032601-F

Development of SAR Algorithm for Mapping Soil Moisture and Vegetation Biomass

Final Report

University of Michigan Technical Report 032601-F

NASA Grants: **NAG5-3849**
NAGW-4180

Submitted To: Eric Wood
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Submission Date: May 12, 1999

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1.0 Introduction

This is the final report for research funded under NASA grants NAGW-4180 for the period from October 1, 1994 to September 30, 1997 and continuation under NAG5-3849 for the period from October 1, 1997 to September 30, 1998. This report briefly states (1) the objectives of the project, (2) a summary of the technical results, and (3) a complete tabulation of publications and technical presentations given to disseminate the results. Finally, the most recent publication is given in an appendix.

2.0 Research Objectives

The spatial distribution and temporal variation of soil moisture are key parameters in hydrologic, ecologic and climatic models at both regional and global scales. Also, the type of vegetation cover and its biomass, which are highly correlated with available soil moisture, significantly affect energy fluxes and evapotranspiration. It is well known that radar backscatter is very sensitive to both soil moisture and the vegetation biomass. In addition, radar backscatter is dependent upon geometrical considerations such as the surface roughness of the soil and the structure or architecture of the vegetation cover. Due to the complexity of the scattering problem, no algorithms were available at the out set of this program that could provide accurate quantitative estimates of these parameters. In this study we combined theoretical scattering models with experimental observations to develop and deliver an inversion algorithm for soil moisture and vegetation biomass - with a focus on soil surfaces covered with short vegetation canopies such as agricultural crops excluding tree-crops.

In order to accomplish these goals, we developed a three-phase research plan:

(1) Development of a radar image classifier to segment land-cover into simple categories: (a) bare soil surface, (b) short vegetation, (c) tall vegetation such as trees and (d) urban areas. This classifier would determine areas where retrieval of soil moisture was possible (i.e., for categories (a) and (b)) and secondly determine the appropriate form of the inversion model (i.e., separate bare soil from short vegetation).

(2) Development of a comprehensive radar scattering model for vegetation, capable of characterizing the polarimetric scattering from the land-cover subclasses and architectures of interest (i.e., leaf-dominated grasses, stalk-dominated grasses and shrubs).

(3) Development of inversion algorithms to retrieve soil moisture and vegetation biomass from radar data. Due to the effects of canopy architecture on various scattering mechanisms it is necessary to further subclassify short vegetation into structural groups such as (a) grass-like (graminoid) with erectorphile leaf blades and cylindrical stems that are small relative to wavelength, (b) shrub-form (woody and herbaceaous) that have bifurcating stems and broadleaf, and (c) stalk-dominated (tree-like) herbaceous vegetation that has a large (relative to wavelength) vertically-oriented stem and broadleaf. Successful classification of vegetation structural type enables the development of simplified forward scattering

models for each subclass and the application of simplified inversion algorithms for each vegetation category separately.

3.0 Summary of Research Results

This research effort consisted of both theoretical and experimental components. Experimental data was acquired in Northern Michigan as part of the SIR-C/X-SAR Mission over mixed forest and agricultural sites. Additional experimental work was conducted in 1995 and 1996 at the Kellogg Biological Station, an NSF long-term Ecological Research Site in southwest Michigan, and consisted of both an AirSAR flight program and daily observations of agricultural fields with the University of Michigan truck-mounted polarimetric scatterometer system.

Airborne SAR imagery from Northern Michigan was used to develop a simple land-cover classification to separate bare soil, short vegetation, tree-cover and urban areas with greater than 95% accuracy. This algorithm was validated with independent AirSAR data from other sites at other times of year and also with the SIR-C/X-SAR data. Successful classification at even this simple level allows us to determine those areas appropriate for application of existing algorithms for retrieval of soil moisture from bare soils as well as determination of those areas where soil moisture retrievals cannot be expected to be successful (i.e., urban and forested regions).

The development of polarimetric scattering models proceeded along two tracks: one for grasses and another for shrub-like herbaceous vegetation. The model for grasses was developed by Jim Stiles and the results form the basis of his Ph.D. dissertation; the model for shrub-like vegetation such as soybeans was developed by Tsen-Chieh Chiu and constitutes his Ph.D. dissertation. Both models have been widely published.

These forward scattering models are very flexible in accommodating various vegetation dielectric and geometric parameters and consequently lead to very accurate predictions of experimental observations over wide ranges of conditions. However, because of the large number of parameters involved in characterization of the vegetation and underlying ground surface, inversion proved to be unstable with the possibility of large errors if certain structural parameters could not be constrained. As a consequence, it became evident that a more sound approach would be to further constrain the vegetation structural attributes prior to soil moisture inversion via more specific classification of vegetation cover class.

The AirSAR data collected over a two month growing period at the Kellogg Biological Station was used to train and test classification algorithms for separation of crop types. Using polarimetric SAR data and L- and C-bands, we have found that separation of wheat, alfalfa, corn and soybeans is possible with a greater than 90% accuracy over a range of soil moisture and crop stages. This effort constitutes the Ph.D. dissertation of Yanni Kouskoulas (expected in 1999) and has been disseminated through symposia and workshop proceedings.

Given a successful methodology for fine discrimination of vegetation structural category, it now becomes possible to develop simplified class-specific forward and inverse scattering models. Such models were constructed for grasses (i.e., wheat) and shrub-like vegetation (i.e., soybeans) using time series of polarimetric scatterometer observations and associated plant and soil measurements. The simple models are based upon first-order radiative transfer with the elimination of terms for unnecessary scattering pathways. This treatment leads to straightforward simple approximation of the more complete scattering models, but with far fewer terms in the inverse model. Inverse models have been developed for both wheat and soybeans and require dual-frequency (L- and C-band) polarimetric data. This approach can lead to very accurate estimates of soil moisture under agricultural crops. For example, the water mass of a soybean canopy can be estimated with an RMS error of 0.07 kg/m^2 and volumetric soil moisture with an RMS error of less than 2%. These results have also been submitted for publication (see Appendix).

Our results show that the multi-step inversion process that we have developed yields (1) accurate estimates of land-cover and crop-type, (2) accurate estimates of vegetation wet-biomass, and (3) high accuracy estimates of near-surface soil moisture. Algorithms have been developed and the basic concept has been tested with SAR and truck-mounted scatterometer data. Independent validations have not been conducted on the inversions. We recommend that a follow-up study be conducted that uses multi-temporal AirSAR data to validate and extend the promising results of this effort.

In addition to satisfying the main objectives of this project we have also developed a number of auxiliary image processing tools related to advanced segmentation and filtering approaches and non-Baysian clustering algorithms. We have also used the theoretical models to compare the sensitivity of active-radar and passive-radiometric sensitivity to soil moisture as a function of vegetation canopy parameters; they are found to be comparable in most cases.

4.0 Students Supported

This research supported the efforts of the following graduate students:

Tsen-Chieh Chiu
Roger DeRoo
Yang Du
Yanni Kouskoulas
Jim Stiles
Elif Tepeli

The project resulted in the publication of 4 Ph.D. dissertations

Roger D. DeRoo, Dissertation, 1996, Theory and measurement of bistatic scattering of X-band microwaves from rough dielectric surfaces, University of Michigan.

James M. Stiles, Dissertation, 1996. A coherent, polarimetric microwave scattering model for grassland structures and canopies, University of Michigan.

Tsen-Chieh Chiu, Dissertation, 1998. Electromagnetic scattering from rough surfaces covered with short branching vegetation, University of Michigan.

Yanni Kouskoulas - expected in December 1999.

4.1 Journal Publications

Ulaby, F.T., P.C. Dubois, and J. van Zyl, "Radar Mapping of Surface Soil Moisture," *Journal of Hydrology,* 184 , 57-84, 1996.

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.

Sarabandi, K., and E.S. Li, "A microstrip ring resonator for non-invasive dielectric measurements," *IEEE Trans. on Geosc. and Remote Sensing,* vol. 35, no. 5, pp. 1223-1231, Sept. 1997, 1998.

