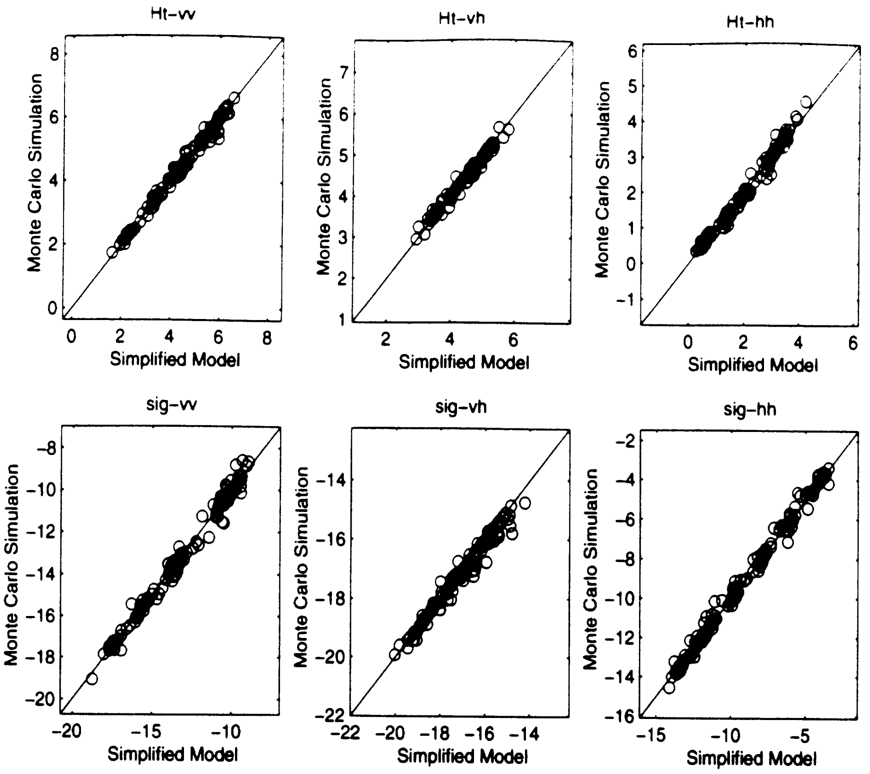


Figure 13: A comparison between an empirical scattering model and the Coherent Monte Carlo model for a red pine stand.

TGB algorithms. This is particularly the case when the objective function is highly non-linear and the dimension of the parameter space is large. GAs perform equally well independent of objective function's smoothness condition and after convergence provide a list of high quality solutions which can further be assessed according to criteria not included in the objective function. On the other hand there are certain disadvantages associated with the GAs. A major drawback of GAs is their lack of computational efficiency. Basically, far more calculation of the objective function is required to achieve a convergence when compared with TGBs. Another shortcoming of the GAs is that they do not provide any insight as to the character of the objective function during the course of the optimization process. It should also be noted that after convergence the solution may not necessarily be the true extremum of the objective function. The algorithm is based on a number of ad hoc steps including: 1) discretization of the parameter space, 2) development of an arbitrary encoding algorithm to establish a one-to-one relationship between each code and the discrete points of the parameter space, 3) random generation of a trial set known as initial population, 4) selection of high performance parameters according to the objective function known as natural selection, 5) mating and mutation, 6) recursion of steps 4 and 5 until a convergence is reached. The population size is provided by the user and a population of the given size is generated randomly.

3.5 Investigation on the Utility of Multi-Baseline INSAR

As mentioned earlier, our priliminary investigation shows that application of multi-baseline INSAR data drastically improves the accuracy of the surface topographic measurement.The proposed activity is 1) complete the Boreas demonstration by investigating a wide variety of scenes (the current demonstration represented only about 20% of the data available) 2) determine the utility of the combination of multi-baseline INSAR and polarimetry (POLSAR), and 3) demonstrate the estimation of vegetation and surface characteristics from the INSAR/POLSAR combination. There were many features of the current Boreas demonstration, e.g. anomalously low extinction coefficients, that were not thoroughly studied with the full data set. A sufficiently large dual-baseline INSAR data set is available for establishing the robustness of the algorithms and approaches developed in [10]. The material in two presentations this year [27] suggest that the combination of multi-baseline INSAR with POLSAR will enable the estimation of vertical profile details of vegetation in the presence of ground-trunk/volume returns. The ground-trunk/volume returns were not considered in [10] but are treated in [27], and based on that and [28], it appears that the combination POLSAR and multi-baseline INSAR will be a powerful tool for understanding forest vegetation vertical profiles and underlying topography. We therefore propose to continue the physical modeling and algorithm development which combines POLSAR and multi-baseline INSAR and demonstrate the combination with Boreas and Kellogg data. Although simultaneous INSAR and POLSAR were not acquired with TOPSAR, INSAR and POLSAR at different epochs should be a useful first step, coupled with repeat-pass interferometry, for which POLSAR is simultaneously acquired. The repeat-pass interferometry will, however, pose the additional challenge of understanding the temporal decorrelation to vegetation movement and chemical change between passes.

3.6 INSAR Lidar Data Fusion

Data fusion from independent remote sensing instruments can drastically improve the success of inversion processes. A laser altimetry system that can provide high-resolution, geolocated measurements of vegetation vertical structure and ground elevations beneath canopies is of great value to the overall goal of PHASE II investigation. The principle of operation is rather simple and is based on precise timing of the round-trip travel time of short-duration pulses of a near-infrared (1.06 microns) laser illuminating a forest canopy. Digitization of the backscattered return energy, or laser echo, as a function of time yields a waveform which is a measure of the vertical distribution of intercepted, nadir-projected surface area. The waveform is composed of both canopy elements (foliage, needles, stems, branches) and the underlying ground's height distribution introduced by surface slope and roughness [29, 30, 31]. The lidar elevation data will be used as an independent set of measurements in the inversion process as well as evaluating the inversion process in the absence of laser data.

A laser altimeter known as Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) was piggybacked on the ASAS C-130 deployment during the BOREAS Summer 1996 Intensive Field Campaign in July (ASAS is a high-res, multi-angle hyperspectral imaging system). During acquisition of ASAS images at the Southern and Northern Study Area flux tower sites, SLICER acquired nadir transects of canopy vertical structure and sub-canopy ground topography. Typically, the transects extend outward from the tower sites for a distance of approximately 10 km. The transects consist of narrow swaths nominally composed of five cross-track footprints, each circular and 8 m in diameter. There are also two long transects acquired during the transit between the southern and northern study areas, which were acquired in SLICER single-beam profiling mode.

The lidar backscatter is digitized at 11 cm vertical sampling, in order to obtain the complete time-varying distribution of return pulse energy from multiple targets at varying heights within a large footprint. By using large diameter footprints on the order of one to two times the typical crown widths, each waveform includes returns from the highest elements of the canopy and from the ground. Ground returns occur where there are sufficient intra- or inter-crown gaps of any size extending at nadir to the canopy floor, which is usually the case in all but the densest canopies. The laser footprints are geolocated, at footprint scale absolute horizontal accuracy, by combining the laser ranging data with aircraft position, obtained from a differential kinematic GPS trajectory, and laser pointing knowledge, obtained from an Inertial Navigation System. By scanning the laser footprint across the track of the aircraft flight line, a narrow swath of three-dimensional laser waveform data is acquired.

¿From each laser backscatter echo the ground elevation and canopy height are readily derived at meter-level absolute vertical accuracy, and from adjacent laser footprints the slope and azimuth of the canopy top and underlying ground surfaces can be determined. By accounting for extinction of the laser light with depth through the canopy, the raw echoes can also be converted to canopy height profiles which are a normalized measure of the vertical distribution of canopy surface area [32]. Height profiles of absolute, nadir-projected canopy surface area and closure can be derived where ancillary information on ground and canopy reflectance at 1 micron are available, as for example from ground measurements or pixel unmixing of hyperspectral imaging radiometer data.

A comprehensive set of figures characterizing the SLICER results at all the BOREAS Southern Study Area flux towers is already completed, and analysis of the Northern Study area flux towers is in progress. For each tower site the plots include detailed map views of the ground tracks, 3-D perspective views of canopy top and ground elevations along the transects, contour plots of the vertical distribution of normalized canopy area and closure, and average canopy height profiles. Figure 14 shows average canopy height profiles for the Southern Study Area flux tower sites. The stand structures are differentiated by total height, the thickness of the upper story, and the presence or absence of an understory.

Initial work on INSAR-lidar fusion will focus on constraining analysis of single wavelength, baseline length, and polarization INSAR data using lidar profiles, thus providing methodologies appropriate for the integration of Shuttle Radar Topography Mission (SRTM) and Vegetation Canopy Lidar (VCL) data. SRTM will provide nearly complete INSAR global coverage at L-band in late 1999, and VCL will provide globally distributed surface lidar profiles at 1.06 microns starting in early 2000. The model development of [7, 10, 13] provide a basis for this INSAR-lidar fusion. For example in the simplified model [10], three surface parameters (the height of the vegetation layer, the vegetation extinction coefficient, and the elevation of the ground surface) are expressed in terms of two INSAR parameters (amplitude and phase of the normalized cross section). This under determined system was evaluated for vegetation height and ground elevation by applying independent measurements of extinction coefficient. However, it was difficult to differentiate sources of ambiguity in the height and elevation results between instrumental, model, and extinction coefficient errors. For the BOREAS region, we will use the SLICER data to provide independent measures of vegetation height and ground elevation, and thus in the presence of the SLICER data the model of [10] will be over determined and we can solve for the extinction coefficient. Instrumental errors can also be assessed, particularly the necessary conversion of the measured normalized cross-correlation amplitude to an absolute vegetation cross-correlation based on range correlation and noise corrections. The vegetation height profile, closure, and ground slope measurements provided by the lidar can be used to assess extensions of the simple

