Volumetric Effects in Cross-Polarized Airborne Radar Data

ANDREW J. BLANCHARD, MEMBER, IEEE, RICHARD W. NEWTON, MEMBER, IEEE, LEUNG TSANG, MEMBER, IEEE, AND BUFORD RANDALL JEAN, MEMBER, IEEE

Abstract—In recent years the detection of soil moisture using remote sensing technology has become of interest to investigators and a variety of state and federal government agencies. The parameter of interest is important in agricultural, meteorological, biological, and hydrological applications. The use of active microwave devices has shown to provide capability for remote measurement from space. Problems do exist however, in isolating moisture information from the effects of other parameters such as roughness and vegetation. Of special concern is the suppression of the roughness effects in the radar return.

This paper presents an analysis of airborne cross-polarized radar measurements of agricultural scenes. The relative responses of the system to moisture and surface roughness are presented and compared to predicted responses using radar backscatter models. It is shown that the depolarized model predictions are sensitive to soil moisture, but are much less sensitive to surface roughness effects.

INTRODUCTION

In the past ten years much theoretical and experimental work has been done to identify the sensitivity of microwave backscatter data to soil moisture. Microwave backscatter is dependent upon the geometry and the electrical characteristics of the target. Target geometry includes both surface roughness and the discontinuities which exist within the volume. The electrical characteristics are expressed in terms of the complex permittivity of the subsurface. Theoretical and experimental attempts have been made to unravel the dependence of backscatter upon these geometric and electrical parameters (Bradley and Ulaby [1], Fung [2], Blanchard and Rouse [3], Beckman [4], Tsang and Kong [5], Hirosawa et al. [6]).

This paper addresses two issues. First, the sensitivity of backscatter return to soil moisture as a function of incident angle and secondly, the sensitivity of the cross polarized radar return to surface roughness. Analysis of the first issue indicates that a volumetric effect contributes to the decrease in sensitivity of radar backscatter to soil moisture as a function of incident angle. From this analysis we conclude that the volume contribution is significant. The volume backscatter model used in this analysis predicts cross-polarized cross sections which are a function of properties of the volume and which are independent of surface roughness. Some controversy still exists regarding the significance of surface induced depolarization in radar backscatter measurements. The capability of a low permittivity surface to support significant depolarization is still debatable. Recently, theories have been developed which account for surface induced scatter and depolarization [7], [8]. However, these theories require large permittivity values (those generally associated with sea and ocean media) to generate realistic values. The model used in this analysis reflects the opinion that depolarized surface effects in earth/land target situations are insignificant. The results of this model predict depolarized cross sections which are dependent on subsurface characteristics (permittivity and volume reflection coefficient) and independent of surface roughness effects.

As an additional issue we address the problem of making an accurate cross-polarized radar backscatter measurement. The accuracy of this measurement depends upon the isolation characteristics between the like- and cross-polarized radar channels. We identify specific criteria in terms of integrated antenna polarization isolation necessary to make an accurate cross-polarized measurement.

MEASUREMENTS

The decrease in sensitivity to soil moisture as a function of incident angle has been observed in a number of airborne radar data sets. Fig. 1 presents measurements [1] acquired over Colby, KS, by the National Aeronautics and Space Administration (NASA) in 1978 at three frequencies. The target scene is a randomly rough field with varying moisture content. The trend of interest here is the decrease in the difference between the wet and the dry curves for like-polarized radar backscatter as the incident angle increases. This phenomenon is observed at 1.6, 4.75, and 13.3 GHz.

Blanchard [9] conducted an experiment using the same NASA scatterometers over a test site in the Brazos River Valley in Brazos County, TX. The radar systems were flown over selected fields seven times over a two month period in the Fall of 1976. The owners had been previously contacted and all of the fields were left undisturbed and fallow for that two month period. Selected fields were marked and sample points were flagged in each field. Gravimetric and bulk density samples were collected at five depths.

The best linear fit for all look angles of the 1.6-GHz like-polarized Brazos County measurements as a function of soil moisture is shown in Fig. 2. Observe that the sensitivity of the back-
Fig. 1. (a) Like- and cross-polarized 1.6-GHz radar cross section for two moisture conditions. Randomly rough bare field. (b) Same 4.75 GHz. (c) Like-polarized, only 13.3 GHz (from Bradley and Ulaby [11]).

