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Look Direction Modulation Function of the Radar Backscattering Coefficient of Agricultural Fields

In terms of remote sensing applications such as soil moisture estimation and crop identification, frequencies above 4 GHz should be used to avoid the look direction ambiguity problem.

Introduction

In order to extract accurate information concerning a particular environmental variable—soil moisture or crop type, for example—from radar imagery, it is necessary to understand the degree to which other variables, either in the radar system itself or in the scene, influence the radar return. Questions which must be answered include the following: At which combination of frequency, polarization, and incidence angle is a microwave system most sensitive to the parameters of interest? How much does vegetation cover interfere with radar sensitivity to soil moisture? To what extent does soil moisture variation degrade the radar's ability to distinguish among crop types? How greatly do soil type and soil surface roughness affect backscatter? And ultimately, is it possible to design a system that is strongly sensitive to the scene parameters of key interest and simultaneously relatively insensitive to scene variables of less or no interest?

These and other related questions have been treated in several investigations (Batlivala and Ulaby, 1977b; Ulaby *et al.*, 1978a, 1978b; Bush and Ulaby, 1978). This paper examines the influence of crop row direction relative to the radar look direction throughout the 1-18 GHz band and considers its potential effect on soil moisture estimation and crop identification with radar.

KEY WORDS: **Angle of incidence; Backscattering; Corn; Frequency; Look direction modulation; Microwave frequencies; Orientation; Radar; Soybeans; Wheat**
ABSTRACT: An experimental evaluation is presented of the look direction modulation function, M, which describes the dependence of the radar backscattering coefficient, σ°, on the orientation of the radar look direction relative to the row direction of agricultural fields. The look direction modulation function was investigated for angles of incidence from 0° (nadir) to 60°, microwave frequencies from 1 GHz to 18GHz (30 cm to 1.67 cm in wavelength) and for all linear polarization configurations (HH, HV, and VV). Based on experiments conducted for fields of corn, wheat, and soybeans under several different growth conditions, the results indicate a strong dependence of the like-polarized σ° on look direction at 1 GHz, decreasing exponentially with frequency to an insignificant dependence above 4 GHz. The cross-polarized σ° shows no significant dependence on look direction at any frequency or angle of incidence.
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Definition of Look Direction Modulation Function

The radar backscattering coefficient, σ^0, of an extended target is defined as the scattering cross-section of the target per unit area in the direction of the illumination source (transmitting antenna). In general, σ^0 is a function of the angle of incidence (relative to the target) and microwave frequency (or wavelength) of the incident radiation, the polarization configurations of the transmit and receive antennas, and the target geometrical and electrical properties. Aside from the effects of system and range parameters, variations in tone on a radar image are in response to variations in the magnitude of σ^0. Because σ^0 is a normalized quantity (ratio of the scattering cross-section to the physical cross-section of the illuminated area) and because its angular response usually varies over several orders of magnitude, it is customary to express it in decibels (dB), i.e.,

$$\sigma^0 \text{ (dB)} = 10 \log \sigma^0. \tag{1}$$

For the purpose of this paper, we define $\sigma^0_\perp$ and $\sigma^0_\parallel$ as σ^0 measured with the radar look direction perpendicular and parallel to the crop row direction, respectively, as demonstrated by the insets in the figures. We further postulate that, for targets with a periodic geometrical structure (such as row crops), the radar backscattering coefficient is in general given by

$$\sigma^0(\phi) = A + B \sin^n\phi \tag{2}$$

where ϕ is the angle between the radar look direction and the row direction and the parameter, n, governs the skewness of the angular dependence. Thus,

$$\sigma^0(0°) = \sigma^0_\parallel = A, \text{ and}$$

$$\sigma^0(90°) = \sigma^0_\perp = A + B$$

The Look Direction Modulation Function, M, is defined as

$$M = \sigma^0_\perp / \sigma_\parallel{}^0 \tag{3}$$

or, in dB,

$$M(\text{dB}) = \sigma^0_\perp(\text{dB}) - \sigma^0_\parallel(\text{dB}). \tag{4}$$

The scattering coefficient, σ^0, of a periodic surface is governed by several surface parameters. Figure 1 shows two types of surfaces that are commonly used in agricultural practices. The first surface (a) is approximately sinusoidal while the second (b) is a composite of a short trough region and a long plateau region. Superimposed on these undulations (large scale structure) is a small scale structure. In the absence of the large scale structure, σ^0 is determined by the small scale structure, measured in terms of the wavelength, λ. If the small scale structure is small compared to λ, σ^0 exhibits a strong dependence on the angle of incidence, θ. With the large scale structure present, the illuminating beam includes a certain range of the local angle of incidence at the surface, and hence σ^0 as measured by the radar represents an integration over this range of angles. Thus, for an electromagnetically smooth surface (in terms of small scale structure), σ^0 will depend on the shape of the macrostructure; its amplitude, h, and spacing, d; and on the angle, ϕ. On the other extreme, if the small scale structure is very rough (such as if λ is short) so that σ^0 (θ) is very weakly dependent on θ in the absence of the large scale structure, the addition of the large scale structure would have a minor effect on σ^0. This analysis suggests that for a given surface, M should approach unity as the frequency, f, is increased.