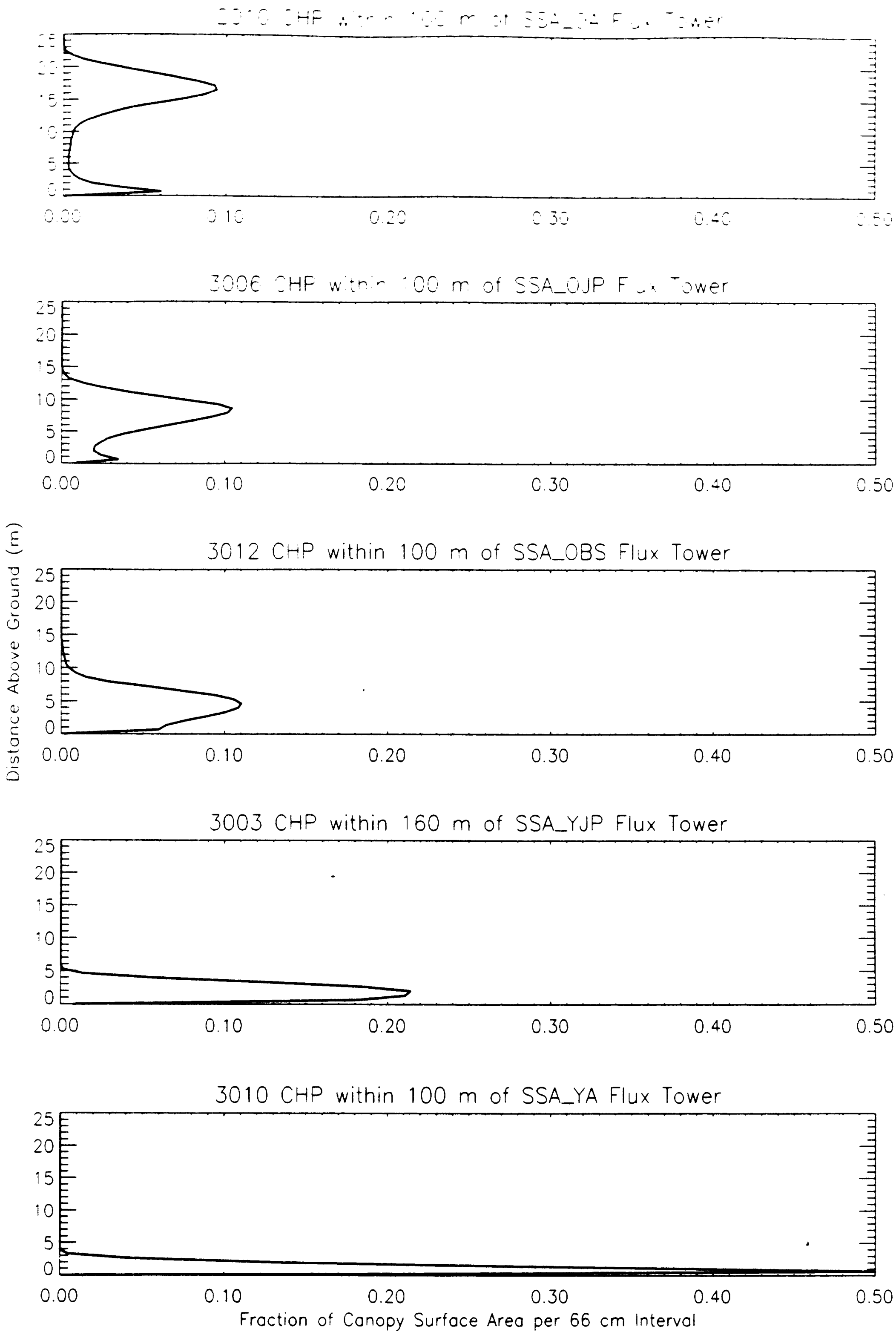


Figure 14: Average canopy height profiles (CHP) for SLICER lidar footprints near five BOREAS Southern Study Area flux towers (OA = old aspen, OJP = old jack pine, OBS = old black spruce, YJP = young jack pine, YA = young aspen), expressed as normalized distributions (fraction of total nadir-projected canopy surface area per 66 cm measurement interval) above the ground surface.

models of [7, 10] (dense, homogeneous vegetation layer extending to the ground, a flat ground surface, and no ground scattering interactions) to account for layered vegetation, sloped ground, and a ground scattering contribution. Additionally, the lidar data can be used as input to the more sophisticated model of [13].

The limited spatial coverage of the SLICER lidar data for BOREAS, and ultimately globally from VCL, will require methods to extend the lidar constraints to areas of INSAR coverage in the absence of the lidar data. We will evaluate the following methodology for the BOREAS region:

1. define vegetation cover types based on the amplitude and texture of cross-correlation and backscatter INSAR images,
2. for cover regions crossed by a subset of lidar profiles, apply the model of [10] constrained by lidar vegetation height and ground elevation in order to determine instrumental correction factors and each cover types vegetation extinction coefficient,
3. apply the derived extinction coefficients, based on cover type, throughout the INSAR images using the model of [10] in order to determine vegetation height and ground elevation in the absence of lidar data,
4. use a subset of the lidar profiles, withheld from step 2, to assess the accuracy the resulting vegetation height and ground elevation images.

This approach should provide a means to utilize near-term INSAR and lidar assets, without relying on access to multi-wavelength, baseline length, or polarization INSAR data.

4 Management and Cost Plan

4.1 Schedule

The proposed investigation will require a three year period of performance. The EM model enhancement, and the development of inversion algorithm will be conducted during the first year of the study. Validation of the inverse model using TOPSAR and INSAR data taken over HNF and KBS will be performed in the second year. The KBS data analysis and interpretation of TOSAR and polarimetric scatterometer will be done during the first two years. Activities related to polarimetric interferomtry using SIR-C will start from the onset of the Phase II project and should last about two years. Research activities concerning dual baseline SAR interferomtry over BOREAS will be conducted throughout the project. SLICER data preparation and analysis and comparison with the existing TOSAR data will be performed during the first two years. Data fusion, implementation of inversion algorithm for BOREAS stands will be completed in the third year.

4.2 Personnel

The proposed research will be performed under the direction of professor Kamal Sarabandi. He will be principally assisted by four Co-Investigators: Mr. M. Craig Dobson (UM), Dr. David Harding(GSFC), Dr. Robert Treuhaft (JPL), and Dr. Jakob van Zyl (JPL). The UM team will be responsible for the development, validation, and implementation of the forward and inverse model. They will also be responsible for the activities related to polarimetric SAR interferometry using SIR-C data as well as the KBS data analysis and interpretation. JPL team will be responsible for the dual baseline INSAR activities and TOPSAR data extraction and analysis of BOREAS site. The JPL team will also be continuing work on forward and inverse models for the INSAR-POLSAR combination. Dr. Harding who has extensive experience in lidar research will be responsible for the data interpretation of SLICER and will collaborate in the data fusion activity. All will be engaged in the development and validation of the proposed algorithms. Two graduate student research assistants will be supported by this project.

4.3 Facilities and Required Resources

All necessary equipment and facilities required are available within the Radiation Laboratory at the University of Michigan, Jet Propulsion Laboratory, and NASA Goddard Space Flight Center; no additional equipment will be purchased with the requested funding.

5 Budget

The total cost of the proposed three-year project is $466,146, of which $454,977 is requested from NASA and the balance of $11,169 will be provided by The University of Michigan in the form of cost sharing. Out of total costs of $454,977 to NASA, $295,177 is requested by the University of Michigan, $70,000 by GSFC, and the remainder of $89,800is requested by JPL.

References

[1] F. T. Ulaby, K. Sarabandi, K. MacDonald, M. Whitt, and M. C. Dobson, " Michigan Microwave Canopy Scattering Model", *Int. J. Remote Sensing*, Vol. 11, No. 7, pp. 1223-1253, 1990.

[2] M. A. Karam, A. K. Fung, R. H. Lang, and N. H. Chauhan, " A microwave scattering model for layered vegetation," *IEEE Trans. Geosci. Remote Sensing.*, vol. 30, no. 4, pp. 767-784, July 1992.

[3] K. Sarabandi, *Electromagnetic Scattering from Vegetation Canopies*, Ph.D. Dissertation, University of Michigan, 1989.

[4] R. L. Jordan, B. L. Huneycutt, and M. Werner, "The SIR-C/X-SAR synthetic aperture radar system," *IEEE Trans. Geosci. Remote Sensing.*, vol. 33, pp. 829-839, July 1996.

[5] Zebker, H/A., S. N. Madsen, J. Martin, K. B. Wheeler, T. Miller, Y. Lou, G. Alberti, S. Vetrella, and A. Cucci, " The TOPSAR interferometric radar topographic mapping instrument," *IEEE Trans. Geosci. Remote Sensing.*, vol.30, No.5, pp.933-940, 1992.

[6] Rodriguez, E., and J.M. Martin, "Theory and design of interferometric synthetic aperture radars," *IEE Proceedings,* vol. F139, no. 2, pp. 147-159, 1992.

[7] Sarabandi,K., "Δk-Radar equivalent of Interferometric SARs: A Theoretical Study for determination of vegetation height,"*IEEE Trans. Geosci. Remote Sensing.*, accepted for publication (Dec. 96).

[8] Sarabandi,K., A. Nashashibi,"Analysis and applications of backscattered frequency correlation function,"*IEEE Trans. Geosci. Remote Sensing.*, submitted for publication (April 97).

[9] R. N. Treuhaft, M. Moghaddam, and J. J. van Zyl, "Inteferometric Remote Sensing of Vegetation and Surface Topography," Radio Science, vol. 31, pp. 1449-1485.

[10] Lin, Y.C., and K. Sarabandi, "Electromagnetic scattering model for a tree trunk above a tilted ground plane," *IEEE Trans. Geosci. Remote Sensing.*, vol. 33, no. 4, pp. 1063-1070, July 1995.

[11] Lin, Y.C., and K. Sarabandi, "A Monte Carlo Coherent Scattering Model For Forest Canopies Using Fractal Generated Trees," *IEEE Trans. Geosci. Remote Sensing.*, submitted for publication (Sept. 96).

[12] Sarabandi, K., and Y.C. Lin, "Simulation of Interferometric SAR Response for Characterization of Scattering Phase Center Statistics of Forest Canopies," *IEEE Trans. Geosci. Remote Sensing.*, submitted for publication (Feb. 97).

[13] Chiu, T.C., and K. Sarabandi, "Electromagnetic scattering interaction between a dielectric cylinder and a slightly rough surface," *IEEE Trans. Antennas Propagat.*, submitted for publication (June 1997).

[14] Sarabandi, K., and P.F. Polatin, "Electromagnetic scattering from two adjacent objects," *IEEE Trans. Antennas Propagat.*, vol. 42, no. 4, pp. 510-517, April 1994.

[15] Polatin, P.F., K. Sarabandi, and F.T. Ulaby,"Monte Carlo simulation of electromagnetic scattering from a heterogeneous two-component medium," *IEEE Trans. Antennas Propagat.*, vol. 43, no. 10, pp. 1048-1057, Oct. 1995.

[16] Goldstein, R.M., H.A. Zebker, and C.L.Werner, "Satellite radar interferometry: Two-demensional phase unwrapping," *Radio Sci.*, vol.23, no.4, pp. 713-720, July-August 1988.

[17] Gens, R., and J.L. van Genderen, "Review article: SAR interferometry issues,techniques,applications," *Inter. J. of Remote Sensing*, vol. 17, no. 10,pp. 1803-1835, 1996.