Sarabandi, K., and T.C Chiu, "Electromagnetic scattering from slightly rough surfaces with inhomogeneous dielectric profile, " *IEEE Trans. Antennas Propagat.*, vol. 45, no. 9, Sept. 1997.

Stiles, J.M., and K. Sarabandi, "Electromagnetic scattering from grassland: Part I, A fully coherent scattering model," accepted *IEEE Trans. on Geosc. and Remote Sensing,* Oct., 97.

Chiu, T.C., and K. Sarabandi, "Electromagnetic scattering from short branching vegetation," submitted to *IEEE Trans. on Geosc. and Remote Sensing,* Jan, 1998.

Ulaby, F.T. and E. Tepeli, "A New Model for Backscatter from Random Surfaces," Submitted to *IEEE GRS-S,* April 1998.

Du, Y., F.T. Ulaby and M.C. Dobson, "Sensitivity to soil moisture by active and passive microwave sensors," *IEEE Trans. Geosci. Remote Sensing*, accepted for publication, April 1999.

Hauck, B. and F.T. Ulaby "Experimental Evaluation of the Small Perturbation Model for Bistatic Scattering," submitted to *IEEE Trans. Antennas and Propagation,* June, 1998.

Stiles, J.M., K. Sarabandi, and F.T. Ulaby, "Electromagnetic scattering from grassland: Part II, Measurement and modeling results," *IEEE Trans. Geosci. Remote Sensing*, accepted for publication, Oct. 97.

DeRoo, R.D., Y. Du, F.T. Ulaby, and M.C. Dobson, "A semi-empirical backscattering model at L-band and C-band for s soybean canopy with soil moisture inversion, submitted for publication in IEEE Trans. on Geosci. and Rem. Sens. 1999.

4.2 Symposia and Workshops

Dobson, M. Craig, "Remote Sensing of Soil Moisture," Development of Environmentally Sustainable Management Systems for the Desert Locust, *Schistocerca Gregaria*, UN/Food and Agriculture Organization, International Fund for Agricultural Development, Rome, Sept. 25-27, 1995, (Invited).

van Zyl, J., C. Dobson, J. Dozier, P. DuBois, D. Evans, J. A. Kong, T. Le Toan, J. Melack, E. Rignot, S. Saatchi, J. C. Shi, and F. T. Ulaby, "Preliminary Science Results from the SIR-C/X-SAR Mission," Int. Symp. on Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications, Toulouse, France, Oct. 10-13, 1995.

Chiu, T., K. Sarabandi, and F.T. Ulaby, “Polarimetric Backscattering Measurements of Herbaceous Vegetation: A Sensitivity Study for Soil Moisture Retrieval,” IGARSS ‘96 Symposium, Lincoln, Nebraska, May 1996.

DeRoo, R. and M. C. Dobson, “Estimation of Near-Surface Soil Moisture Under Vegetation Using Radar,” KBS All Investigator Symposium, pp. 23, July 16 - 17, 1996, W.K. Kellogg Biological Station, Michigan State Univ., Hickory Corners, MI.

DeRoo, R.D and F.T. Ulaby, “A modified Physical Optics model of the rough surface reflection coefficient,” AP-S Symposium, June 1996.

Stiles, J.M., K. Sarabandi, and F.T. Ulaby, “Scattering from Cultural Grass Canopies: Measured and Modeled Data,” IGARSS ‘96 Symposium, Lincoln, Nebraska, May 1996.

Ulaby, F.T. “Multi-dimensional SAR, Terrain Classification, and Biophysical Mapping: A Winning Combination,” IGARSS ‘96 Symposium, Lincoln, Nebraska, May 1996.

DeRoo, R.D., F.T. Ulaby and M.C. Dobson, “Using Multifrequency Radar for Soil Moisture and Biomass Measurements of Soybean Canopies,” IGARSS’98, July 6-10, 1998, Seattle, Washington.

Kouskoulas, Y. and M.C. Dobson, “Classification of Short Vegetation Using Multifrequency SAR,” IGARSS’98, July 6-10, 1998, Seattle, Washington.

Ulaby, F.T., "SAR Algorithm for Mapping Soil Moisture and Vegetation Biomass", Soil Hydrology Meeting, Baltimore, Md., March, 1998.

Ulaby, F.T., "Terrain Applications of Multichannel SAR," ESLAB Symposium, ESTEC, The Netherlands, 15-20 September, 1998.

Du, Y.C, F.T. Ulaby and M.C. Dobson, “Sensitivity to Soil Moisture by Active and Passive Microwave Sensors,” Proc. IGARSS’99, June 28 – July 2, 1999, Hamburg, Germany.

Kouskoulas, Y., L. Pierce, F.T. Ulaby and M.C. Dobson. “Classification of Short Vegetation Using Multifrequency SAR,” Proc. IGARSS’99, June 28 – July 2, 1999, Hamburg, Germany.

A Semi-Empirical Backscattering Model at L-band and C-band for a Soybean Canopy with Soil Moisture Inversion

Roger D. De Roo, Yang Du, Fawwaz T. Ulaby
and M. Craig Dobson

Abstract

Radar backscatter measurements of a pair of adjacent soybean fields at L-band and C-band are reported. These measurements, which are fully polarimetric, took place over the entire growing season of 1996. To reduce the data acquisition burden, these measurements were restricted to 45° in elevation and to 45° in azimuth with respect to the row direction. Using the first order radiative transfer solution as a form for the model of the data, four parameters were extracted from the data for each frequency/polarization channel to provide a least squares fit to the model. Using the results of the forward model as a guide to show the dependencies of the different radar channels, linear regressions of particular channel combinations were derived which can be used to invert for the soil moisture and area density of vegetation water mass. Using L-band cross-polarization and VV-polarization, the vegetation water mass can be regressed with an $R^2 = 0.867$ and a root-mean-square error of 0.0678 kg/m^2. Similarly, while a number of channels, or combinations of channels, can be used to invert for soil moisture, the best combination observed, namely, L-band VV-polarization, C-band HV- and VV-polarizations, can achieve a regression coefficient of $R^2 = 0.898$ and volumetric soil moisture root-mean-square error of 1.75%.

1 Introduction

For bare-soil surfaces, the backscattering coefficient, σ^0, is strongly dependent on the roughness and the moisture content of the soil surface layer [1–3]. Given two or more radar channels (such as simultaneous multi-polarization or multi-frequency observations), it is possible to estimate the volumetric moisture content, m_v, with good precision. Specifically, when multi-polarized L-band observations were used, the precision of the retrieved moisture was about 3.2% [3]. The data included observations made by a truck-mounted radar, by the JPL airborne AirSAR system, and by SIR-C.

This paper addresses the vegetation-covered case for a soybeans canopy. The first part describes the test site and data acquisition process; it is then followed with an analysis of the "direct problem", namely matching the measured data to a backscatter model; and then it ends with the development of an inversion algorithm (inverse problem) that predicts soil moisture content and vegetation biomass on the basis of multi-channel radar observations as input.

2 Experimental Measurements

The measurements reported in this study were conducted during the summer of 1996 at the Long-Term Ecological Research (LTER) site of the Kellogg Biological Station in Hickory Corners, Michigan. Three primary types of vegetation canopies were chosen for measurement: corn, which represents agricultural fields in which a stem or stalk is a dominant feature at microwave frequencies; soybeans and alfalfa, which represent agricultural fields that lack a dominant stem; and a field which had lain fallow for many years and is now populated with many native grasses. The present study will address the soybean observations only.

The radar backscatter measurements were made by a truck mounted radar system. All measurements were made at an incidence angle of 45° and at a range of 12-m in a fully polarimetric mode at both L-band (1.25 GHz) and C-band (5.4 GHz). Calibration accuracy is estimated at ± 0.5 dB for the copolarized backscattering coefficients, σ^0_{vv} and σ^0_{hh}, ± 1.0 dB for the cross-polarized backscattering coefficient, σ^0_{hv}, and ±15° for phase difference between polarizations.