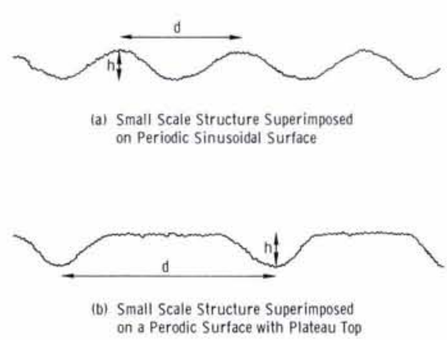

FIG. 1. Periodic soil surfaces.

PREVIOUS OBSERVATIONS IN RADAR IMAGERY

Morain and Coiner (1970), in examining X-band (λ = 3 cm) synthetic aperture radar imagery of agricultural sites in Finney County, Kansas, detected distinct variations in image brightness level which were related to direction of crop rows relative to viewing angle. In fields of recently cut alfalfa with a canopy less than 30 cm tall, lineations parallel to the long axis of the fields were observed. These linear features, caused by backscatter from irrigation dikes within the fields, gradually disappeared as the alfalfa exceeded 30 cm in height; by the time the alfalfa canopy reached a height of 60 cm, it appeared completely homogeneous. In fields of recently emergent wheat, field quadrants wherein row direction was orthogonal to look direction gave a brighter return than quadrants with rows parallel to look direction. When the wheat canopy exceeded 8 cm in height, effects of row direction disappeared. Grain sorghum showed an opposite effect; fields with rows orthogonal to look direction were consistently darker, for both HH and HV polarizations, than those with rows parallel to look direction.

Morain and Coiner postulated that in the former case the major portion of the return might be coming from the grain heads, while in the latter case the backscatter involved a complex interaction of the signal with leaves, stalks, and heads. They found no within-field variation due to row effects for fields of mature corn and sugar beets.

Batlivala and Ulaby (1977b) compared L-band ($\lambda = 21$ cm) and X-band ($\lambda = 3.75$ cm) imagery from the same Finney County agricultural site. They noted a pronounced row direction effect for sorghum and wheat stubble at L-band, for both HH and VV polarizations. The effects of row direction were not evident for L-band cross polarization or for any of the X-band polarizations.

Previous Scatterometer Measurements

In an earlier report (Batlivala and Ulaby, 1976), results were presented of a 1974 experiment in which radar backscatter was measured both parallel and orthogonal to crop row direction for a fully grown field of forage sorghum. The measurements were conducted at eight frequencies between 2.75 GHz and 7.25 GHz for HH (horizontal transmit-horizontal receive) and VV (vertical transmit-vertical receive) polarizations. The Look Direction Modulation Function, M(dB), the difference between $\sigma^0_\perp$(dB) and $\sigma^0_\parallel$(dB), was observed to be both frequency and angle of incidence dependent; the difference increased from 0 dB at nadir to 5-9 dB (depending on frequency) in the 10° to 20° range and then decreased to 0 dB at about 50°. In broad terms, the factors responsible for the observed behavior of M(dB) can be identified as (a) soil surface anisotropy (row direction), (b) vegetation canopy anisotropy, and (c) vegetation attenuation. The relative significance of each of these factors could not be determined, however, from the observations of the 1974 experiment. To gain a better understanding of this phenomenon and to evaluate its effects on the radar estimation of soil moisture content of fields planted with economically important crops like wheat and corn, a detailed investigation was conducted, the results of which are reported below.

Experiment Description

The data reported here were acquired by the University of Kansas Microwave Active Spectrometer (MAS) Systems at a test site near Eudora, Douglas County, Kansas, in 1975, except for a field of very short (7.5 cm tall) soybeans examined in 1976 and used here to illustrate the behavior of an approximately bare field. The MAS systems are calibrated scatterometers fixed atop truck-mounted booms. Two systems were used, one covering the 1-8 GHz band; and the other, the 8-18 GHz band. Table 1 provides a summary of the field conditions associated with each data set. Where the "Frequency Range" entry is 1-8 or 8-18, it means that only one of the systems was operational during the acquisition of that data set. Each data set consists of $\sigma^0_\perp$ and $\sigma^0_\parallel$ measurements at seven angles, θ, between 0° (nadir) and 80° for HH, HV, and VV polarizations over the 1-8 GHz band and only HH and VV polarizations over the 8-18 GHz band. Each measurement of σ^0 is actually an average of 20 spatially independent measurements of different spots on the field (at the same angle, θ, frequency, f, polarization configuration, p, and look direction, $\perp$ or $\parallel$).