Fig. 2. 1.6-GHz like-polarized radar backscatter cross section plotted as a function of volumetric moisture for various incident angles (from Blanchard [9]).

Fig. 3. 1.6-GHz cross-polarized radar backscatter cross section plotted as a function of volumetric moisture for various incident angles (from Blanchard [9]).

scatter cross section to soil moisture decreases as the incident angle increases. For the like-polarized data, the moisture sensitivity decreases for angles up to 15°, then remains constant for larger incident angles. However, for the cross-polarized data acquired over the same fields, the sensitivity to moisture remains approximately constant as a function of incident angle. These results are shown in Fig. 3. There is some inconsistency in the slope for the cross-polarized data especially near nadir but these may be introduced by system artifacts. An interesting point to note is that the moisture sensitivities behave differently for like and cross-polarized data at angles less than 15°, but for angles greater than 15 or 20° the slope of the like-polarized moisture sensitivity saturates to the slope of the cross-polarized moisture sensitivity. It is as if two different phenomena were governing the behavior of like- and cross-polarized radar cross sections at angles less than 15°, while the same phenomena governs behavior at incident angles greater than 15°. The behavior of the like-polarized return is present in a number of radar data sets including those taken using ground based systems (Ulaby et al. [10]).

The difficulty arises in being able to identify the phenomena which cause this response to occur. Theoretical models which include single scatter surface effects do not predict this effect. Because these surface models (assuming constant surface roughness) are driven by the surface reflection coefficient, the
variation in scattering coefficient as a function of permittivity changes is essentially constant for incident angle up to 50°. There must be some other phenomena to account for the sensitivity change observed in the data.

THEORETICAL MODELS

Models that only consider surface scatter do not explain the behavior of experimental measurements. As a result, a model described by Blanchard and Rouse [3] which includes both surface roughness interaction process and a volumetric interaction process was investigated. This model was programmed on the digital computer and representative responses were calculated. The results of these calculations are presented in Fig. 4-9.

These figures present model responses as a function of surface roughness, soil complex permittivity (or soil moisture), and volume reflection coefficients.

The approach, similar to that used by Rouse [11], is to identify the nature of microwave interaction phenomena that may influence the measurement of microwave backscatter from natural terrain, in particular, depolarization processes. The backscatter response is described as a function of a variety of physically measurable parameters, i.e., surface roughness, permittivity, etc. In most cases it has been very difficult if not impossible to measure subsurface discontinuities. These processes must still be dealt with, however.

This paper addresses the relative interplay between scatter from rough surface and scatter from within an inhomogeneous volume bounded by a rough surface. The backscatter from such a target is assumed to arise from two incoherent processes: 1) scatter from the surface and 2) scatter from the subsurface. The surface theory uses the Kirchhoff approximation and predicts only polarized scatter. The subsurface is described by a parameter similar to surface reflection coefficient, termed the volume reflection coefficient γ. This term, in general, can be represented by a tensor in polarization, a polarized and depolarized reflection coefficient for each incident polarization. If the statistics of the three-dimensional permittivity fluctuations are approximately equal, then γ is independent of incident angle. If, however, the statistics vary differently in one dimension, then the incident wave effectively "sees" a different scattering geometry as a function of angle. The volume reflection coefficient would then have to be a function of incident angle. Our attempt then is to quantify scattering volumes in terms of the volume reflectivity γ.

Fig. 4(a) shows the response of backscatter cross section as a function of permittivity changes when there is no subsurface scatter. The permittivity values used to make these computations were laboratory measurements acquired at 1.6 GHz [12]. These backscatter predictions were calculated for a slightly rough surface. The response versus incident angle is typical, exhibiting a rapid falloff. Also, the cross section increases with increasing values of permittivity since the cross section is a function of the Fresnel reflection coefficient.