To reduce signal-fading variations of the backscattered signal, multiple

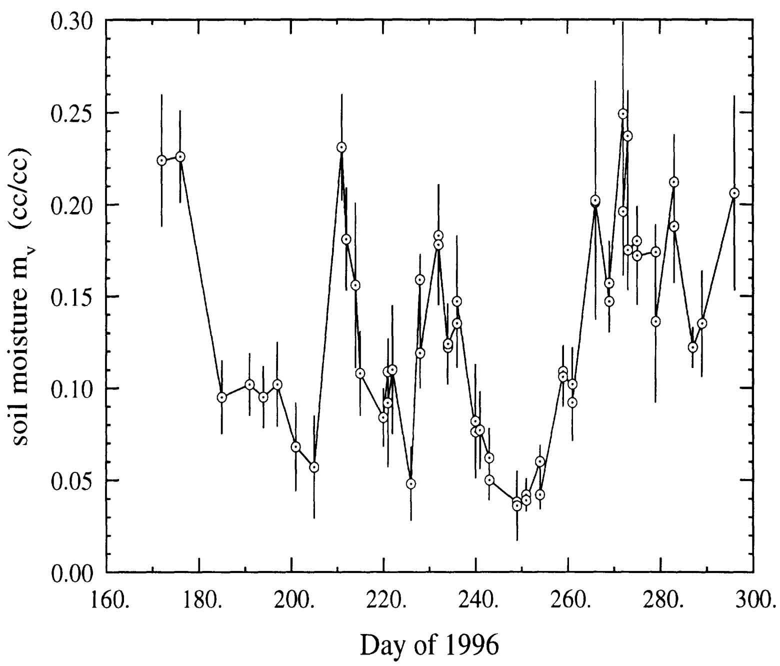

Figure 1: Variation of the soil moisture under the soybean canopy.

measurements of the same target were performed under the same radar parameters (frequency, polarization and angle of incidence), but with a translation or rotation of the radar antennas. The figure of merit for the reduction of fading is the number of independent samples, which is the product of the number of independent samples per spatial sample (due to frequency averaging) and the number of spatial samples measured. For each measurement reported in this study, the number of independent samples is 205 at L-band and 157 at C-band.

The radar measurements and associated canopy and soil observations were commenced on 20 June, 1996 and were completed on 26 October. A total of 57 data sets were acquired, covering a wide range of conditions, extending from 0.02 kg/m^2 to 0.97 kg/m^2 in vegetation water mass, 3% to 26% in volumetric soil moisture, and 12 cm to 63 cm in canopy height. The variation of the moisture in the soybean fields measured in the growing season of 1996 is shown in Figure 1.

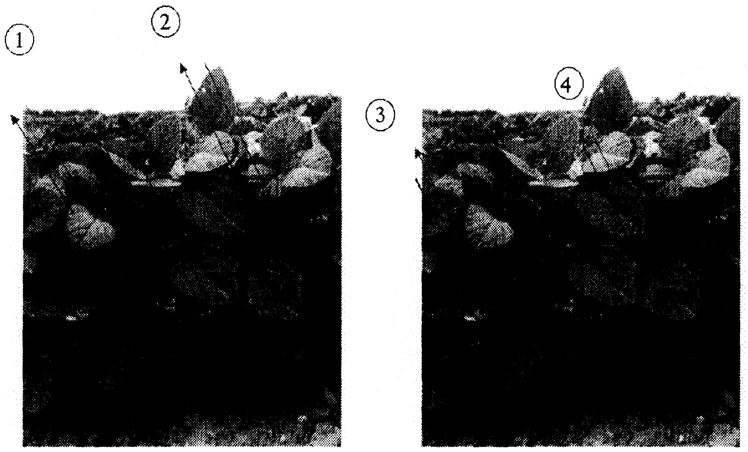

Figure 2: Scattering mechanisms considered in this paper for soybean canopies.

3 Backscatter Model

The Michigan Microwave Canopy Scattering (MIMICS) model was developed several years ago for predicting the backscatter from forest stands [4, 5]. We shall adopt the basic structure of the model for characterizing the backscatter from soybeans, but we shall delete the scattering component associated with ground-trunk scattering because the architecture of a soybean plant does not have a vertical stalk. Hence, σ^0_{pq}, the *pq*-polarized backscattering coefficient (where p and q are each either v or h polarization) of the canopy may be expressed as:

$$\sigma^0_{pq} = \sigma^0_{pq_1} + \sigma^0_{pq_2} + \sigma^0_{pq_3} + \sigma^0_{pq_4}, \tag{1}$$

where each component represents a scattering mechanism, as illustrated in Fig. 1. For a particular *pq*-polarization configuration, these components are:

σ^0_1 = direct backscatter contribution from the canopy,

$\sigma^0_2 = \sigma^0_{21} + \sigma^0_{22}$ = total ground-canopy and canopy-ground forward scattering contribution,

σ^0_3 = ground-canopy-ground scattering contribution

σ^0_4 = direct backscatter contribution of the underlying soil surface (including two-way attenuation by the canopy).

The expressions for the four components are:

$$\sigma^0_{pq_1} = \frac{\sigma_{pq_1}\cos\theta}{\kappa_p + \kappa_q}(1 - T_p T_q), \tag{2}$$

$$\sigma^0_{pq_2} = 2T_p T_q(\Gamma_p + \Gamma_q)h\sigma_{pq_2} \tag{3}$$

$$\sigma^0_{pq_3} = \sigma^0_{pq_1} T_p T_q \Gamma_p \Gamma_q \tag{4}$$

$$\sigma^0_{pq_4} = \sigma^0_{pqs} T_p T_q, \tag{5}$$

where:

σ_{pq_1} = backscatter cross section per unit volume of the leaves and stems, (m^2/m^3),
σ_{pq_2} = bistatic cross section per unit volume of the leaves and stems, (m^2/m^3),
κ_p = p-polarized extinction coefficient of vegetation canopy, (Np/m),
T_p = p-polarized one-way transmissivity of the canopy,
= $e^{-\kappa_p h \sec\theta}$,
h = canopy height, m
Γ_p = p-polarized reflectivity of ground surface,
= $\Gamma_{po}\exp\left[-(2ks\cos\theta)^2\right]$
Γ_{po} = Fresnel reflectivity of a specular surface,
k = $2\pi/\lambda$,
s = rms height of ground surface, (m)
σ^0_{pqs} = backscattering coefficient of soil surface in the absence of vegetation cover.

3.1 Soil Surface Model

For the soil surface, we adopt the semi-empirical model developed by Oh *et al.*, which was first introduced in 1992 [1] and then improved in a later study in 1994 [2]. The soil backscattering coefficient is given by:

$$\sigma^0_{vvs} = \frac{g\cos^3\theta}{\sqrt{p}}[\Gamma_v(\theta) + \Gamma_h(\theta)] \tag{6}$$

$$\sigma^0_{hhs} = p\sigma^0_{vvs} \tag{7}$$

$$\sigma^0_{hvs} = q\sigma^0_{vvs} \tag{8}$$

where

$$p = \frac{\sigma^0_{hhs}}{\sigma^0_{vvs}} = \left[1 - \left(\frac{2\theta}{\pi}\right)^{(0.314/\Gamma_0)} \cdot \exp(-ks)\right]^2 \tag{9}$$

$$q = \frac{\sigma^0_{hvs}}{\sigma^0_{vvs}} = 0.25\sqrt{\Gamma_0}(0.1 + \sin^{0.9}\theta)[1 - e^{-(1.4-1.6\Gamma_0)ks}] \tag{10}$$

$$g = 0.7\left[1 - e^{-0.65(ks)^{1.8}}\right], \tag{11}$$

$$\Gamma_0 = \left|\frac{\sqrt{\epsilon_s} - 1}{\sqrt{\epsilon_s} + 1}\right|^2, \tag{12}$$

$$\Gamma_{ho}(\theta) = \left|\frac{\cos\theta - \sqrt{\epsilon_s - \sin^2\theta}}{\cos\theta + \sqrt{\epsilon_s - \sin^2\theta}}\right|^2, \tag{13}$$

$$\Gamma_{vo}(\theta) = \left|\frac{\epsilon_s\cos\theta - \sqrt{\epsilon_s - \sin^2\theta}}{\epsilon_s\cos\theta + \sqrt{\epsilon_s - \sin^2\theta}}\right|^2, \tag{14}$$

and ϵ_s is the relative complex dielectric constant of the soil:

$$\epsilon_s = \epsilon'_s - j\epsilon''_s. \tag{15}$$

The incidence angle θ is in radians and the models used for relating ϵ'_s and ϵ''_s to m_v, the volumetric soil moisture content, are given in Hallikainen *et al.*[6]. According to field tests, the soil was 51% sand and 13% clay.