[18] Zebker, H.A., C. L. Werner, P.A. Rosen, S. Hensley, "Accuracy of Topographic Maps Derived from ERS-1 Interferometric Radar," *IEEE Trans. Geosci. Remote Sensing.*, vol. 32,no.4, pp. 823-836, July 1994.

[19] Kirkpatrick, S., J.C.D. Gelatt, and M.P. Vecchi, "Optimization by simulated annealing," *Sci.*, vol. 220, pp. 671-680, 1983.

[20] Holland, J.H., "Genetic Algorithms," *Scientific American*, pp. 66-72, July 1992.

[21] DeJong, K.A.,"An Analysis of the behavior of a class of genetic adaptive systems," Ph.D. dissertation, The University of Michigan, Ann Arbor, 1975.

[22] Michielssen, E., and R. Mittra, "RCS reduction of dielectric cylinders using a simulated annealing approach," *IEEE Trans. Microwave Theory Tech.*, vol. 41, no.6/7, pp. 1024-1031, 1993.

[23] Haupt, R.L., "Thinned arrays using genetic algorithms," *IEEE Trans. Antennas Propagat.*, vol. 42, no. 7, pp. 993-999, 1994.

[24] Sarabandi, K., and E. Li, "Characterization of Optimum Polarization for Multiple Target Discrimination Using Genetic Algorithms,"*IEEE Trans. Antennas Propagat.*, submitted for publication (August 1996).

[25] Treuhaft, R.N., E. Rodriguez, M. Moghaddam, J.J. van Zyl, and K. Sarabandi, "Estimating vegetation and surface characteristics with multifrequency SAR interferometry," *URSI General Assembly*, Lille, France, August 1996 (invited).

[26] Treuhaft, R.N., M. Moghaddam, and J. J. van Zyl, "Combining Radar Interferometry and Polarimetry to Estimate Forest Vegetation and Surface Parameters," PIERS97, Cambridge, Massachusetts, July 1997 (invited).

[27] Cloude, S.R., and K. Papathanassiou, "Polarimetric Effects in Radar Interferometry," PIERS97, Cambridge, Massachusetts, July 1997.

[28] Blair, J.B., D.B. Coyle, J.L. Bufton, and D.J. Harding, 1994, Optimization of an Airborne Laser Altimeter for Remote Sensing of Vegetation and Tree Canopies, Proceedings of IGARSS'94, Vol. II, 939-941.

[29] Harding, D.J., J.B. Blair, J.B. Garvin, W.T. Lawrence, 1994, Laser Altimetry Waveform Measurement of Vegetation Canopy Structure, Proceedings of IGARSS'94, Vol II, 1251-1253.

[30] Harding, D.J.,, J.B. Blair, E. Rodriguez, T. Michel, 1995, Airborne Laser Altimetry and Interferometric SAR Measurements of Canopy Structure and Sub-Canopy Topography in the Pacific Northwest, Proc. Second Topical Symposium on Combined Optical - Microwave Earth and Atmosphere Sensing (CO-MEAS'95), 22-24.

[31] Lefsky, M.J., 1997, Application of Lidar Remote Sensing to the Estimation of Forest Canopy Structure, Univ. of Virginia, Ph.D. Dissertation, 185 pp.

Digital Topography From SAR Interferometry: Determination of and Correction for Vegetation

Budget Summary

From March 15, 1998 to March 14, 1999

YEAR ONE

		NASA USE ONLY	
	A	B	C
1. Direct Labor (salaries, wages, and fringe benefits)	$57,721		
2. Other Direct Costs:			
a. Subcontracts	0		
b. Consultants	0		
c. Equipment	0		
d. Supplies	1,500		
e. Travel	4,000		
f. Other (Graduate Student tuition)	4,884		
3. Indirect Costs	33,191		
4. Other Applicable Costs	-		
5. Subtotal--Estimated Costs	101,296		
6. Less Proposed Cost Sharing (if any)	3,578		
7. Carryover Funds (if any)			
a. Anticipated amount ______			
b. Amount used to reduce budget	-		
8. Total Estimated Costs	$97,718		XXXXXXX
APPROVED BUDGET	XXXXXXX	XXXXXXX	

Budget detail and breakdowns are included following the NASA Budget Summary pages.

Instructions

1. Provide a separate budget summary sheet for each year of the proposed research.

2. Grantee estimated costs should be entered in Column A. Columns B and C are for NASA use only. Column C represents the approved grant budget.

3. Provide in attachments to the budget summary the detailed computations of estimates in each cost category, along with any narrative explanation required to fully explain proposed costs.

---------------------- ADDITIONAL INSTRUCTIONS ON REVERSE ----------------------

Digital Topography From SAR Interferometry: Determination of and Correction for Vegetation

Budget Summary

From March 15, 1999 to March 14, 2000

YEAR TWO

		NASA USE ONLY	
	A	B	C
1. Direct Labor (salaries, wages, and fringe benefits)	$ 58,158		
2. Other Direct Costs:			
a. Subcontracts	0		
b. Consultants	0		
c. Equipment	0		
d. Supplies	1,500		
e. Travel	4,000		
f. Other (Graduate Student tuition)	5,078		
3. Indirect Costs	33,420		
4. Other Applicable Costs	-		
5. Subtotal–Estimated Costs	102,156		
6. Less Proposed Cost Sharing (if any)	3,721		
7. Carryover Funds (if any)			
a. Anticipated amount ___________			
b. Amount used to reduce budget	-		
8. Total Estimated Costs	$98,435		XXXXXXX
APPROVED BUDGET	XXXXXXX	XXXXXXX	

Budget detail and breakdowns are included following the NASA Budget Summary pages.

Instructions

1. Provide a separate budget summary sheet for each year of the proposed research.
2. Grantee estimated costs should be entered in Column A. Columns B and C are for NASA use only. Column C represents the approved grant budget.
3. Provide in attachments to the budget summary the detailed computations of estimates in each cost category, along with any narrative explanation required to fully explain proposed costs.

-------------------- ADDITIONAL INSTRUCTIONS ON REVERSE ------------------------

Digital Topography From SAR Interferometry: Determination of and Correction for Vegetation

Budget Summary

From March 15, 2000 to March 14, 2001
YEAR THREE

		NASA USE ONLY	
	A	B	C
1. Direct Labor (salaries, wages, and fringe benefits)	$ 58,508		
2. Other Direct Costs:			
a. Subcontracts	0		
b. Consultants	0		
c. Equipment	0		
d. Supplies	1,500		
e. Travel	4,000		
f. Other (Graduate Student tuition)	5,282		
3. Indirect Costs	33,604		
4. Other Applicable Costs	-		
5. Subtotal--Estimated Costs	102,894		
6. Less Proposed Cost Sharing (if any)	3,870		
7. Carryover Funds (if any)			
a. Anticipated amount ____			
b. Amount used to reduce budget	-		
8. Total Estimated Costs	$ 99,024		XXXXXXX
APPROVED BUDGET	XXXXXXX	XXXXXXX	

Budget detail and breakdowns are included following the NASA Budget Summary pages.

Instructions

1. Provide a separate budget summary sheet for each year of the proposed research.
2. Grantee estimated costs should be entered in Column A. Columns B and C are for NASA use only. Column C represents the approved grant budget.
3. Provide in attachments to the budget summary the detailed computations of estimates in each cost category, along with any narrative explanation required to fully explain proposed costs.

-------------------- ADDITIONAL INSTRUCTIONS ON REVERSE --------------------

Digital Topography From SAR Interferometry: Determination of and Correction for Vegetation

Budget Summary

From March 15, 1998 to March 14, 2001

SUMMARY - YEARS One - Three

	A	NASA USE ONLY B	NASA USE ONLY C
1. Direct Labor (salaries, wages, and fringe benefits)	$ 174,387		
2. Other Direct Costs:			
a. Subcontracts	0		
b. Consultants	0		
c. Equipment	0		
d. Supplies	4,500		
e. Travel	12,000		
f. Other (Graduate Student Tuition)	15,244		
3. Indirect Costs	100,215		
4. Other Applicable Costs	-		
5. Subtotal--Estimated Costs	306,346		
6. Less Proposed Cost Sharing (if any)	11,169		
7. Carryover Funds (if any) a. Anticipated amount ____ b. Amount used to reduce budget	-		
8. Total Estimated Costs	$295,177		XXXXXXX
APPROVED BUDGET	XXXXXXX	XXXXXXX	

Budget detail and breakdowns are included following the NASA Budget Summary pages.

Instructions

1. Provide a separate budget summary sheet for each year of the proposed research.

2. Grantee estimated costs should be entered in Column A. Columns B and C are for NASA use only. Column C represents the approved grant budget.

3. Provide in attachments to the budget summary the detailed computations of estimates in each cost category, along with any narrative explanation required to fully explain proposed costs.

-------------------- ADDITIONAL INSTRUCTIONS ON REVERSE ------------------------

Digital Topography From SAR Interferometry:
Determination of and Correction for Vegetation - March 15, 1998 - March 14, 2001

YEAR ONE - March 15, 1998 - March 14, 1999

	UM	NASA	TOTAL
DIRECT COSTS			
Prof. Kamal Sarabandi, P.D.	1,833	5,906	7,739
5% x 9 months, 0.5 summer month (8147/month)			
M. Craig Dobson, Co-P.I. 10%, 12 mos. (6760/month)		8,112	8,112
Adm. Assistant, 5%, 12 mos. (3963/month)		2,378	2,378
Graduate Student Research Assistant			
2 @ 1414/month each, 1@12 months, 1@7 months		26,866	26,866
Total Salaries and Wages	1,833	43,262	45,095
Fringe Benefits@ 28%	513	12,113	12,627
Other Direct Costs			
Tuition for two graduate students*		4,884	4,884
(Two terms per student per year)			
Travel			
Working Group Meeting (1 person, 3 days)		1,400	1,400
Field Experiments (3 persons, 5 days)		2,600	2,600
Lab and Consumable Supplies		1000	1000
Communications (FAX, Xerox, Postage)		500	500
TOTAL DIRECT COSTS	2,346	65,759	68,105
Total Indirect Costs @ 52.5% TDC	1,232	31,959	33,191
TOTAL COSTS	3,578	97,718	101,296

*The College will pay the portion of GSRA tuition not paid by the sponsor.