Table 1. Field Conditions of the 1975 Row Direction Experiments

Crop Type	Frequency Range (GHz)	Date	Row Spacing d (cm)	Row Height* h (cm)	Crop Height (cm)	Crop Mositure (% wt wt.)	Soil Moisture 0-1 cm (g/cm³)	Soil Moisture 0-5 cm (g/cm³)
Wheat	1-8	5/20/75	15	2	116	74	0.13	0.15
Wheat	1-18	6/17-18/75	15	2	96	59	0.37	0.35
Wheat stubble	8-18	7/7/75	15	2	37	25	0.05	0.08
Corn	8-18	6/24/75	91	6	235	87	0.40	0.29
Corn	1-18	7/1/75	91	6	300	84	0.09	0.13
Corn	1-18	7/22/75	91	5	285	73	0.06	0.07
Corn	1-18	8/5/75	91	5	280	48	0.05	0.04
Corn Stubble	1-18	9/2/75	91	3	5-30	13	0.06	0.18
Soybeans	8-18	7/8/75	91	6	43	78	0.03	0.08
Soybeans	1-18	7/15/75	91	6	42	76	0.06	0.08
Soybeans	1-18	7/29/75	91	6	58	73	0.05	0.05
Soybeans	1-18	8/12/75	91	6	70	71	0.04	0.05

* Trough to peak.

Ground truth information acquired contemporaneously with the radar data included crop height, row spacing, plant moisture content, and soil moisture content. Samples of photographs taken in a direction parallel to the rows are shown in Figures 2a and 2b for fully grown corn plants 300 cm tall and soybean plants approximately 7.5 cm tall, respectively. The soil surface of the wheat fields when first planted was characterized by the type shown in Figure 1a but had weathered to a surface like that shown in Figure 1b by the time measurements were begun. The corn and soybean fields were similar to the type shown in Figure 1b throughout the observation period.

Background

Before we proceed with data presentation and analysis, let us define $\sigma_\perp^0$ and $\sigma_\parallel^0$ in terms of the following simple model:

$$\sigma_\perp^0 = \sigma_{\perp_v}^0 + \sigma_{\perp_s}^0\, e^{-2\alpha_\perp} \quad (5)$$

$$\sigma_\parallel^0 = \sigma_{\parallel_v}^0 + \sigma_{\parallel_s}^0\, e^{-2\alpha_\parallel} \quad (6)$$

where $\sigma_{\perp_v}^0$ is the backscatter contribution of the vegetation, $\sigma_{\perp_s}^0$ is the backscatter contribution of the underlying soil in the absence of vegetation, and $\alpha_\perp$ is the one-way attenuation through the vegetation, all for perpendicular look direction. Analogous definitions apply to $\sigma_{\parallel_v}^0$, $\sigma_{\parallel_s}^0$, and $\alpha_\parallel$ for parallel look direction. In terms of this simple model, the

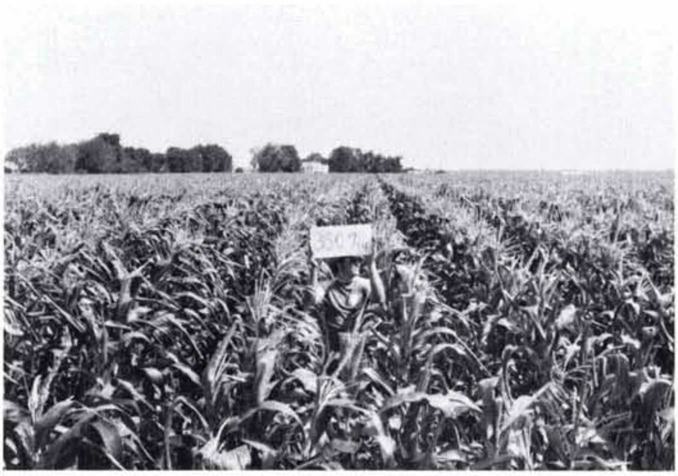

Fig. 2a. View of corn field with rows parallel to look direction. Plants are 300 cm tall.

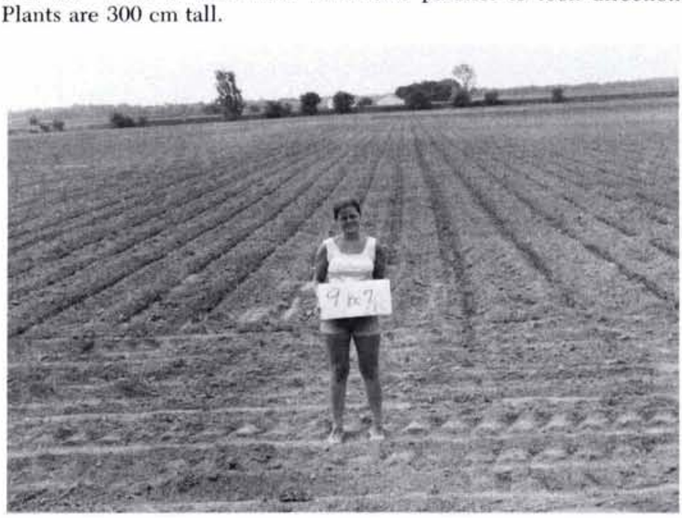

Fig. 2b. View of nearly bare soybean field. Rows are perpendicular to look direction in foreground, parallel in the background. Plants are 7.5 cm tall.