The effect of soil surface roughness comes into the picture not only in terms of the direct soil backscatter component, $\sigma^0_{pq_4}$, but also in terms of forward scattering by the soil surface, $\sigma^0_{pq_2}$ and $\sigma^0_{pq_3}$; the p-polarized Fresnel surface reflectivity, Γ_{po}, is reduced by the exponential factor $[-(2ks\cos\theta)^2]$.

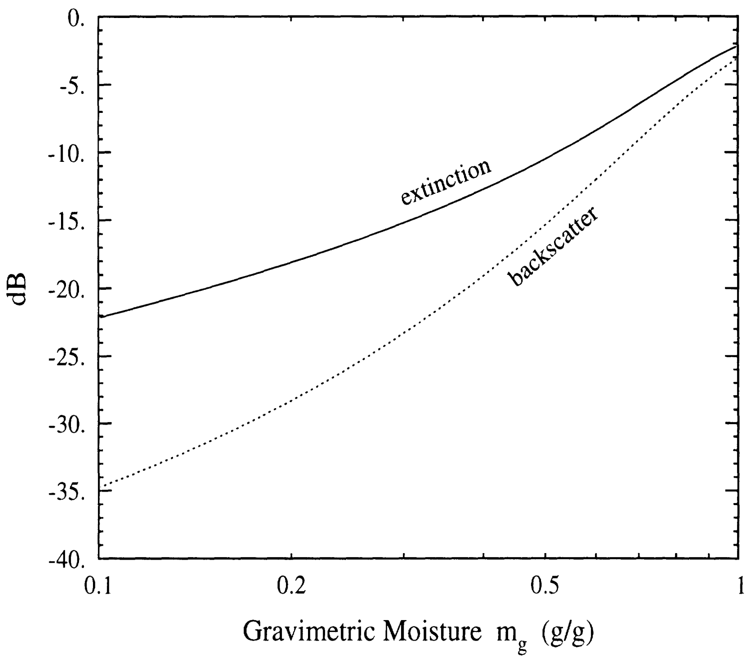

Figure 3: Dependence of the extinction and backscatter cross section of a single leaf upon its gravimetric moisture, after [7]. The vertical scale is normalized with respect to an equivalent perfectly conducting leaf of the same geometry. The extinction displays an approximately m_g^2 dependence while the backscatter displays an approximately m_g^3 dependence.

3.2 Vegetation Model

Next, we shall relate the electromagnetic parameters of the vegetation, namely $\sigma_{pq_1}, \sigma_{pq_2}$, and κ_p, to two physical parameters: the height, h, and the area density of vegetation water mass, m_w (kg/m^2). We start with the extinction coefficient κ_p. For a given canopy, we expect κ to be a function of (a) the canopy architecture, and (b) the dielectric constant, ϵ_v, of the vegetation material. By canopy architecture, we mean the shapes, orientations, and sizes of the canopy constituents (defined relative to the wavelength λ), the incidence angle θ, and the wave polarization, p. Even though the extinction cross-section of an individual leaf or branch may exhibit a strong dependence on its orientation relative to the incident beam, we shall assume that the extinction coefficient κ_p– which is an ensemble average over the probability distribution characterizing the shapes, sizes, and orientations of leaves and branches– is independent of direction, which is a reasonable assumption for a canopy like soybeans. The dielectric constant of a vegetation material, ϵ_v, is strongly dependent on its moisture content. According to a study reported by Senior *et al.*[7], which included both a theoretical model and experimental verification, the extinction cross-section of a vegetation leaf (where first normalized to the extinction cross-section of a perfectly conductive leaf of the same size) varies approximately linearly with the gravimetric moisture m_g, when both quantities are expressed on a logarithmic scale. The gravimetric moisture m_g is the ratio of the mass of water in the leaf (wet weight - dry weight) to the total mass of the leaf (wet weight). Figure 3 is a reproduction of their results for the gravimetric moisture range between 0.1 and 0.9. The approximately linear response with a slope of approximately 2 (on a log-log scale) suggests that the extinction cross-section of a leaf may be expressed as:

$$\sigma^e = a_o m_g^2, \tag{16}$$

where a_o is a constant. Thus, for a canopy containing, on average, N leaves per m^3, the extinction coefficient becomes

$$\kappa_p = N a_o m_g^2 \quad \text{(Np/m)}. \tag{17}$$

The results of Senior *et al.* suggest that the ratio of scattering to extinction, which appears in (2), is directly proportional to m_g, the leaf gravimetric

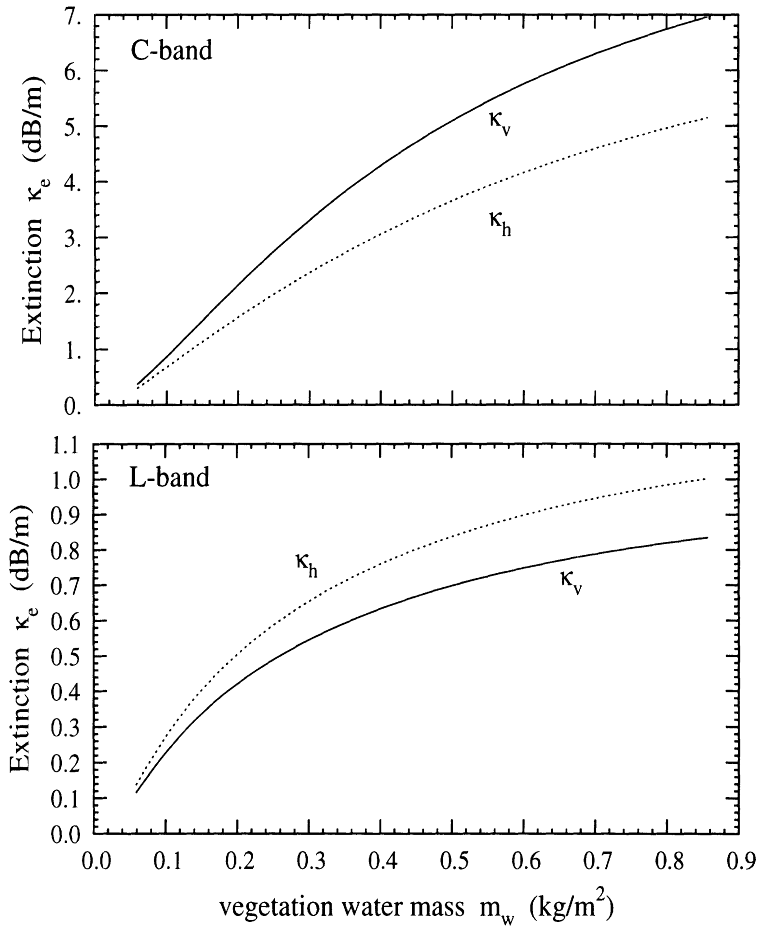

Figure 4: Dependence on the extinction on the area density of vegetation water mass in leaves at C-band and L-band. Whereas the extinction exhibits a strong frequency dependence, all of the extinction rates are approximately proportional to $\sqrt{m_w}$.