YEAR TWO - March 15, 1999 - March 14, 2000

	UM	NASA	TOTAL
DIRECT COSTS			
Prof. Kamal Sarabandi, P.D.	1,906	6,143	8,049
5% x 9 months, 0..5 summer month (8473/month)			
M. Craig Dobson, Co-P.I. 10%, 12 mos. (7030/month)		8,436	8,436
Adm. Assistant, 5%, 12 mos. (4122/month)		2,473	2,473
Graduate Student Research Assistant			
2 @ 1471/month each, 1@12 months, 1@6 months		26,478	26,478
Total Salaries and Wages*	1,906	43,530	45,436
Fringe Benefits@ 28%	534	12,188	12,722
Other Direct Costs			
Tuition for two graduate students**		5,078	5,078
(Two terms per student per year)			
Travel			
Working Group Meeting (1 person, 3 days)		1,400	1,400
Field Experiments (3 persons, 5 days)		2,600	2,600
Lab and Consumable Supplies		1000	1000
Communications (FAX, Xerox, Postage)		500	500
TOTAL DIRECT COSTS	2,440	66,296	68,736
Total Indirect Costs @ 52.5% TDC	1,281	32,139	33,420
TOTAL COSTS	3,721	98,435	102,156

*An annual increment of 4% is included in Year Two for Salaries and Tuition.

*The College will pay the portion of GSRA tuition not paid by the sponsor.

YEAR THREE - March 15, 2000 - March 14, 2001

	UM	NASA	TOTAL
DIRECT COSTS			
Prof. Kamal Sarabandi, P.D.	1,983	6,388	8,371
5% x 9 months, 0.5 summer month (8811/month)			
M. Craig Dobson, Co-P.I. 10%, 12 mos. (7311/month)		8,773	8,773
Adm. Assistant, 5%, 12 mos. (4287/month)		2,572	2,572
Graduate Student Research Assistant			
2 @ 1529/month each, 1@12 months, 1@5 months		25,993	25,993
Total Salaries and Wages*	1,983	43,727	45,709
Fringe Benefits@ 28%	555	12,243	12,799
Other Direct Costs			
Tuition for two graduate students**		5,282	5,282
(Two terms per student per year)			
Travel			
Working Group Meeting (1 person, 3 days)		1,400	1,400
Field Experiments (3 persons, 5 days)		2,600	2,600
Lab and Consumable Supplies		1000	1000
Communications (FAX, Xerox, Postage)		500	500
TOTAL DIRECT COSTS	2,538	66,752	69,290
Total Indirect Costs @ 52.5% TDC	1,332	32,272	33,604
TOTAL COSTS	3,870	99,024	102,894

*An annual increment of 4% is included in Year Three for Salaries and Tuition.

*The College will pay the portion of GSRA tuition not paid by the sponsor.

Digital Topography From SAR Interferometry:
Determination of and Correction for Vegetation - March 15, 1998 - March 14, 2001

SUMMARY - YEARS ONE - THREE

	UM	NASA	TOTAL
DIRECT COSTS			
Prof. Kamal Sarabandi, P.D.	5,722	18,437	24,159
M. Craig Dobson, Co-P.I.		25,321	25,321
Adm. Assistant		7,423	7,423
Graduate Student Research Assistants		79,337	79,337
Total Salaries and Wages*	5,722	130,518	136,240
Fringe Benefits@ 28%	1,602	36,545	38,147
Other Direct Costs			
Tuition for two graduate students** (Two terms per student per year)		15,244	15,244
Travel			
Working Group Meeting (1 person, 3 days each year)		4,200	4,200
Field Experiments (3 persons, 5 days per year)		7,800	7,800
Lab and Consumable Supplies		3000	3000
Communications (FAX, Xerox, Postage)		1,500	1,500
TOTAL DIRECT COSTS	7,324	198,807	206,131
Total Indirect Costs @ 52.5% TDC	3,845	96,370	100,215
TOTAL COSTS	11,169	295,177	306,346

*An annual increment of 4% is included in Years Two and Three for Salaries and Tuition.
**The College will pay the portion of GSRA tuition not paid by the sponsor.

JET PROPULSION LABORATORY
JPL California Institute of Technology **NASA PROPOSAL COST PLAN**
4800 Oak Grove Drive
Pasadena, California 91109

Proposal Title		DIGITAL TOPOGRAPHY FROM SAR INTERFEROMETRY:									
RTOP No. (If applicable)		Determination of and Correction for Vegetation Height							Date Prepared		Jun-97
A. Direct Compensation		Product DETERMINATION OF AND						Annual	Total, $K		
(By Classification)		Workhours			Workyears			Salary	FY'98	FY'99	FY'00
	Fiscal	FY'	FY'	FY'	FY'	FY'	FY'	Rate	Forward Pricing Index		
	Year	98	99	0	98	99	0	$K	1.000	1.050	1.125
Engineering/Scientist	E	274.8	274.8	274.8	0.2	0.2	0.2	88	13.2	13.9	14.9
Administrative	A				0.0	0.0	0.0		0.0	0.0	0.0
Office/Clerical	O				0.0	0.0	0.0		0.0	0.0	0.0
Technician/Service	T/S				0.0	0.0	0.0		0.0	0.0	0.0
Subcontractor (S)					0.0	0.0	0.0				
Total Workhours	A.1	274.8	274.8	274.8							
Labor Subtotal	A.2								13.2	13.9	14.9
A.3 Applied Paid Leave	A.3				17.5	17.5	17.5		2.1	2.2	2.3
(% * A.2)	(A.2+A.3)=A.4								15.3	16.1	17.2
A.5 Benefits (% * A.4)	A.5				22.0	22.6	23.2		3.4	3.6	4.0
Total JPL Direct Compensation	(A.4+A.5)=A.6								18.7	19.7	21.1

B. Travel	Destination		# trips	Cost ea.	Travel Subtotal		
1	Field work		2	7	0.0	0.0	
2	Conferences		2	2	0.0	0.0	
				B	0.0	0.0	0.0
C. Service	List by type, eg. computing, documentation, etc.			Rate	Service Subtotal		
1	Publications				0.0	0.0	
2							
				C	0.0	0.0	0.0
D. Procurement	List by type				Procurement Subtotal		
1							
2							
				D	0.0	0.0	0.0
E. Facilities	List as either new construction or modification				Facilities Subtotal		
1							
2							
				E	0.0	0.0	0.0

F. Total Direct Cost			Total $K	F	18.7	19.7	21.1
G. Indirect Costs	FY'98	FY'99	FY'00				
G.1. Laboratory Burden (% * A.6) Percent of Total Direct Compensation	10.7	10.7	10.7	G.1	1.9	2.0	2.1
G.2. Project Staff Burden Percent of Total Direct Compensation	11.2	11.1	11.3	G.2	2.0	2.1	2.2
G.3. Technical Division Burden ($/hour * A.1)	9.15	9.90	10.44	G.3	2.6	2.7	2.9
H. Subtotal Indirect Costs (G.1+G.2+G.3)				H	6.5	6.8	7.3
I. Subtotal Costs Before Support and General Burden (F+H)				I	25.2	26.5	28.4
J. Support Burden (% * I)	5.6	6.4	7.6	J	1.4	1.7	2.0
K. Subtotal Costs Before General Burden (I+J)				K	26.6	28.2	30.4
L. General Burden (% * K)	5.2	6.3	6.2	L	1.4	1.8	1.4
M. Total JPL Costs (K+L)				M	28.0	30.0	31.8

Terrestrial Ecology Program: NRA-97-MTPE-08

Digital Topography from SAR Interferometry: Determination of and Correction for Vegetation Height

GSFC Budget Component

	YR1	YR2	YR3
Manpower (Full Time Equivalents - FTE)			
GSFC Civil Servant (D. Harding)	0.2	0.2	0.2
GSFC On-site Contractor	0.2	0.2	0.2
Budget ($k)			
Contractor Salary	15	16	17
Publication Page Charges	0	2	2
GSFC MPS Assessment (per FTE)	5	5	5
GSFC Branch Assessment	1	1	1
TOTAL ($k)	21	24	25

Requested Start Date: March 15, 1998. Requested Duration: 36 months

CURRICULUM VITAE
February 1997

PERSONAL

NAME	**Kamal Sarabandi** **Associate Proferssor**
ADDRESS	3225 EECS Building, Radiation Laboratory Ann Arbor, MI 48109-2221. e-mail: saraband@engin.umich.edu **Office Phone** 313-936-1575
HOME ADDRESS	2780 Emberway, Ann Arbor, MI 48104. **Home Phone** 313-995-1031
RESEARCH INTERESTS	Development of scattering models for natural targets (for remote sensing purposes), scattering and propagation of electromagnetic waves in random media, inverse scattering problem, applied computational electromagnetics, and microwave circuits and antenna.

EDUCATION

1986 - 1989	**The University of Michigan, Ann Arbor** Ph.D. in Electrical Engineering. Thesis Advisers: Prof. F.T. Ulaby and Prof. T.B.A. Senior. Dissertation topic: Electromagnetic scattering from vegetation canopies. During five years of graduate studies G.P.A.= 8.41 (A=8.0).
1987 - 1989	**The University of Michigan, Ann Arbor** M.S. in Mathematics (May 1989), concentration in Applied Math.
1984 - 1986	**The University of Michigan, Ann Arbor** M.S.E. in Electrical Engineering, fundamental courses in electromagnetics, optics, and communications.
1975 - 1980	**Sharif University of Technology, Tehran, Iran** B.Sc. in Electrical Engineering.