Fig. 2. Representative photos of fields used for row direction experiment.

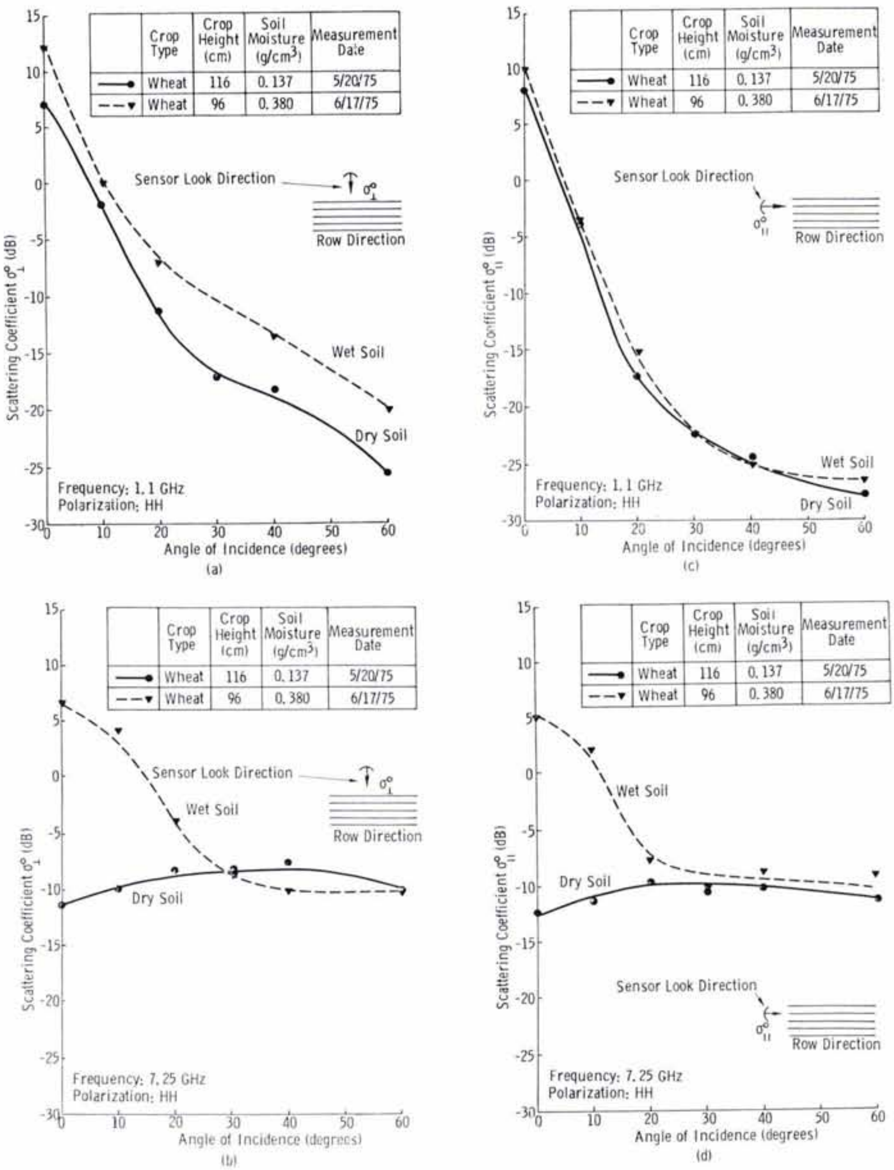

FIG. 3. Multifrequency comparison of the angular response of σ^0 of a wheat field for HH polarization: (a) $\sigma^0{}_\perp$ at 1.1 GHz; (b) $\sigma^0{}_\perp$ at 7.25 GHz; (c) $\sigma^0{}_\parallel$ at 1.1 GHz; and (d) $\sigma^0{}_\parallel$ at 7.25 GHz (adapted from Batlivala and Ulaby, 1977b).

objective of this section is to provide answers to the following questions:

(a) What is the relative magnitude of the vegetation and attenuated soil backscatter contributions to the total return as a function of θ, f, and p for each of the two look directions? Under what circumstances is $\sigma^0_\perp$ (or $\sigma^0_\parallel$) approximately equal to $\sigma^0_{\perp_v}$ (or $\sigma^0_{\parallel_v}$) and conversely, under what circumstances is $\sigma^0_\perp$ (or $\sigma^0_\parallel$) dominated by the attenuated soil backscatter component?