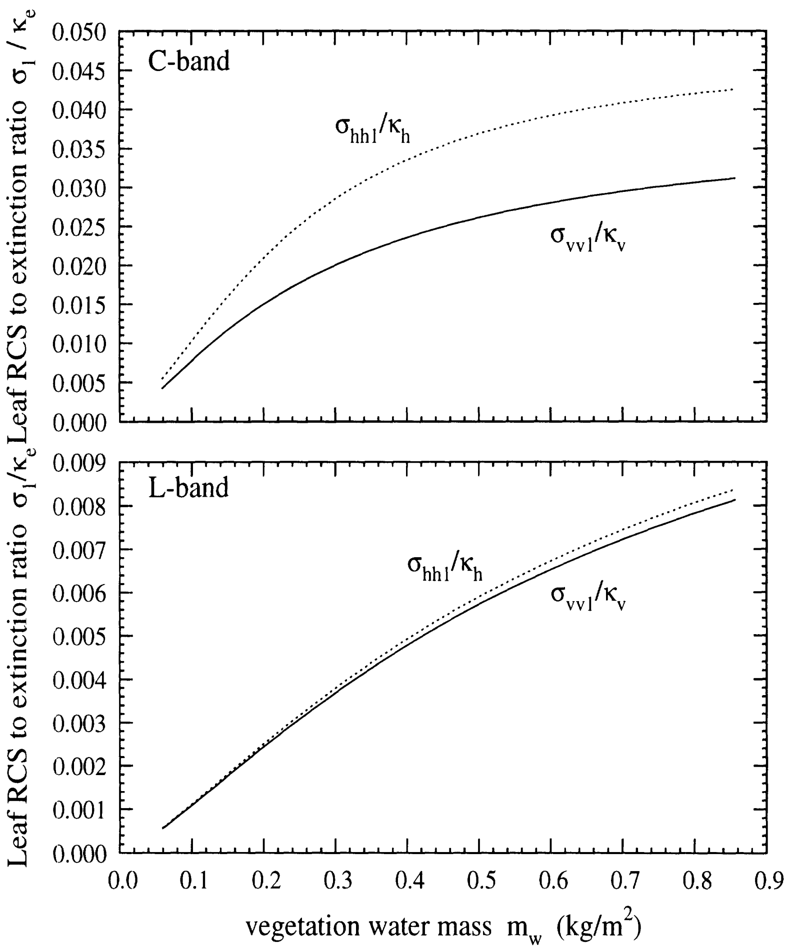

Figure 5: Dependence of the ratio of the backscatter RCS per unit volume to the extinction coefficient on the area density of vegetation water mass in leaves at C-band and L-band. Both VV and HH exhibit a dependence which is roughly $\sqrt{m_w}$.

moisture. But this conclusion is valid only for the restrictive case where the leaves are oriented to backscatter specularly from the surface of the leaves. For the more complicated and more realistic case of a broad distribution of orientations of the leaves, the MIMICS radiative transfer model [4, 5] was used to find the backscatter to extinction ratio averaged over the shape, size and orientation distributions of the detailed soybean vegetation parameters as provided in [8–10]. The results of these calculations for L-band and C-bands are shown in Figure 4. It was found that for both VV and HH polarizations, the mean extinction was proportional to $\sqrt{m_w}$, where m_w is the area density of vegetation water mass in kg/m^2. The MIMICS model calculations for ratio of mean backscatter to mean extinction, shown in Figure 5, also exhibit a $\sqrt{m_w}$ dependence, implying that the backscattering alone has a linear dependence on m_w when averaging over leaf orientations is taken into account. MIMICS model calculations for the backscatter and bistatic phase matrices indicate that this linear relationship is appropriate for both the backscatter and bistatic canopy scattering terms in the radiative transfer model.

3.3 A semi-empirical forward scattering model

Combining the first order radiative transfer solution of eqn. 1 with the results of the study of the dependence of the scattering and extinction on the vegetation water mass, we obtain the following equation to which the data must be fit:

$$\sigma^0_{pq} = \frac{\sigma_{pq_1}\cos\theta}{2\kappa_{pq}}\left(1 - T^2_{pq}\right)\left(1 + T^2_{pq}\Gamma_p\Gamma_q\right) + T^2_{pq}\left(2(\Gamma_p + \Gamma_q)h\sigma_{pq_2} + a_{\text{bias}}\sigma^0_{pqs}\right) \tag{18}$$

where

$$\sigma_{pq_1} = a_2 m_w / h \tag{19}$$

$$\sigma_{pq_2} = a_3 m_w / h \tag{20}$$

$$\kappa_{pq} = a_4\sqrt{m_w} \tag{21}$$

$$T_{pq} = e^{-\kappa_{pq} h \sec\theta} \tag{22}$$

and the remaining symbols $(h, \theta, \Gamma_p, \Gamma_q, \sigma^0_{pqs})$ retain their definitions from the previous section. The units of a_2 and a_3 are in RCS per kilogram of vegetation moisture, and a_4 is in Nepers per root kilogram of vegetation moisture.

With the form of the scattering equation known, and a set of parameters either known (θ, λ, p, q) or measured $(\sigma^0_{pq}, h, m_w, m_g, m_v)$, the task of obtaining a semi-empirical forward scattering model becomes that of finding the unknown parameters $(a_{\text{bias}}, a_2, a_3, a_4, s)$ keeping in mind the fixed relationships between some of these parameters. The measured parameters, radar backscatter and soil moisture, are combined with interpolated values for the vegetation parameters (water mass, height and leaf gravimetric moisture) and inserted into a program which searches for the least squares error between the predicted backscatter and the measured backscatter, by varying the free parameters over their valid range in discrete steps. When a close fit is found, a Levenberg-Marquardt algorithm [11] is implemented which finds a local minimum of the error with respect to all the free parameters at once. The set of free parameters which provides the global minimum to the error is chosen as the set of free parameters most likely to represent the scattering mechanisms observed. This process is done independently for each frequency and polarization pair.

The rms surface height of the soil was found by inverting a pair of polarimetric measurements made early in the season, before substantial biomass accumulated on the plants. These measurements were conducted under different soil moisture conditions, and because of the low biomass condition, these measurements were not included in the data set used for finding the forward model or the inverse model. The semi-empirical soil surface scattering model of Oh *et al.* [2] was used to invert the soil roughness, and a value of $s = 2.8$ cm was obtained.

Surface scattering from a natural surface such as plowed soils is not well understood, partly because the surface correlation is not known (but certainly not Gaussian). Because of this, the semi-empirical soil surface scattering model of Oh *et al.* was employed, but it is not immediately clear if that model, based on measurements of plowed and raked bare surfaces, is directly applicable to a surface under a growing crop. Rain, for example, will weather a bare soil quite differently from one shrouded by a soybean canopy. Thus, a bias term was added to the set of free parameters of the model to make up for the deficiencies of the semi-empirical soil surface scattering model, and for the time differences from the measurement of the surface height to the measurements of the canopy.

The free parameters that were found to provide the best fit for the set of soybean measurements are shown in Table 1. The rms error and maximum error are given in dB. The goodness-of-fit measure Q [11] represents the

Freq	Pol	a_2	a_3	a_4	bias	rms error	max error	Q
		m^2/kg	m^2/kg	$Np/kg^{1/2}$	dB	dB	dB	%
C	HH	5.01	85.2	0.176	1.56	0.69	1.37	29
C	VV	1.31	20600	1.08	1.70	0.65	1.33	44
C	HV	0.674	3880	1.42	2.50	0.63	1.92	53
L	HH	1.85	47.2	0.0173	1.20	0.86	1.84	0.3
L	VV	0.500	2.54	0.892	2.25	0.65	1.99	32
L	HV	24.5	47.1	0.010	3.25	1.05	2.85	10^{-4}

Table 1: Best fit free parameters for semi-empirical soybean model. The bias and errors are given in dB.

probability that a repetition of the measurements would result in a worse fit to the model, assuming that this model and the values of these parameters are correct. The measure Q takes into account the known or assumed errors in the measurements, while the rms error or maximum error measures do not. Values of Q greater than approximately 5% indicate that a more complicated model is unlikely to provide a better fit to the data. The very low values of Q for L-band HV and HH indicate that the model is not a very good representation of the observations.