FUNDED RESEARCH PROJECTS

1. "Development of an advanced wireless and microwave experimental facilities," Sponsor: Hewlett-Packard Company, submission date: January 1997, $279,967, PI: K. Sarabandi, L. Katehi, and B. Gilchrist.
2. "Components and systems for communications: An undergraduate design Laboratory," Sponsor: National Science Foundation, Submission date: Nov. 1996, $100,000. Co-PIs: L. Katehi, K. Sarabandi, B. Gilchrist, G. Rebeiz.
3. "A novel millimeter-wave, low-loss, electronically controlled phase shifter for monolithic, beam-steering phased array antenna applications," 8/96-12/96, $25,054, Sponsor ONR, PI:K. Sarabandi.
4. "Low Energy Electronic Design for Mobile Platforms," 9/96-9/01, $5,000,000/5 Yrs. Sponsor: Army Research Office, Co-PIs: J Coffey, J. East, A. Hero, L. Katehi, S. Lafortune, P. Mazumder, D. Neuhoff, K. Sarabandi, D. Teneketzis, and K. Wasserman.
5. "ARL Federated Laboratories: MMW radar phenomenology," 1/96-12/95, $500,000/Yr. Sponsor: ARL, PI: F.T. Ulaby, L. Katehi, G. Rebeiz, and K. Sarabandi ($86,685/Yr.).
6. "Lane Detection for Automotive Sensors," 5/96-5/97, $167,374/1 Yr., Sponsor:TACOM, Co-PIs:K. Kluge, S. Lakshmanan, and K. Sarabandi.
7. "Millimeter-wave radars as advanced vehicle control and warning systems: A feasibility study," 5/96-5/98, $139,167/2 Yrs. Sponsor: General Motors, PI: K. Sarabandi, Co-I Adib Nashashibi.
8. "Evaluation of radar techniques for assessing snowcover conditions and their effect on the detection of hard targets," 4/95-8/96, $40,000/ 1 Yr. Sponsor: Office of Naval Research, PI: K. Sarabandi, Co-I: F.T. Ulaby.
9. "Digital topography from SAR interferometry: Determination of and correlation for vegetation height," 3/95-3/98, $375,417/3 Yrs. Funded by NASA. PI: K. Sarabandi, CoIs: M.C. Dobson and J.J. van Zyl.
10. "Development and construction of a 77 GHz dual-polarized planar antenna array and associated reflector," 10/95-10/97, $276,000/2 Yrs. Funded by DaimlerBenz Company, Co-PIs: G.M. Rebeiz, K. Sarabandi, and L.P. Katehi.
11. "Development of SAR algorithm for mapping soil moisture and vegetation biomass," 10/94-10/97, $482,716/3 Yrs. Funded by NASA. PI: F.T. Ulaby, CoIs: K. Sarabandi and C. Dobson.
12. "Multi-Frequency, multi-polarization external calibration of the SIR-C/X-SAR," 10/93-10/96, $259,217/3 Yrs. Funded by: JPL. PI: K.Sarabandi, CoI: F.T. Ulaby.
13. "Construct and Deliver an X-band bistatic radar system," 9/93-5/94, $102,000. Funded by U.S. Army Engineer Waterways. PI: F.T. Ulaby, CoI: K. Sarabandi.
14. "Retrieval of soil moisture and roughness from the polarimetric radar response," 5/93-10/96, $404,505/3 Yrs. Funded by NASA. PI: K. Sarabandi, CoI: F.T. Ulaby.
15. "Statistical Behavior of Polarimetric Radar Response of Terrain with Emphasis on the Millimeter-wave Region," 1/92-1/95 $472,000/3 Yrs. Funded by Army Research Office. PI: F.T. Ulaby, CoI: K. Sarabandi.
16. "Investigation of Polarimetric Radar Response to Soil Moisture and Surface Roughness," 4/90-4/93 $300,000/3 Yrs. Funded by NASA. PI: F.T. Ulaby, CoI: K. Sarabandi.

17. "Hewlett Packard University Equipment Grants," June 1993, $42,140. Granted by: HP Company. PI: K. Sarabandi.

PENDING PROPOSALS

1. "Multifunction, compact vehicular antennas (MCA): New generation of antenna structures," Sponsor:National Science Foundation, Submission date: January 1997, $482,432. Co-PIs: L. Katehi and K. Sarabandi.
2. "Near-field polarimetric bistatic scattering: System design and measurements," Sponsor: Air Force, submission date: January 1997, $124,000/3yrs. PI: K. Sarabandi.
3. "Wire Obstacle Detection Radar Sensor For Ground Vehicles," Sponsor: DARPA, submission date: October 1996, $375,104/2 Yrs. PI: K.Sarabandi, Co-PIs: S. Lakshmanan, and K.C. Kluge.
4. "Characterization of Bistatic Scattering Coefficient of Some Distributed Targets at Microwave and Millimeter-wave Frequencies," Sponsor: U.S. Army Missile Command, submission date: Oct. 1996, $96,775/yr., PI: K. Sarabandi.
5. "Construction of a 77 GHz Polarimetric Radar Front-End for Assessment of Radar Sensors for Automotive Applications," submission date: Feb. 1997, $60,000/1yr. Sponsor: General Motors Corporation, PI: K. Sarabandi.
6. "Retrieval Algorithms for Active Remote Sensing," Sponsor: Synoptics (a Sub-contract from European Space Agnecy), Submission date: June 96, $25,000/1Yr. PI: K.Sarabandi.
7. "Target Classification and Estimation of Biophysical Parameters Using The Correlation Function of the Radar Backscatter," Sponsor: Joint Reseach Center of European Commission, submission date: July 1996, $147,611/1yr. PI: K. Sarabandi.
8. "Initial Testbed Study of Automotive Radar," submission date: Feb. 1996, $50,000/1yr. Sponsor: TRW Company, Co-PIs: Robert Ervin, Gabriel Rebeiz, and Kamal Sarabandi.

PATENTS

1. Sarabandi, K., and R. Hartikka, "Microwave and millimeter wave polarization controller," Disclosure submitted to University of Michigan Intellectual Property Office, May 1994.

BOOK CHAPTERS

1. Kendra, J.R., F.T. Ulaby, and K. Sarabandi, "Snow probe for *in situ* determination of wetness and density," in Microwave Aquametry: Electromagnetic Wave Interaction with Water-Containing Materials, A. Kraszewski editor, IEEE Press, New York, 1996.
2. Ulaby, F.T., and K. Sarabandi, "Characterization of Antenna Polarization and Brightness Temperature Stokes Vector," in AIAA Space Based Microwave Systems Calibration Manual, J.P. Hollinger, editor, 1993.
3. Senior, T.B.A., and K. Sarabandi, "Scattering Models for Point Targets," in Radar Polarimetry for Geoscience Applications, F.T. Ulaby and C. Elachi, eds., Artech House, Dedham MA, 1990.
4. Whitt, M.W., F.T. Ulaby, and K. Sarabandi, "Polarimetric Scatterometer Systems and Measurements," in Radar Polarimetry for Geoscience Applications, F.T. Ulaby and C. Elachi, eds., Artech House, Dedham MA, 1990.

JOURNAL PUBLICATIONS

1. Chiu, T.C., and K. Sarabandi, "Electromagnetic scattering interaction between a dielectric cylinder and a slightly rough surface," *IEEE Trans. Antennas Propagat.*, submitted for publication (June 1997).

2. Ulaby, F.T., A. Nashashibi, A. El-Rouby, E. Li, R. Deroo, K. Sarabandi, R. Wellman, and B. Wallace, "Millimeter-wave scattering by terrain at near grazing incidence," *IEEE Trans. Antennas Propagat.*, submitted for publication (May 1997).

3. Sarabandi,K., A. Nashashibi,"Analysis and applications of backscattered frequency correlation function,"*IEEE Trans. Geosci. Remote Sensing.*, submitted for publication (April 97).

4. Sarabandi, K., Eric S. Li, A. Nashashibi, and B. Litkouhi, "Modelling and Measurements of Scattering from Road Surfaces at Millimeter-wave Frequencies," *IEEE Trans. Antennas Propagat.*, submitted for publication (Feb. 1997).

5. Sarabandi, K., and Y.C. Lin, "Simulation of Interferometric SAR Response for Characterization of Scattering Phase Center Statistics of Forest Canopies," *IEEE Trans. Geosci. Remote Sensing.*, submitted for publication (Jan. 97).

6. Lin, Y.C., and K. Sarabandi, "A Monte Carlo Coherent Scattering Model For Forest Canopies Using Fractal Generated Trees," *IEEE Trans. Geosci. Remote Sensing.*, submitted for publication (Sept. 96).

7. Sarabandi, K., and E. Li, "Characterization of Optimum Polarization for Multiple Target Discrimination Using Genetic Algorithms,"*IEEE Trans. Antennas Propagat.*, submitted for publication (August 1996).

8. Sarabandi,K., and T.C. Chiu "Electromagnetic scattering from slightly rough surfaces with inhomogeneous dielectric profile," *IEEE Trans. Antennas Propagat.*, submitted for publication (April 1996).

9. Sarabandi,K., "Δk-Radar equivalent of Interferometric SARs: A Theoretical Study for determination of vegetation height,"*IEEE Trans. Geosci. Remote Sensing.*, accepted for publication (Dec. 96).

10. Ulaby, F.T., P.R. Sequeira, A. Nashashibi, and K. Sarabandi, "Semi-empirical model for radar backscatter from snow at 35 and 95 GHz," *IEEE Trans. Geosci. Remote Sensing.*, vol. 34, no. 5, pp. 1059-1065, Sept. 96.

11. Kendra, J. R., and K. Sarabandi, "A hybrid experimental/theoretical scattering model for dense random media,"*IEEE Trans. Geosci. Remote Sensing.*, submitted for publication (Sept. 95).

12. Kendra, J. R., K. Sarabandi, F.T. Ulaby, "Radar measurements of snow: Experiment and analysis,"*IEEE Trans. Geosci. Remote Sensing.*, submitted for publication (Sept. 95).

13. Nashshibi, A., and K. Sarabandi, "Experimental characterization of the effective propagation constant of dense random media," *IEEE Trans. Antennas Propagat.*, submitted for publication (August 1995).

14. Siqueira, P.R., and K. Sarabandi, "Method of moments evaluation of the two-dimensional quasi-crystalline approximation,"*IEEE Trans. Antennas Propagat.*, vol. 44, no. 8, pp. 1067-1077, Aug. 1996.

15. Sarabandi, K., and E. S. Li, "A microstrip ring resonator for non-invasive dielectric measurements," *IEEE Trans. Geosci. Remote Sensing.*, accepted for publication (May 95).

16. Dobson, M.C., F.T. Ulaby, L.E. Pirece, T.L. Sharik, K.M. Bergen, J. Kellndorfer, J.R. Kendra, E. Li, Y.C. Lin, A. Nashashibi, K. Sarabandi, and P. Siqueira, "Estimation of Forest Biomass," *IEEE Trans. Geosci. Remote Sensing.*, vol. 33, no. 4, pp. 887-895, July 1995.

17. Sarabandi, K., and P. Siqueira, "Numerical scattering analysis for two dimensional dense random media: characterization of effective permittivity," *IEEE Trans. Antennas Propagat.*, vol. 45, no. 5, May 1997.

18. Freeman, A., M. Alves, B. Chapman, J. Cruz,, Y. Kim, S. Shaffer, J. Sun, E. Turner, and K. Sarabandi, "SIR-C Calibration Results," *IEEE Trans. Geosci. Remote Sensing.*, vol. 33, no. 4, pp. 848-857, July 1995.

19. Stiles, J.M., and K. Sarabandi, "A scattering model for thin dielectric cylinders of arbitrary cross-section and electrical length," *IEEE Trans. Antennas Propagat.*, vol. 44, no.2,260-266, Feb. 1996.

20. Sarabandi, K., and A. Nashashibi, "A novel bistatic scattering matrix measurement technique using a monostatic radar," *IEEE Trans. Antennas Propagat.*, vol. 44, no. 1, 41-50, Jan. 1996.

21. Sarabandi, K., L. Pierce, M.C. Dobson, F.T. Ulaby, J. Stiles, T.C. Chiu, R. De Roo, R. Hartikka, A. Zambetti, and A. Freeman, "Polarimetric calibration of SIR-C using point and distributed targets," *IEEE Trans. Antennas Propagat.*, vol. 33, no. 4, pp. 858-866, July 1995.