(b) How does $\sigma^0_{\perp_v}$ compare to $\sigma^0_{\parallel_v}$?

(c) How does $\sigma^0_{\perp_s}$ compare to $\sigma^0_{\parallel_s}$?

(d) How does $\alpha_\perp$ compare to $\alpha_\parallel$?

VEGETATION ATTENUATION

Previous work has shown that σ^0 increases with soil moisture content for both bare soil (Ulaby *et al.*, 1978a) and vegetation-covered soil (Ulaby *et al.*, 1978b). In the latter case, the sensitivity to soil moisture decreases with angle of incidence and frequency due to increased attenuation by the vegetation (Bush and Ulaby, 1978). Thus, by comparing two $\sigma^0_\perp$ (or $\sigma^0_\parallel$) angular responses of the same field under different soil moisture conditions, it is possible to determine the relative significance of the soil backscatter contribution. Such a comparison is presented for wheat at two frequencies in the 1-8 GHz band in Figures 3a and 3b for $\sigma^0_\perp$(dB) and in Figures 3c and 3d for $\sigma^0_\parallel$(dB). The observed difference in level between the wet and dry soil curves of $\sigma^0_\perp$(dB) at 1.1 GHz (Figure 3a) and both $\sigma^0_\perp$(dB) (Figure 3b) and $\sigma^0_\parallel$(dB) (Figure 3d) at 7.25 GHz indicates that the soil backscatter contribution is significant at angles between nadir and about 30°. The lack of significant difference between the wet and dry soil curves of $\sigma^0_\parallel$(dB) at 1.1 GHz for θ above 10° (Figure 3c) can be interpreted as a result of one or more of the following factors: (a) the soil term $\sigma^0_{\parallel_s}$ is insensitive to soil moisture for this configuration, (b) the attenuation by the vegetation is so high that it masks the ground, and (c) $\sigma^0_{\parallel_v} >> \sigma^0_{\parallel_s} e^{-2\alpha_\parallel}$. Because of the greater vegetative mass encountered by the indicent and backscattered wave in the perpendicular direction in comparison to the parallel direction, one would expect $\sigma^0_{\perp_v} \geq \sigma^0_{\parallel_v}$ and $\alpha_\perp \geq \alpha_\parallel$. Since $\sigma^0_\parallel$(dB) at 1.1 GHz (Figure 3a) does show a response to soil moisture, and since σ^0(dB) does not respond to moisture at higher frequencies (Figure 4), factors (b) and (c) do not provide satisfactory explanations.

To illustrate the dependence over the 8-18 GHz band, dry and wet soil responses of a corn field are shown in Figures 5a and 5b. The perpendicular scattering coefficient, $\sigma^0_\perp$, responds to soil moisture content for angles lower than 30°, and the difference between the wet and dry soil curves is generally smaller at 17 GHz than at 8.6 GHz. Thus, it is clear that in general the attenuation is not large enough to mask the underlying soil over the entire 1-8 GHz region for angles below 30°.

Although the above analysis has been limited to HH polarization, the same behavior (in terms of response to soil moisture variations) was observed for VV polarization across the 1-18 GHz band and HV polarization over the 1-8 GHz band (no HV data are available over the 8-18 GHz band).

Backscatter Dependence on Look Direction

Because of the large number of data sets acquired in this investigation and the large

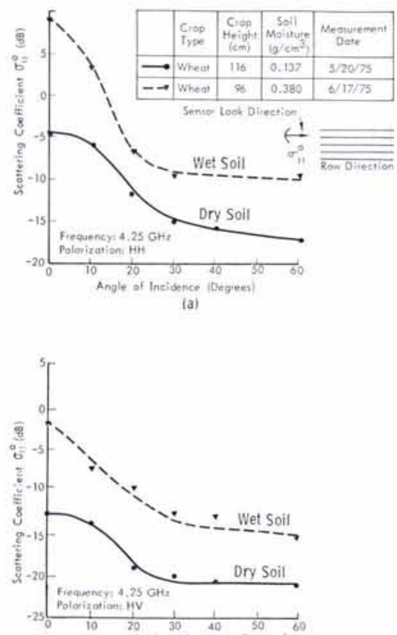

Fig. 4. Comparison of the angular response of $\sigma^0_\parallel$ of a wheat field under wet and dry soil moisture conditions at 4.25 GHz for (a) HH polarization and (b) HV polarization.