While the free parameters for each polarization and frequency are derived independently of each other, certain known relationships exist between them. The extinction parameter, a_4, while not independent of polarization, should be only weakly sensitive to polarization, but should be much higher for C-band than for L-band. The canopy scattering terms, a_2 and a_3, should also be much higher for C-band than L-band. Within a given frequency and polarization, it is expected that the bistatic scattering from the canopy would be stronger than backscattering, and so $a_3 > a_2$. All of these expectations are realized in the values of the free parameters derived.

An analysis of the contributions from the mechanisms described in Figure 2 show that the ground-canopy-ground scattering interaction described by σ^0_{pq3} in equation (4) is negligible for all polarizations and both frequencies investigated. For all of the C-band measurements, the direct crown scattering of equation (2) is either overwhelmingly dominant (for cross-polarization) or at least comparable to the direct ground as attenuated by the canopy (for VV and HH). At L-band, the bistatic crown-ground and ground-crown terms given by equation (3) contribute the most to the total scattering, with the direct ground being contributions a few dB smaller than the bistatic contribution. For L-band VV-polarization, direct crown scattering is comparable to the ground contribution; for cross-polarization, the direct crown scattering is nearly comparable to the bistatic contribution. The model predicts the direct crown backscatter at L-band HH polarization to be practically negligible.

Comparisons of the semi-empirical model calculations with the measured data are shown Figures 6 and 7.

4 Inversions

The objective of the exercise is not to simply understand how the backscattering from a crop such as soybeans depends on scientifically and commercially important quantities like soil moisture and biomass, but to use the measurements of backscatter to determine estimates of these important quantities. This section outlines the approaches used to invert the semi-empirical model developed in the previous section.

As a first step, the desired invertible quantities, namely soil moisture and vegetation water mass, are regressed against the six radar channels (L-band and C-band, each with VV, HH, and HV), as shown graphically in Figure 8. The fifteen combinations of ratios of those radar channels were similarly regressed against m_v and m_w. The vast majority of these regressions show very poor correlation between the radar quantity and the desired parameter, but a few show modest correlations. The single channel with the best correlation with soil moisture is, not surprisingly, L-band VV polarization, since the relatively long wavelength permits substantial penetration of the canopy and the vertically polarized Fresnel reflection coefficient of the surface is sensitive to soil moisture. For all polarizations, L-band has a much higher dynamic range than C-band, and much larger measurement to measurement variation. For the three L-band polarizations, VV is most faithfully described by the forward model.

The channel ratio with the best correlation to soil moisture is the L-band cross-pol to C-band cross-pol ratio. The L-band cross-pol data has a slightly larger dynamic range than does either co-pol, and the C-band cross-pol has the smallest sensitivity of all channels measured to soil moisture. This particular combination provides the large dynamic range of the L-band measurements to soil moisture with a correction for vegetation water mass

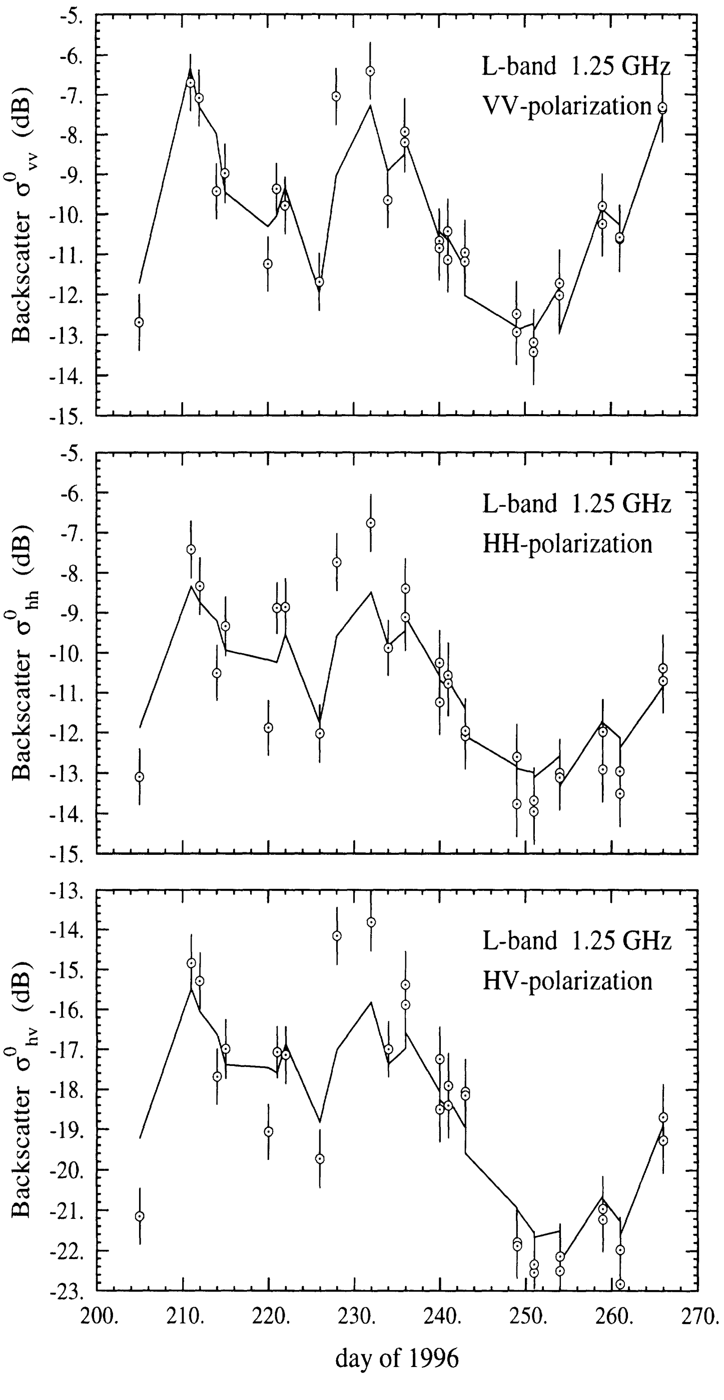

Figure 6: Comparison of the semi-empirical model to the measured data at L-band. The angle of incidence is fixed at 45° and the look direction relative to the row direction was also fixed at 45°.