The Kirchhoff scattering theory used to obtain the calculations of Fig. 4(a) predicts no surface induced depolarization. It is interesting to compare the results of the surface theory with measurements made with crossed polarizations, as shown in Figs. 5-6.
with those of the surface/volume theory of Blanchard and Rouse [3]. According to this theory the like-polarized cross section is composed of two components, a surface component which increases with increasing permittivity and a subsurface term which increases with increasing volumetric reflectivity. Fig. 4(a) shows the response due to the surface term alone. However, Fig. 4(b) shows the complete model with the volume term included. For angles less than 20° the surface term dominates and the response trend is shown in Fig. 4(a). However, after 20° the subsurface term begins to influence the like-polarized backscatter by decreasing the sensitivity of the cross section to soil moisture variations.

Fig. 5 shows the variation of cross-polarized return as a function of incident angle and volume reflection coefficient. The calculations were performed for permittivity values corresponding to 10-percent volumetric soil moisture and the volume reflection coefficients from 0.05 to 0.15. The response of the depolarized cross section is relatively flat for incidence angles as great as 55°. The cross section is sensitive to changes in volumetric reflection coefficients.

Fig. 6 shows the depolarized cross section variation as a function of soil moisture. The depolarized term is obviously less sensitive to the transmission coefficient across the air/soil boundary (and therefore soil moisture changes) than for changes in volumetric reflection coefficient. These calculations are also independent of surface roughness, which is an inherent characteristic of the model.

Using both the surface model and the surface/volume model we investigated the behavior of the predictions as a function of moisture sensitivity and backscatter return. Fig. 7 shows the sensitivity of the HH return as a function of soil moisture for a variety of incident angles, computed using only the surface term model. As expected, this model predicts constant sensitivity to moisture as a function of incident angle. These curves were calculated at a frequency of 1.6 GHz.

Because only the surface term was included, the volume reflection coefficient is 0.0. When both the surface and subsurface terms are included, the predictions for like-polarized backscatter as a function of moisture and incident angle are shown in Fig. 8. We see that the sensitivity decreases as a function of incident angle, just as we had observed in the data shown in Figs. 1 and 2. The frequency for these calculations is again 1.6 GHz. Fig. 9 shows the response of the predicted cross-polarized radar return using values of volumetric reflection coefficient (γ) of 0.100 and 0.134 corresponding to 0.0 and 0.3 volumetric soil moisture, respectively. Cross-polarized behavior is constant as a function of incident angle.

The significance of these results is that we have identified the nature of the interaction process between soil volume and radar backscatter, and that we have been able to predict the trend in their response of backscatter sensitivity as a function of soil moisture.

The volume backscatter model used in this analysis predicts cross-polarized cross sections which are a function of properties of the volume. This model predicts depolarized cross sections which are independent of surface roughness. This result is significant in that the theory predicts that we are ca-
pable of making a volume dependent measurement (soil moisture) independent of surface effects.

**Measurement Errors**

In 1980 Blanchard [3] analyzed the influence of polarization isolation on purity of the depolarized measurement. He observed a significant decrease in measurement purity as a function of degradation in polarization isolation. The analyses showed that quality depolarized measurements required a total integrated antenna isolation across the antenna beamwidth that is 16 dB greater than the difference in the like-polarized return and the expected depolarized return. If this criteria is not met, significant feedthrough of like-polarized energy into the cross-polarized channel can occur.

This signal degradation can be illustrated by the following figures. Fig. 10(a) represents like- and cross-polarized backscatter cross section predicted by Blanchard and Rouse [3]. The target is an inhomogeneous volume bounded by a slightly rough surface. If the integrated isolation between polarizations is approximately 12 dB, the feedthrough of the like-polarized return into the cross-polarized channel can be calculated. The results are shown in Fig. 10(b). Significant degradation has taken place in the depolarized term, especially in the region where the difference in like- and cross-polarized measurements is large. Like-polarized feedthrough causes the near nadir cross-polarized measurement to peak.

An antenna system with polarization isolation of approximately 20 dB across the beamwidth was used to simulate a cross-polarized measurement and the results are shown in Fig. 10(c). For comparison, data taken by the NASA/Johnson Space Center 1.6-GHz airborne scatterometer are shown in Fig. 10(d). Wang [14] in 1976 investigated the polarization isolation of the 1.6-GHz scatterometer and his results show that this figure is on the order of 20 dB. These simulations illustrate that the quality of the depolarized 1.6-GHz airborne scatterometer measurements is of questionable value for incident angles less than 30°.