22. Sarabandi, K., and T.C. Chiu," An optimum corner reflector for calibration of imaging radars," *IEEE Trans. Antennas Propagat.*, vol. 44, no. 10, Oct. 1996.

23. Lin, Y.C., and K. Sarabandi, "Electromagnetic scattering model for a tree trunk above a ground plane," *IEEE Trans. Geosci. Remote Sensing.*, vol. 33, no. 4, pp. 1063-1070, July 1995.

24. Oh, Y., and K. Sarabandi, "An improved numerical simulation of electromagnetic scattering from perfectly conducting random surfaces," *IEE Proceedings- Microwave, Antennas and Propagat.*, accepted for publication.

25. Nashashibi, A., K. Sarabandi, F.T. Ulaby, "A calibration technique for polarimetric coherent-on-receive radar system," *IEEE Trans. Antennas Propagat.*, vol. 43, no. 4, pp. 396-404, April 1995.

26. Siqueira, P., K. Sarabandi, and F.T. Ulaby, "Numerical simulation of scatterer positions in a very dense medium with an application to the two-dimensional Born approximation," *Radio Sci.*, vol. 30, no. 5, pp 1325-1339, 1995.

27. Sarabandi, K., "A technique for dielectric measurement of cylindrical objects in a rectangular waveguide," *IEEE Trans. Instrum. Meas.*, vol. 43, no. 6, pp. 793-798, Dec. 1994.

28. Polatin, P.F., K. Sarabandi, and F.T. Ulaby,"Monte Carlo simulation of electromagnetic scattering from a heterogeneous two-component medium," *IEEE Trans. Antennas Propagat.*, vol. 43, no. 10, pp. 1048-1057, Oct. 1995.

29. Pierce, L.E., F.T. Ulaby, K. Sarabandi, and M.C. Dobson,"Knowledge-based classification of polarimetric SAR images," *IEEE Trans. Geosci. Remote Sensing.*, vol. 32, no. 5, pp. 1081-1086, Sept. 94.

30. Nashashibi, A., F.T. Ulaby, and K. Sarabandi, "Measurement and modeling the millimeter-wave backscatter response of soil surfaces," *IEEE Trans. Antennas Propagat.*, vol. 34, no. 2, 561-572, March 1996.

31. Kendra, J.R., F.T. Ulaby, and K. Sarabandi, "Snow probe for *in situ* determination of wetness and density," *IEEE Trans. Geosci. Remote Sensing.*, vol. 32, no. 6, 1152-1159, Nov. 1994.

32. Sarabandi, K., "A waveguide polarization controller," *IEEE Trans. MTT*, vol. 42, no. 11, 2171-2174, Nov. 1994.

33. Sarabandi, K., and P.F. Polatin, "Electromagnetic scattering from two adjacent objects," *IEEE Trans. Antennas Propagat.*, vol. 42, no. 4, pp. 510-517, April 1994.

34. Sarabandi, K., Y. Oh, and F.T. Ulaby, "A numerical simulation of scattering from inhomogeneous dielectric random surfaces," *IEEE Trans. Geosci. Remote Sensing*, vol. 34, no.2, 425-432, March 1996.

35. Sarabandi, K., L. Pierce, Y. Oh, and F.T. Ulaby, "Power lines: Radar measurements and detection algorithm for polarimetric SAR images," *IEEE Trans. Aerospace and Electronic Sys.*, vol. 30, no. 2, 632-648, April 1994.

36. Sarabandi, K., L.E. Pierce, Y. Oh, M.C. Dobson, A. Freeman, and P. Dubois, "Cross calibration experiment using JPL AIRSAR and truck-mounted polarimetric scatterometers," *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 5, 975-985, Sept. 1994.

37. Stiles, J.M., K. Sarabandi, and F.T. Ulaby, "Microwave scattering model for grass blade structures," *IEEE Trans. Geosci. Remote Sensing*, vol. 31, no. 5, 1051-1059, Sept. 1993.

38. Sarabandi, K., "Calibration of a polarimetric synthetic aperture radar using a known distributed target" *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 3, 575-582, May 1994.

39. Pierce, L.E., K. Sarabandi, and F.T. Ulaby, "Application of an artificial neural network in a canopy scattering model inversion," *Int. J. Remote Sensing*, vol. 15, no. 16, 3263-3270, 1994.

40. Polatin, P.F., K. Sarabandi, and F.T. Ulaby, "An iterative inversion algorithm with application to the polarimetric radar response of vegetation canopies," *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 1, 62-71, Jan. 1994.

41. Sarabandi, K., P.F. Polatin, and F.T. Ulaby, "Monte carlo simulation of scattering from a layer of vertical cylinders," *IEEE Trans. Antennas Propagat.*, vol. 41, no. 4, 465-475, April 1993.

42. Sarabandi, K., Y. Oh, and F.T. Ulaby, "Measurement and calibration of differential Mueller matrix of distributed targets," *IEEE Trans. Antennas Propagat.*, vol. 40, no. 12, 1524-1532, Dec. 1992.

43. Dobson, M.C., L.E. Pierce, K. Sarabandi, F.T. Ulaby, and T. Sharik, "Preliminary analysis of ERS-1 SAR for forest ecosystem studies," *IEEE Trans. Geosci. Remote Sensing.*, vol. 30, no. 2, 203-211, March 1992.

44. Oh, Y., K. Sarabandi, and F.T. Ulaby,"An empirical model and an inversion technique for radar scattering from bare soil surfaces," *IEEE Trans. Geosci. Remote Sensing.*, vol. 30, no. 2, 370-381, March 1992.

45. Sarabandi, K., A. Tavakoli, and F.T. Ulaby, "Propagation in a two-dimensional periodic random medium with inhomogeneous particle distribution," *IEEE Trans. Antennas Propagat.*, vol. 40, no. 10, 1175-1186, Oct. 1992.

46. Sarabandi, K., "Derivation of phase statistics of distributed targets from the Mueller matrix," *Radio Sci.*, vol. 27, no. 5, pp 553-560, 1992.

47. Ulaby, F.T., K. Sarabandi, and A. Nashashibi,"Statistical properties of the Mueller matrix of distributed targets," *IEE Proceedings-F: "Remote Sensing Radars"*, vol. 139, no. 2, 136-146, 1992.

48. Sarabandi, K., "Scattering from dielectric structures above impedance surfaces and resistive sheets," *IEEE Trans. Antennas Propagat.*, vol. 40, no. 1, 67-78, Jan. 1992.

49. Tavakoli, A., K. Sarabandi, and F.T. Ulaby, " Microwave propagation constant for a vegetation canopy at X-band", *Radio Sci.*, vol.28, no.4, 549-588, July-Aug. 1993.

50. Sarabandi, K., L.E. Pierce, and F.T. Ulaby, "Calibration of a polarimetric imaging SAR", *IEEE Trans. Geosci. Remote Sensing.*, vol. 30, no. 3, 540-549, May 1992.

51. Sarabandi, K., Y. Oh, and F.T. Ulaby, " Application and performance characterization of polarimetric active radar calibrator", *IEEE Trans. Antennas Propagat.*, vol. 40, no. 10, 1147-1154, Oct. 1992.

52. Tavakoli, A., K. Sarabandi, and F.T. Ulaby, " Horizontal propagation through periodic vegetation canopies", *IEEE Trans. Antennas Propagat.*, vol. 39, no. 7, 1014-1023, July 1991.

53. Sarabandi, K., and F.T. Ulaby, " High frequency scattering from corrugated stratified cylinders", *IEEE Trans. Antennas Propagat.*, vol. 39, no. 4, 512-520, April 1991.

54. Sarabandi, K.," Simulation of a periodic dielectric corrugation with an equivalent anisotropic layer", *Int. J. Infrared and Millimeter Waves*, vol. 11, no. 11, 1303-1321, Nov. 1990.

55. Ulaby, F.T., M.W. Whitt, and K. Sarabandi, "AVNA-Based polarimetric scatterometers", IEEE Antennas Propagat. Magazine, vol. 32, no. 5, Oct. 1990.

56. Sarabandi, K., and F.T. Ulaby, " A convenient technique for polarimetric calibration of radar systems", *IEEE Trans. Geosci. Remote Sensing*, vol. 28, no. 6, 1022-1033, Nov. 1990.

57. Sarabandi, K., "Scattering from variable resistive and impedance sheets", *J. Electromag. Waves and Applics.*, vol. 4, no. 9, 865-891, 1990.

58. Sarabandi, K., and T.B.A. Senior, "Low frequency scattering from cylindrical structures at oblique incidence", *IEEE Trans. Geosci. Remote Sensing*, vol. 28, no. 5, 879-885, Sept. 1990.

59. Senior, T.B.A., K. Sarabandi, J.Natzke, "Scattering by a narrow gap", *IEEE Trans. Antennas Propagat.*, vol. 38, no. 7, 1102-1110, July 1990.

60. Ulaby, F.T., K. Sarabandi, K. McDonald, M. Whitt, M.C. Dobson, "Michigan Microwave Canopy Scattering Model", *Int. J. Remote Sensing*, vol. 11,no. 7, 1223-1253, July 1990.

61. Sarabandi, K., F.T. Ulaby, and T.B.A. Senior, "Millimeter wave scattering model for a leaf", *Radio Sci.*, 25, 9-18, Jan. 1990.

62. Sarabandi, K., F.T. Ulaby, and M.A. Tassoudji, "Calibration of polarimetric radar systems with good polarization isolation", *IEEE Trans. Geosci. Remote Sensing*, vol. 28, no. 1, 70-75, Jan. 1990.

63. Sarabandi, K., T.B.A. Senior, and F.T. Ulaby, "Effect of curvature on the backscattering from a leaf", *J. Electromag. Waves and Applics.*, 2, 653-670,1988.

64. Sarabandi, K., and F.T. Ulaby, "Technique for measuring the dielectric constant of thin materials", *IEEE Trans. Instrum. Meas.*, vol 37, no. 4, 631-636, 1988.

65. Senior, T.B.A., K. Sarabandi, and F.T. Ulaby, "Measuring and modeling the backscattering cross section of a leaf", *Radio Sci.*, 22, 1109-1116,1987.