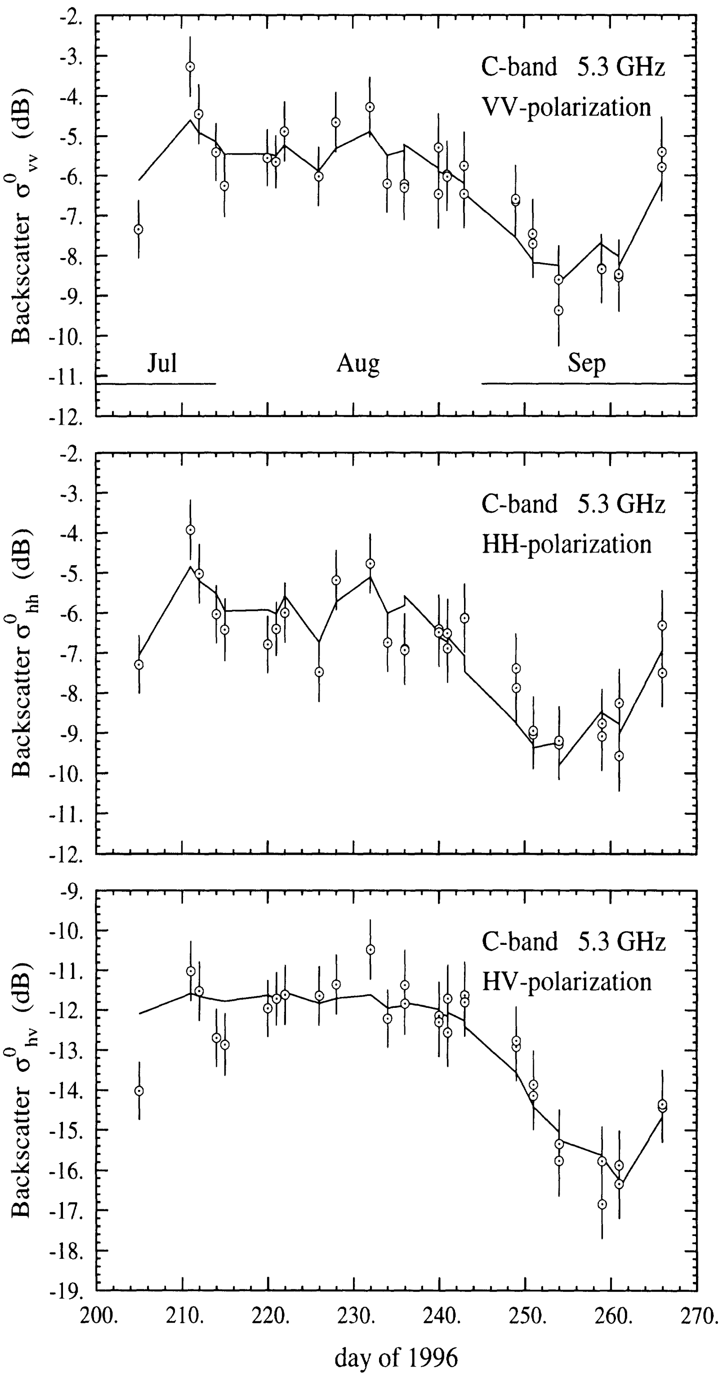

Figure 7: Comparison of the semi-empirical model to the measured data at C-band. The angle of incidence is fixed at 45° and the look direction relative to the row direction was also fixed at 45°.

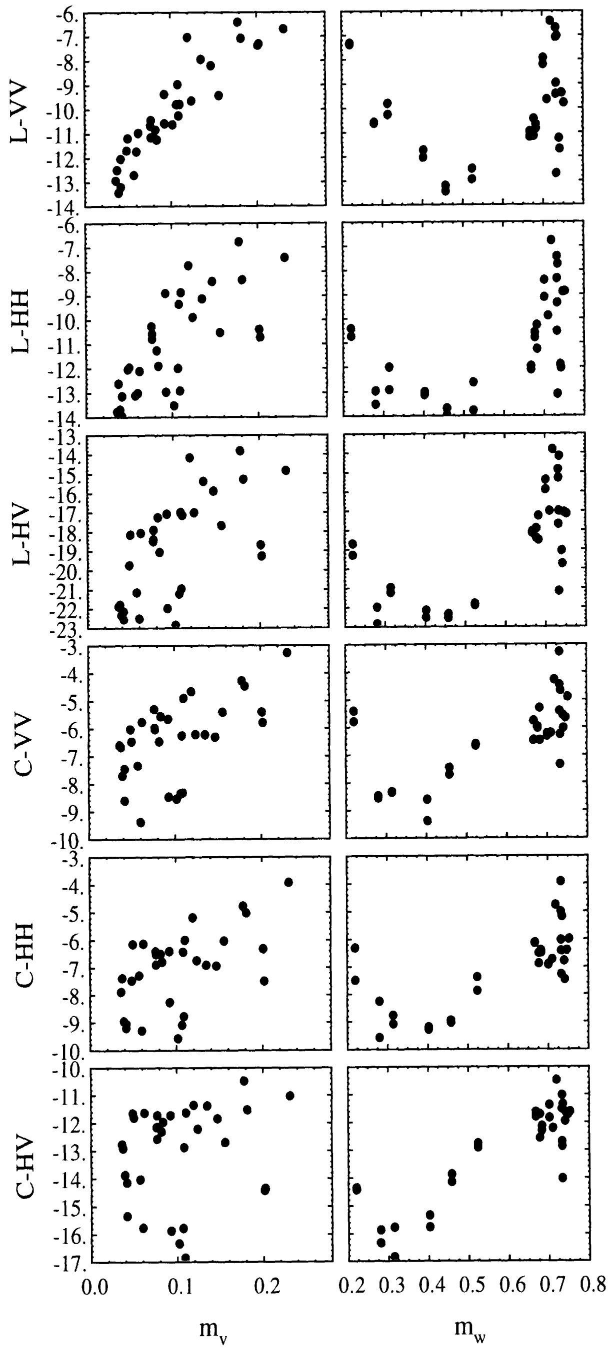

Figure 8: Visual results of the regression of the measured soil moisture m_v, left column, the area density of the vegetation water mass m_w, right column, and the six radar channels. Only L-band VV shows a strong direct correlation with m_v.

provided by the C-band channel.

The channel ratio with the best correlation to vegetation water mass is L-band cross-pol to L-band VV-polarization. The best fits to our measured data, together with the root-mean-squared error and the regression coefficients, for each of these physical quantities are given by

$$\frac{\sigma^0_{L-HV}}{\sigma^0_{C-HV}} = 1.9360 m_v^{0.8237} \qquad \text{rmse} = 3.25\% \qquad R^2 = 0.633 \quad (23)$$

$$\frac{\sigma^0_{L-HV}}{\sigma^0_{L-VV}} = 0.2510 m_w^{1.0277} \qquad \text{rmse} = 0.0678 \text{ kg/m}^2 \qquad R^2 = 0.867 \quad (24)$$

In these equations, σ^0 is given in RCS per unit area (m^2/m^2). Figures 9 and 10 show the resultant inversion of our measured data for the soil moisture and vegetation water mass.

While the regression for vegetation water mass in (24) is quite good, the use of (23) for inversion is less than ideal. The single channel with the highest sensitivity to soil moisture is the L-band VV-polarization, as is evident from Figures 6 and 7. The following equations show the linear regression of this channel, together with two combinations of channel ratios which improve the correlation significantly.

$$m_v = 0.3489 + 0.0244\sigma^0_{L-VV} \qquad \text{rmse} = 2.13\% \qquad R^2 = 0.842 \quad (25)$$

$$\begin{aligned} m_v = {} & 0.2338 + 0.0244\sigma^0_{L-VV} \\ & - 0.0142\left(\sigma^0_{C-HV} - \sigma^0_{C-VV}\right) \end{aligned} \qquad \text{rmse} = 1.75\% \qquad R^2 = 0.898 \quad (26)$$

$$\begin{aligned} m_v = {} & 0.2483 + 0.0272\sigma^0_{L-VV} \\ & - 0.0139\left(\sigma^0_{C-HV} - \sigma^0_{C-VV}\right) \\ & - 0.0063\left(\sigma^0_{L-HV} - \sigma^0_{C-HV}\right) \end{aligned} \qquad \text{rmse} = 1.72\% \qquad R^2 = 0.904 \quad (27)$$

In these equations, σ^0 is given in dB.

Use of L-band VV-polarization alone is an improvement over the exclusive use of the L-band to C-band cross-pol ratio, but it is improved with the inclusion of the C-band cross-to-co-pol ratio, which is essentially a correction for the dependence of L-band VV on the vegetation water mass. Further inclusion of L-band to C-band cross-pol ratio provides negligible improvement in the correlation. Figure 11 shows the improved inversion of our measured data for the soil moisture using equation (26).