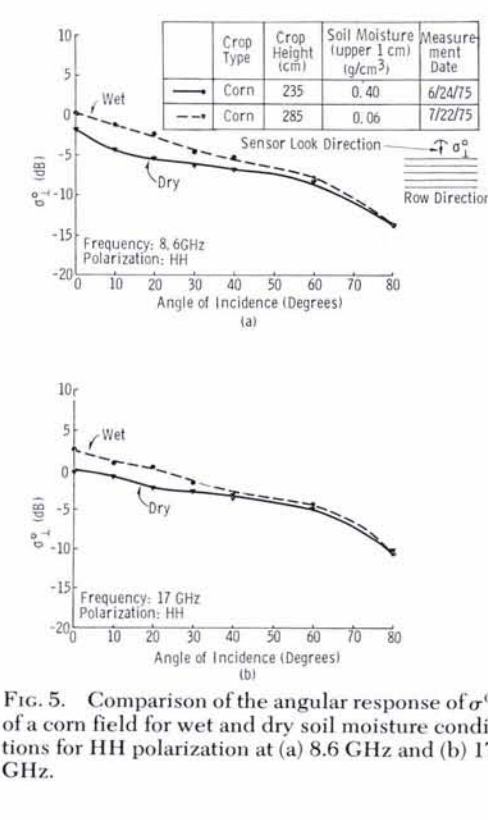

Fig. 5. Comparison of the angular response of $\sigma^0_\perp$ of a corn field for wet and dry soil moisture conditions for HH polarization at (a) 8.6 GHz and (b) 17 GHz.

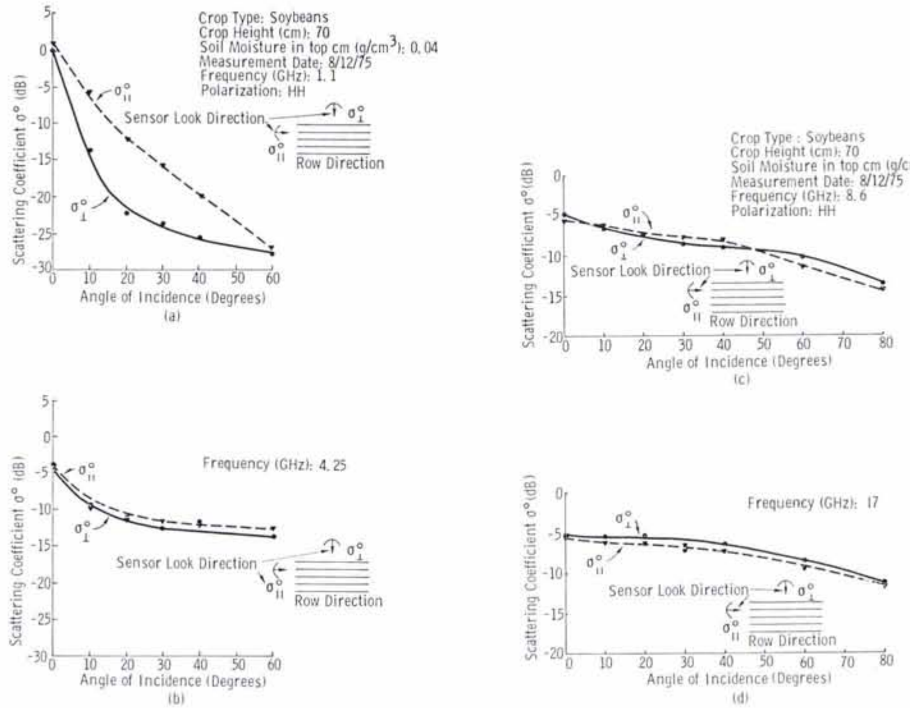

FIG. 6. Comparison of the angular response of $\sigma^0_\perp$ and $\sigma^0_\parallel$ of a soybean field for HH polarization at (a) 1.1 GHz, (b) 4.25 GHz, (c) 8.6 GHz, and (d) 17 GHz.

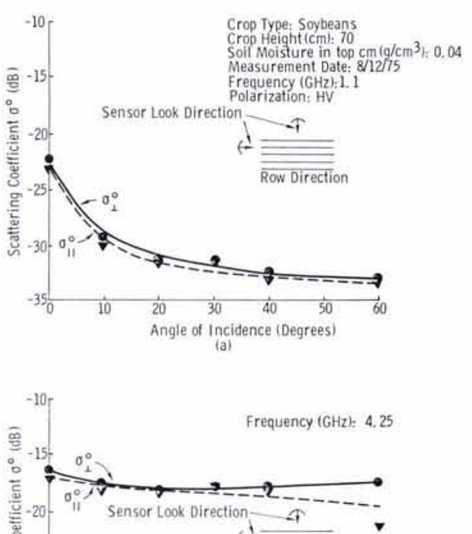

FIG. 7. Comparison of the angular response of $\sigma^0_\perp$ and $\sigma^0_\parallel$ of a soybean field for HV polarization at (a) 1.1 GHz and (b) 4.25 GHz.

number of associated sensor configurations (frequency, angle, polarization), only a representative sample of the results will be presented. Analysis of the data has shown that, among the three polarizations, VV and HH exhibit similar behavior so far as sensitivity to look direction is concerned. The cross-polarized configuration, HV, exhibits a different behavior, however. Hence only HH and HV data will be presented.