**Conclusions**

Our results have shown that cross-polarized measurements are potentially useful in determining soil moisture. Cross-polarized radar return demonstrates a sensitivity to soil moisture that is independent of incident angle. It is also claimed that cross-polarized return is independent of surface roughness effects and that it depends purely on subsurface geometry and permittivity. The like-polarized term consists both of surface and subsurface scatter.

Antenna polarization characteristics have a significant effect on cross-polarized backscatter measurements. An analysis of cross-polarized backscatter must take into account the isolation requirements of the antenna to make sure that the cross-polarized return does not reflect the feedthrough of like-polarized channel into the cross-polarized measurements. Antenna isolation must be appropriately characterized if the measured cross-polarized backscatter data are to be correctly interpreted. The isolation figure of merit must be based on the integrated isolation over the processed beamwidth. There is evidence to support that the discrepancy between theory and experimental cross-polarized data lies in the measurement technique.

**References**


Andrew J. Blanchard (S'70-M'77) received the B.S. degree from the University of Southwestern Louisiana, Lafayette, in 1972, the M.S. degree from Colorado State University, Fort Collins, in 1973, and the Ph.D. degree in 1977 from Texas A&M University, College Station, all in electrical engineering.

He is presently an Assistant Professor with the Department of Electrical and Computer Science at Massachusetts Institute of Technology, Cambridge, in 1971, 1973, and 1976, respectively.

He is presently an Assistant Professor with the Department of Electrical Engineering and Computer Science at Massachusetts Institute of Technology from 1978 to 1980. He was with the Schlumberger-Doll Research Center, Ridgefield, CT between 1976 and 1978. His research interests include ground-based subsurface probing with dipole antennas, microwave remote sensing, acoustic logging and ultra-sonic scattering by granular media.

Dr. Tsang is a member of AGU, Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and Commission B of the International Union of Radio Science.

Richard W. Newton (S'76-M'77) was born in Baytown, TX on August 26, 1948. He received the B.S., M.S., and Ph.D. degrees from Texas A&M University, College Station, in 1970, 1971, and 1977, respectively, all in electrical engineering.

From 1971 to 1973 he was employed by Lockheed Electronics Company, at the NASA Johnson Space Center, Texas. He joined the Remote Sensing Center at Texas A&M University in 1973, working in the area of microwave remote sensing technique development, sensor system development, and signal processing. He is currently Director of the Remote Sensing Center, a Division of the Texas Engineering Experiment Station and Associate Professor in the Electrical Engineering Department at Texas A&M University.

Dr. Newton is a registered Professional Engineer in the State of Texas and a member of Eta Kappa Nu, Tau Beta Pi, and Sigma Xi.

Leung Tsang (S'73-M'76) received the B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, in 1978, 1973, and 1976, respectively.

He is presently an Assistant Professor with the Department of Electrical Engineering and an Associate Research Engineer with the Remote Sensing Center, Texas A&M University, College Station. He was a Research Associate with the Research Laboratory of Electronics and a Lecturer with the Department of Electrical Engineering and Computer Science at Massachusetts Institute of Technology from 1978 to 1980. He was with the Schlumberger-Doll Research Center, Ridgefield, CT between 1976 and 1978. His research interests are in geophysical subsurface probing with dipole antennas, microwave remote sensing, acoustic logging, and ultrasonic scattering by granular media.

Dr. Tsang is a member of AGU, Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and Commission B and F of the International Union of Radio Science.

Buford Randall Jean (S'67-M'71) was born in Hillsboro, TX on May 14, 1948. He received the B.S. degree in electrical engineering from Texas A&M University, College Station, in 1970, and the M.S. degree in 1971, and the Ph.D. degree in 1978.

He returned to Texas A&M as an Engineering Research Associate at the Remote Sensing Center in 1974 from the Bendix Research Labs, Southfield, MI, where he was an Engineer in the Electromagnetic Systems and Technology Department. He currently holds a joint appointment between the Remote Sensing Center and the Department of Electrical Engineering.

Dr. Jean's current interests include microwave sensor development and signal processing. He is a member of Phi Eta Sigma, Phi Kappa, Tau Beta Pi, and Eta Kappa Nu. He is a Registered Professional Engineer in the State of Texas.