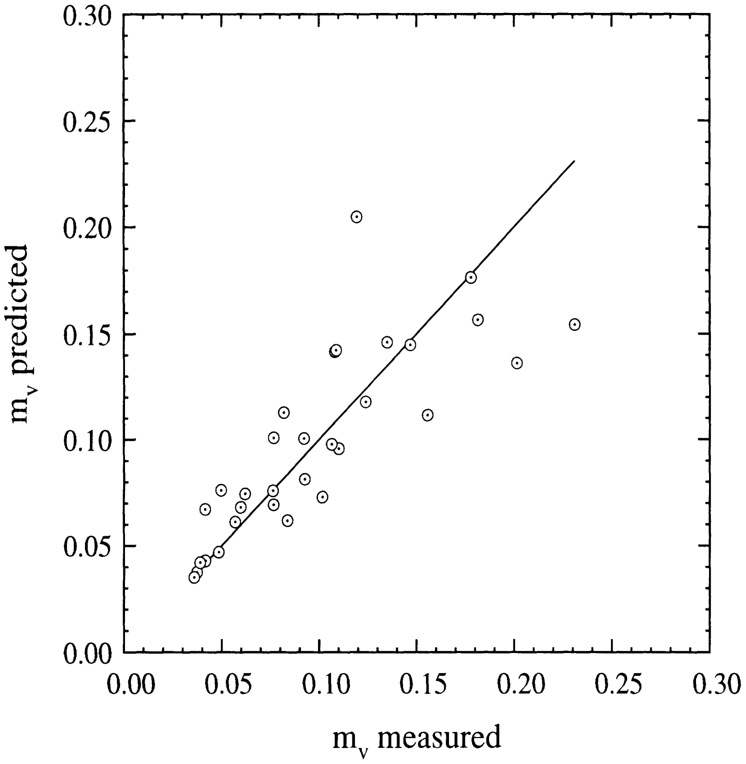

Figure 9: Comparison of the measured soil moisture with inverted soil moisture derived from both L-band and C-band cross-polarization radar measurements.

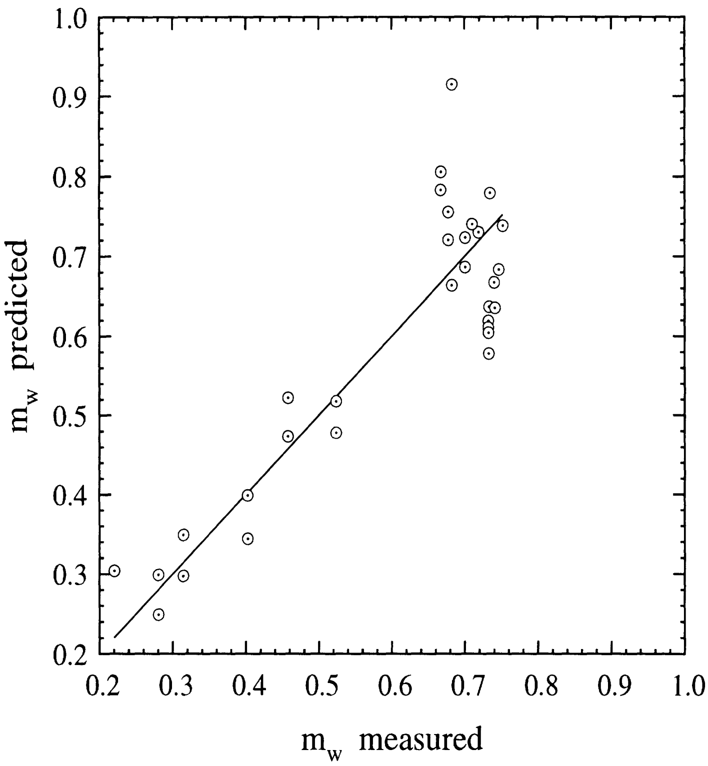

Figure 10: Comparison of the measured vegetation water mass with inverted vegetation water mass derived from both L-band VV- and cross-polarization radar measurements.

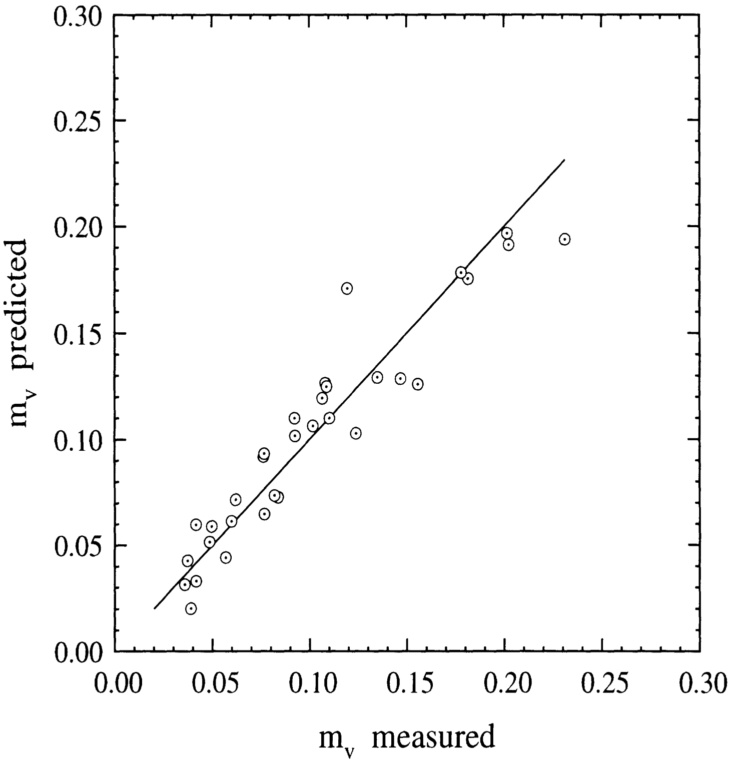

Figure 11: Comparison of the measured soil moisture with inverted soil moisture derived from radar measurements using equation (26).

5 Conclusions

A series of measurements of the radar backscatter from soybeans is reported. The soybeans fields were located at the Kellogg Biological Station in Hickory Corners, MI, USA. The series of 57 measurements on these fields commenced on 20 June 1996 and were completed on 26 October 1996. Each measurement was fully polarimetric at both L-band and C-band, made at an incidence angle of 45° and also at 45° with respect to the crop row structure, and contains a minimum of 157 independent samples. With each measurement is a set of soil core samples used to determine the volumetric soil moisture; several destructive samples over the growing season were used to obtain measures of the above-ground biomass, including the area density of vegetation water mass. Measurements the center of this period, when the soybean biomass was not negligible, were used to create a semi-empirical forward scattering model. This forward scattering model is based on the first-order radiative transfer solution, akin to MIMICS, used for the prediction of forest backscatter. Four parameters are determined from the data: two for scattering from the leaves and one for extinction through the canopy, and one for the rough ground. Another parameter for describing the rough ground backscatter, the effective rms surface height, was independently determined from radar measurements early in the growing season; these measurements are not included in the dataset used to fit the radiative transfer model. A slightly modified semi-empirical model proposed by Oh *et al.* [2] is used for direct backscatter from the ground in the forward scattering model. The four parameters are determined independently for each frequency and polarization; very good fits to the model are achieved for all polarizations at C-band and for VV-polarization at L-band.

Subsets of the measured data in frequency and polarization are used to obtain inversion models. For a measure of the biomass, a combination of C-band VV-polarization and HV-polarization was found to have the highest correlation to the area density of vegetation water mass, with a regression coefficient $R^2 = 0.867$ and a root-mean-square error of 0.0678 kg/m^2. Numerous polarizations and frequencies, singly or in combination, can be used to invert for soil moisture. The use of cross-polarized backscattering at both L-band and C-band for soil moisture inversion, first reported here, provides an adequate measure for the soil moisture. L-band VV-polarized backscatter, however, is the single channel with the largest dynamic range due to soil moisture changes and simultaneously well-described by the forward scattering model. Its use, in conjunction with the C-band cross- to co-polarized ratio as a correction for biomass effects, yields a regression against volumetric soil moisture with root-mean-square error of 1.75% and a regression coefficient of $R^2 = 0.898$.

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