Angular responses of $\sigma_\perp{}^0$(dB) and $\sigma_\parallel{}^0$(dB) of soybeans are depicted at four frequencies in Figure 6 for HH polarization and at two frequencies in Figure 7 for HV polarization. These curves indicate the following:

(a) The HH-polarized σ^0(dB) shows strong sensitivity to look direction at 1.1 GHz and independence of look direction at the higher frequencies.

(b) The HV-polarized σ^0(dB) is independent of look direction at all frequencies and angles.

(c) The results of the previous section indicate that for f above 8 GHz and θ larger than about 30°, σ^0(dB) shows no substantial sensitivity to soil moisture variations for either look direction, i.e., $\sigma^0_\parallel \simeq \sigma^0_{\parallel_v}$ and $\sigma^0_\perp \simeq \sigma^0_{\perp_v}$. Since figures 6c and 6d show that $\sigma^0_\perp \simeq \sigma^0_\parallel$, it then follows that $\sigma^0_{\parallel_v} \simeq \sigma^0_{\perp_v}$.

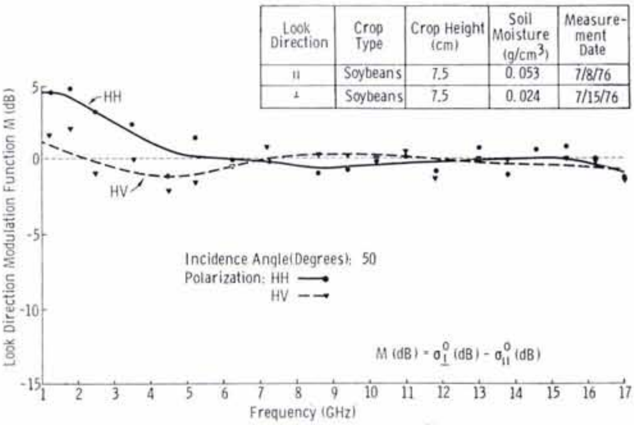

FIG. 8. Comparison of the frequency response of the look direction modulation function of a nearly bare field of soybeans for HH and HV polarizations at an incidence angle of 50°.

(d) Since below 30° the soil contribution is significant, it may then be concluded that $\sigma_{\perp s}^{0}$ is substantially larger than $\sigma_{\parallel s}^{0}$ at 1.1 GHz and that $\sigma_{\perp s}^{0} \simeq \sigma_{\parallel s}^{0}$ at frequencies higher than 4 GHz.

The last conclusion is verified further by the plots of the Look Direction Modulation Function shown in Figures 8 and 9. The data shown in Figure 8 were not acquired for the look direction investigation (which was conducted in 1975); they were acquired in 1976 as part of a soil moisture investigation but they are used herein to illustrate the dependence of the look direction modulation function, M, on frequency for an approximately bare soil case (the soybeans were only about 7.5 cm tall and covered less than 10 percent of the surface). In contrast, the data in Figure 9 are for soybean plants 42 cm tall. Both figures show that σ^0(dB) is independent of look direction for HV polarization and that for HH polarization, M(dB) decreases with frequency from about 5 dB (at 1.1 GHz) to approximately 0 dB for $f \geq 5$ GHz for the bare case (Figure 8) and for $f \geq 3$ GHz for the 42 cm high soybean case (Figure 9).

Are the above conclusions valid only for soybeans, or are they equally valid for wheat and corn? A closer look at the spectral and angular behavior of M(dB) will show that, except for some minor deviations, the overall behavior is also valid for the other two crops.

SPECTRAL AND ANGULAR RESPONSE OF LOOK DIRECTION MODULATION FUNCTION

Spectral response curves of M(dB), the Look Direction Modulation Function at incidence angles (θ) of 0°, 30°, and 60°, are shown in Figures 10, 11, and 12 for corn, soybeans and wheat, respectively. The look

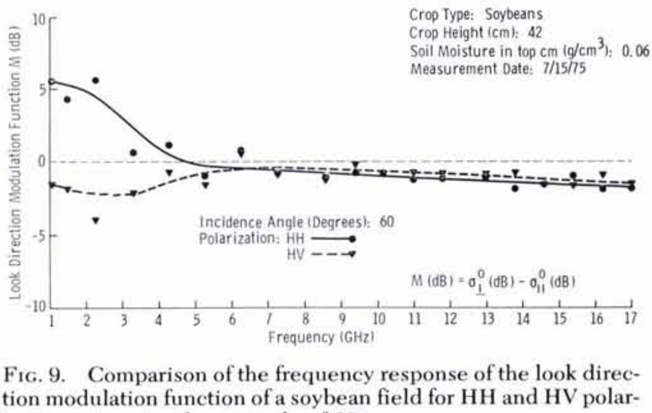

FIG. 9. Comparison of the frequency response of the look direction modulation function of a soybean field for HH and HV polarizations at an incidence angle of 60°.