CONFERENCE PAPERS

More than 110 papers and presentations in national and international conferences and symposia on electromagnetic scattering, random media modeling, microwave measurement techniques, radar calibration, application of neural networks in inverse scattering problems, and microwave sensors. model for radar backscatter from snow at 35 and 94 GHZ," *Proc. IEEE Trans. Geosci. Remote Sensing Symp.*,

HONORS, AWARDS, AND PROFESSIONAL ACTIVITIES

- HP Equipment Award, April 1997.
- Henry Russel Award, The Regent of The University of Michigan, January 1997. (The higest award granted at The University of Michigan).
- Teaching Excellence Award, The University of Michigan, March 1996.
- Second prize, IEEE AP-S'95 paper contest with Adib Nashashibi.
- HP Equipment Award, June 1993.
- Chairman of Geoscience and Remote Sensing Society Southeastern Michigan chapter.
- Member of the Electromagnetics Academy.
- Member of USNC/URSI Commission F.
- Member of review panel for NASA's Earth Science and Applications Division.
- Listed in Who's Who in Electromagnetics.
- Member of steering committee for IEEE AP/URSI symposium, Ann Arbor, June 1993.
- Member of steering committee for IEEE National Radar Conference, Ann Arbor, May 1996.
- Technical chairman and organizer of CEOS (Committee on Earth Observing Satellites) SAR Calibration Workshop, Ann Arbor Sept. 1994.
- Chairman of radar science group in "Remote Sensing Science Workshop," Feb. 27 - March 1 1995, NASA Goddard Space Flight Center.
- Chairman and organizer of numerous technical sessions in IEEE-IGARSS and IEEE-AP/URSI symposia.
- Senior member IEEE, Antennas and Propagation Society, Geoscience and Remote Sensing Society.
- Journal Reviewer
  - IEEE transactions on Geoscience and Remote Sensing.
  - IEEE transactions on Antennas and Propagation.
  - Journal of Electromagnetic Waves and Applications.
  - Radio Science.

M. CRAIG DOBSON

Associate Research Scientist
Radiation Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109-2122

Date of Birth - October 25, 1951	Rochester, New York, USA

B.A. Geology	University of Pennsylvania, Philadelphia, PA, 1973
B.A. Anthropology	University of Pennsylvania, Philadelphia, PA, 1973
M.A. Geography	University of Kansas, Lawrence, KS, 1981

September 1996 - present	Assoc. Research Scientist, Radiation Laboratory
September 1989 - September 1996	Assistant Research Scientist, Radiation Laboratory
September 1984 - August 1989	Sr. Assoc. Research Engineer, Radiation Lab
July 1983 - September 1984	Assoc. Research Scientist, University of Kansas, Center for Research, Remote Sensing Laboratory
January 1981 - July 1983	Project Manager, Microwave Soil Moisture Project, RSL, University of Kansas Center for Research
May 1979 - January 1981	Project Scientist, Remote Sensing Laboratory, University of Kansas Center for Research
September 1973 - January 1975	Geologist, Location and Design Concepts Team, Kansas Department of Transportation

SYNOPSIS OF PUBLICATIONS

- Books:
  - Published (2), Chapt. (1)
- Papers in Refereed Journals:
  - Published (39)
- Papers Published in Conference Proceedings and Digests (77)
- Technical Reports (46)
- Papers Presented at Symposia and Workshops (127)

AWARDS

Prize Paper Award (1994) - IEEE Trans. Geoscience and Remote Sensing
Research Excellence Award (1996) - University of Michigan College of Engineering

BOOKS

Ulaby, F. T. and M. C. Dobson, Handbook of Radar Scattering Statistics for Terrain, Artech House, Inc., Dedham, MA, 1989, 350 pages.

Ulaby, F. T. and M. C. Dobson, Radar Scattering Statistics Software and User's Manual, Artech House, Inc., Dedham, MA, 1989, 100 pages.

Dobson, M.C. and F.T. Ulaby, Manual of Remote Sensing, 3rd Ed. in press, Volume on Radar, chap. on Radar Remote Sensing of Soil, Am. Soc. of Photogrammetry, 1997.

SELECTED RECENT PAPERS

Dobson, M.C., F.T. Ulaby, T. LeToan, A. Beaudoin, E.S. Kasischke, "Dependence of Radar Backscatter on Conifer Forest Biomass," IEEE Trans. Geosci. Rem. Sens, 30:2:412-415,1992.

Dobson, M.C., L. Pierce, K. Sarabandi, F.T. Ulaby, T.L. Sharik, "Preliminary Analysis of ERS-1 SAR for Forest Ecosystem Studies," IEEE Trans. Geosci. Rem. Sens, 30:2:203-211,1992.

Way, J.B., E. Rignot, K. McDonald, R. Oren, R. Kwok, G. Bonan, C. Dobson, L. Viereck, "Evaluating the Type and State of Alaska Taiga Forests with Imaging Radar for Use in Ecosystem Flux Models," IEEE Trans. Geosci. Rem. Sens, 32:2:353-370,1994.

Pierce, L.E., K. Sarabandi, F.T. Ulaby, M.C. Dobson, "Knowledge-Based Classification of SAR Images," IEEE Trans. Geosci. Rem. Sens, 32:5:1081-1086,1994.

Dobson, M.C., L.E. Pierce, F.T. Ulaby, "Knowledge-Based Land-Cover Classification Using ERS-1/JERS-1 SAR Composites," IEEE Trans. Geosci. Rem. Sens, 34:1:83 - 99,1996.

Dobson, M.C., F.T. Ulaby, L.E. Pierce, "Land-Cover Classification and Estimation of Terrain Attributes Using Synthetic Aperture Radar," Rem. Sens. Env., 51:1:199-214, 1995.

Peplinski, N.R., F.T. Ulaby, M.C. Dobson, "Dielectric Properties of Soils in the 0.3-1.3 GHz Range," IEEE Trans. Geosci. Rem. Sens., 33:3:803-807,1995.

Dobson, M.C., F.T. Ulaby, L. E. Pierce, T.L. Sharik, K.M. Bergen, J. Kellndorfer, J.R. Kendra, E. Li, Y.C. Lin, A. Nashashibi, K. Sarabandi, P. Siqueira, "Estimation of Forest Biophysical Characteristics in Northern Michigan with SIR-C/X-SAR," IEEE Trans. Geosci. Rem. Sens., 33:4:877-895,1995.

Kasischke, E.S., J.M. Melack, M.C. Dobson, "The Use of Imaging Radars for Ecological Applications - A Review," Rem. Sens. Env., 59:141-156, 1997.

Pierce, L.E., K.M. Bergen, M.C. Dobson, F.T. Ulaby, "Classification of Northern Forests Using SIR-C/X-SAR," IEEE Trans. Geosci. Rem. Sens, 1997, sub.

Bergen, K.M., M.C. Dobson, L.E. Pierce, F.T. Ulaby, "Characterizing Carbon Dynamics in a Northern Forest Using SIR-C/X-SAR Imagery," Rem. Sens. Env., in press.

Kellndorfer, J.M., M.C. Dobson, F.T. Ulaby, "A Multi-Ecoregion Classifier Based on Existing Orbital Imaging Radar," Proc. 13th William T. Pecora Symp., August 20 - 22, 1996, Sioux Falls, SD.

Dobson, M.C. and J.M. Kellndorfer, "Spatial and Temporal Stability of a Regional-Scale Land-Cover Classification from Orbital SAR," 1996 Ecol. Soc. Am. Symp., Aug. 11-15, 1996, Providence, RI., Sup. Bull. Ecol. Soc. Am., 77:3:115,

Kellndorfer, J.M., M.C. Dobson, F.T. Ulaby, "Toward Consistent Global Physiognomic Vegetation Mapping Using ERS/JERS SAR Classification", IGARSS'97 Digest, August 4-8, 1997, Singapore. 1996.

Robert N. Treuhaft
Radar Science and Engineering Section
Mail Stop 300-235
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
Bob_Treuhaft@radar-email.jpl.nasa.gov
818-354-6216

Education

Ph.D. Physics,	University of California, Berkeley, 1982, thesis topic in high energy nuclear physics: "A (proton, 2-proton) Study of High Momentum Components at 2.1 GeV".
M. S. Physics,	University of California, Berkeley, 1978.
B. S. Physics,	*Magna cum laude*, Departmental Honors, Yale University, 1976.

Employment

1993-1997:	Member technical staff, Radar Science and Engineering, Jet Propulsion Lab.
1986-1993:	Technical Group Supervisor, Astrometric Techniques Group, JPL.
1983-1986:	Project Manager, Radio Metric Technology Development, JPL.

Refereed Publications

R. N. Treuhaft, S. N. Madsen, M. Moghaddam, and J. J. van Zyl, "Vegetation Characteristics and Surface Topography from Interferometric Radar," *Radio Science*, **31**, p. 1449-1485, 1996.

R. P. Linfield, S. J. Keihm, M. J. Mahoney, L. P. Teitelbaum, R. N. Treuhaft, and S. J. Walter, "A Test of WVR-Based Troposphere Calibration Using VLBI Observations on a 21-km Baseline," *Radio Science*, **31**, p. 129-146, 1996.

R. N. Treuhaft, S. T. Lowe, M. Bester, W. C. Danchi, and C. H. Townes, "Vertical Scales of Turbulence at the Mt. Wilson Observatory," *Astrophysical Journal*, **453**, p. 522-531, November 1995.

R. N. Treuhaft and S. T. Lowe, "A Measurement of Planetary Relativistic Deflection," *Astronomical Journal*, **102**, p. 1879-1888, November 1991. (Reviewed in *Science News*, November 9, 1991 and in *Nature*, November 21, 1991).

O. J. Sovers, C. D. Edwards, C. S. Jacobs, G. E. Lanyi, K. M. Liewer, and R. N. Treuhaft, "Astrometric Results of 1978-1985 Deep Space Network Radio Interferometry: The JPL 1987-1 Extragalactic Source Catalog," *Astronomical Journal*, **95**, p. 1647-1658, 1988.

R. N. Treuhaft and G. E. Lanyi, "The Effect of the Dynamic Wet Troposphere on Radio Interferometric Measurements," *Radio Science*, **22**, p. 251-265, 1987.

Presentations and Conference Proceedings

R. N. Treuhaft, M. Moghaddam, and B. J. Yoder, "Forest Vertical Structure from Multibaseline Interferometric Radar for Studying Growth and Productivity" IGARSS97, Singapore, August 1997 (invitec

R. N. Treuhaft, M. Moghaddam, and J. J. van Zyl, "Combining Radar Interferometry and Polarimetry to Estimate Forest Vegetation and Surface Parameters," PIERS97, Cambridge, Massachusetts, July 1997 (invited).

R. N. Treuhaft, E. Rodriguez, M. Moghaddam, K. Sarabandi, and J. J. van Zyl., "Multibaseline, Multifrequency Interferometric SAR for Vegetation and Surface Topographic Parameter Estimation," *URSI 25th General Assembly,* Lille, France, August 1996 (invited).

R. N. Treuhaft, M. Moghaddam, K. Sarabandi, and J. J. van Zyl, "Extracting Vegetation and Surface Characteristics from Multibaseline Interferometric SAR," IGARSS'96, Lincoln, Nebraska, May 1996.

R. N. Treuhaft, "The Information Content of Interferometric Synthetic Aperture Radar: Vegetation and Underlying Surface Topography," 6th Annual JPL Airborne Earth Science Workshop, March 1996 (invited).

R. N. Treuhaft, J. J. van Zyl, and K. Sarabandi, "Extracting Vegetation and Surface Characteristics from Multibaseline Interferometric SAR," *EOS Transactions, American Geophysical Union*, **76**, November 1995.

R. N. Treuhaft and M. Moghaddam, "The Accuracy of Vegetation Characteristics Extracted from Interferometric SAR Data," Proceedings of Progress in Electromagnetics Research Symposium, Seattle Washington, p. 905, July 1995.

R. N. Treuhaft, M. Moghaddam, E. Rignot, S. S. Saatchi, and J. J. van Zyl, "Extracting Vegetation Topographic and Scattering Characteristics from Interferometric SAR," National Radio Science Meeting, Boulder, Colorado, January 6, 1995.

L. P. Teitelbaum, S. J. Keihm, M. J. Mahoney, R. P. Linfield, G. M. Resch, and R. N. Treuhaft, "A Test of WVR-Based Troposphere Delay Calibration Using VLBI Observations on a 20-km Baseline," National Radio Science Meeting, Boulder, Colorado, January 5, 1995.

R. N. Treuhaft, M. Bester, W. C. Danchi, S. T. Lowe, and C. H. Townes, "Toward 10-Milliarcsecond Infrared Astrometry," *Proceedings of SPIE Symposium on Astronomical Telescopes and Instrumentation for the 21st Century,* Kona, Hawaii, March 1994.

R. N. Treuhaft, B. L. Gary, S. J. Keihm, R. P. Linfield, M. J. Mahoney, L. P. Teitelbaum, S. J. Walter, and J. Z. Wilcox, "Minimizing Tropospheric Path Delay Effects in Astrometric and Geodetic VLBI," *URSI 24th General Assembly*, Kyoto, Japan, September 1993 (invited).

M. Bester, W. C. Danchi, C. H. Townes, and R. N. Treuhaft, "Atmospheric Seeing at Infrared Wavelengths," *182nd Meeting of the American Astronomical Society*, Berkeley, California, June 1993.

R. N. Treuhaft, "Subnanoradian, Ground-Based Tracking of Spaceborne Lasers," *NASA/DOD Workshop on Advanced Technologies for Planetary Instruments*, Fairfax, Virginia, April, 1993.

R. N. Treuhaft, "Astrometry for Deep Space Tracking," *National Radio Science Meeting*, Boulder, Colorado (invited), January 7, 1993.

CURRICULUM VITA

April 1994

JAKOB JOHANNES VAN ZYL

ADDRESS:

Radar Science and Engineering Section,
M.S. 300-243, Jet Propulsion Laboratory,
California Institute of Technology,
4800 Oak Grove Drive,
Pasadena, CA 91109
(818) 354-1365.

RESEARCH INTERESTS:

EM wave propagation and scattering, development of remote sensing techniques, radar polarimetry and interferometry, antenna theory.

EDUCATION:

Ph.D., Electrical Engineering, 1986.
California Institute of Technology, Pasadena, CA.
Thesis Title: On the Importance of Polarization in Radar Scattering Problems.

M.S., Electrical Engineering, 1983.
California Institute of Technology, Pasadena, CA.

Hons. B.Eng., (Cum Laude) Electrical Engineering, 1979.
University of Stellenbosch, Stellenbosch, South Africa.

MEMBERSHIPS AND HONORS:

1977 Philips prize for best performing junior in electrical engineering, University of Stellenbosch.

1979 Siemens prize for best achievement in graduating class, electrical engineering, University of Stellenbosch.

1988 JPL Director's Research Achievement award.

1988 IEEE Geoscience and Remote Sensing Transactions Paper Prize.

Patent: Data volume reduction for imaging radar polarimetry.

Patent: Method for providing a polarization filter for processing synthetic aperture radar image data

NASA Certificates of Recognition:

- Data volume reduction for imaging radar polarimetry.
- Unsupervised classification of scattering mechanisms using radar polarimetry data.
- Imaging Radar Polarimetry.
- Polarization filtering of SAR data.
- Data volume reduction for single-look polarimetric imaging radar data: 8-bit and 4-bit quantization.
- Calibration of polarimetric radar images using only image parameters and trihedral corner reflectors.
- Incorporation of polarimetric radar images into multisensor data sets.
- Classification of earth terrain using polarimetric synthetic aperture radar images.
- Approaches to modeling polarization characteristics of surfaces for radar polarimetry.
- Calibration of NASA/JPL DC-8 SAR data.
- Calibration of Stokes and scattering matrix format polarimetric SAR data
- Unsupervised segmentation of polarimetric SAR data using the covariance matrix
- POLCAL Version 4.0
- Iterative Bayesian classification in polarimetric SAR

- Direction angle sensitivity of agricultural field backscatter with AIRSAR data
- Software for calibration of polarimetric SAR data

Memberships:

- The Electromagnetics Academy: Institute for Electromagnetic Modeling and Applications
- IEEE
- Technical Chairman of the 1993 Progress in Electromagnetics Research Symposium

WORK EXPERIENCE:

1980 - 1982:	Institute for Electronics, University of Stellenbosch, South Africa. Member of research staff. Responsible for design and assembly of a microprocessor based radar measurement system for use in study of ocean waves.
1983 - 1985:	Research Assistant, California Institute of Technology, Pasadena, CA. Advisor: Prof. C. H. Papas. Also served as Teaching Assistant for a course on the physics of remote sensing (Teacher: C. Elachi).
1986 - 01/1990:	Member of Radar Sciences group of Geology and Planetology Section at the Jet Propulsion Laboratory, Pasadena, CA.
02/1990 - present:	Group supervisor, Aircraft SAR group in the Radar Science and Engineering Section at the Jet Propulsion Laboratory, Pasadena, CA. Overall technical and line management responsibility for the NASA/JPL multifrequency AIRSAR system

CURRICULUM VITAE
David J. Harding

ADDRESS:
NASA Goddard Space Flight Center
Mail Code 921
Greenbelt, MD 20771
301-286-4849 (voice), -1616 (fax)
harding@denali.gsfc.nasa.gov

EDUCATION:
Ph. D., Cornell University, 1988
  major: geological sciences, minor: remote sensing
B. Sc., Cornell University, 1980
  major: geological sciences

POSITIONS HELD:
1991-current: Staff Scientist, Laboratory for Terrestrial Physics, NASA GSFC
1990-1991: Research Faculty, Department of Geology, University of Maryland
1988-1990: NRC Post-doctoral Research Assoc., Lab for Terrestrial Physics, NASA GSFC

CURRENT FUNDING:
1996-1998: Laser Altimeter Processing Facility (PI, NASA MTPE, $200K in FY97)
1995-1997: Three-Dimensional Canopy Structure: Measurement by Laser Altimetry and Input to Ecology Models (PI, NASA Ecological Processes and Modelling Program, $118K in FY97, final year)
1994-1997: Multi-Beam Laser Altimeter Science Studies (PI, NASA Solid Earth Processes Branch, $20K in FY97)

PENDING PROPOSALS:
1998-2000: this submission
1998-1999: Surface Lidar and Optical Image Fusion for Improved Boreal Forest Canopy Structure Parameterizations (PI, NASA NRA-97-MTPE-08, proposal in preparation)
1998-2000: Northern Forest Biophysical Properties for MODIS Land Product Validation (Co-I, NASA NRA-87-MTPE-03, 0.1 MY per year)
1998-1999: Tropical Forest Canopy Structure from Multi-sensor Remote Sensing (Co-I, NASA NRA-97-MTPE-02, 0.2 MY per year)

PROFESSIONAL SERVICE:
1995: Remote Sensing Sciences Workshop, NASA Ecological Processes and Modelling Program
1994: Peer Review Panel, Topography and Surface Change Program, NASA Solid Earth Processes Branch
1994: Workshop on the Use of Satellites in Natural Disaster Reduction, NASA Solid Earth Processes Branch
1994: SAR Interferometry and Surface Change Detection Workshop, NASA Solid Earth Processes Branch
1993: Airborne Geophysics Workshop, Committee on Geodesy, National Academy of Sci.
1990-1993: Joint NASA - Italian Space Agency Topographic Mission Concept Working Group

SELECTED PUBLICATIONS:
Interferometric SAR and Laser Altimeter Measurement of Canopy Height Characteristics for Coniferous Forests, E. Rodriguez, T. Michel, D. J. Harding, submitted, Radio Science.

Characterization of vertical canopy structure derived from laser altimeter waveforms of Gifford Pinchot National Forest, J.F. Weishampel, D. J. Harding, and J. B. Blair, accepted, Remote Sensing of Environment.

Remote Sensing of Forest Canopies, J.F. Weishampel, K.J. Ranson, D.J. Harding, 1996, Selbyana, 17:6-14.

The Global Topography Mission, T. Farr, D. Evans, H. Zebker, D. Harding, J. Bufton, T. Dixon, S. Vetrella, and D. Gesch, 1995, EOS, Trans. Amer. Geophys. Union, 76(21):213&218 & 76(22):225&228-229.

Airborne Laser Altimetry and Interferometric SAR Measurements of Canopy Structure and Sub-Canopy Topography in the Pacific Northwest, D.J. Harding, J.B. Blair, E. Rodriguez, T. Michel, 1995, Proc. Second Topical Symposium on Combined Optical - Microwave Earth and Atmosphere Sensing (CO-MEAS'95), 22-24.

Laser Altimetry Waveform Measurement of Vegetation Canopy Structure, D.J. Harding, J.B. Blair, J.B. Garvin, W.T. Lawrence, 1994, Proceedings of IGARSS'94, Vol II, 1251-1253.

Optimization of an Airborne Laser Altimeter for Remote Sensing of Vegetation and Tree Canopies, J.B. Blair, D.B. Coyle, J.L. Bufton, and D.J. Harding, 1994, Proceedings of IGARSS'94, Vol. II, 939-941.

Laser Altimetry of Terrestrial Topography: Vertical Accuracy as a Function of Surface Slope, Roughness, and Cloud Cover, D.J. Harding, J.L. Bufton, and J.J. Frawley, 1994, IEEE Trans. Geoscience and Remote Sensing, 32:329-339.

Erosion Dynamics and Patterns on the Ethiopian Plateau of Northeast Africa: a Fractal Process, J. Weissel, A. Malinverno, D. Harding, and G. Karner, 1995, in Fractals in Petroleum Geology and Earth Processes, C. Barton and P. La Pointe, eds., Plenum Press, 127-142.