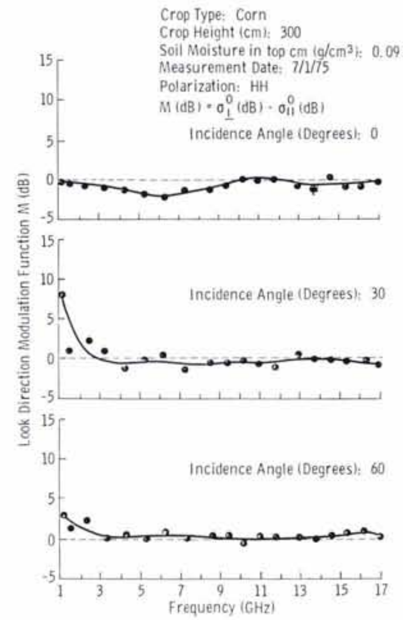

FIG. 10. Comparison of the frequency response of the look direction modulation function of a corn field for HH polarization at incidence angles of 0, 30, and 60 degrees.

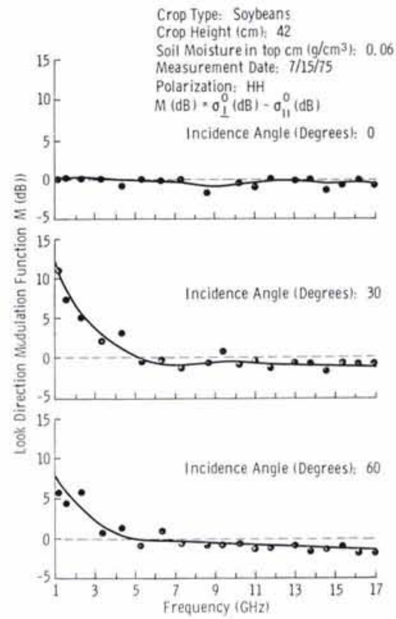

FIG. 11. Comparison of the frequency response of the look direction modulation function of a soybean field for HH polarization at incidence angles of 0, 30, and 60 degrees.

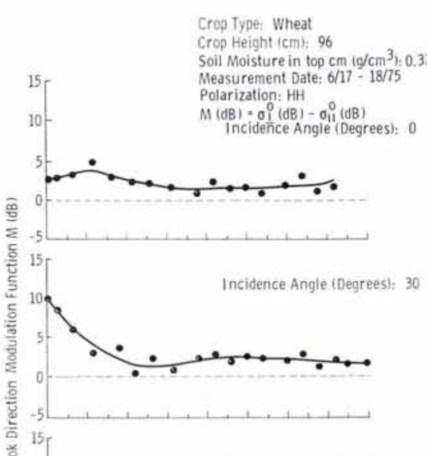

FIG. 12. Comparison of the frequency response of the look direction modulation function of a wheat field for HH polarization at incidence angles of 0, 30, and 60 degrees.

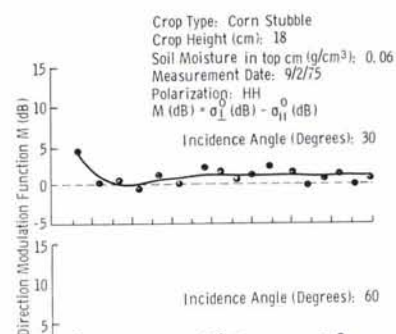

FIG. 13. Comparison of the frequency response of the look direction modulation function of a field of corn stubble for HH polarization at incidence angles of 30 and 60 degrees.

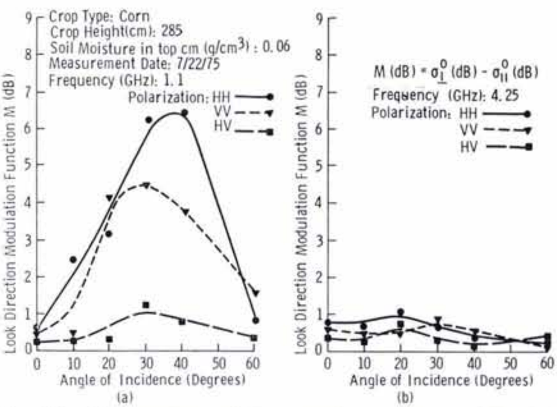

FIG. 14. Comparison of the angular response of the look direction modulation function of a corn field for HH, HV, and VV polarizations at (a) 1.1 GHz and (b) 4.25 GHz (adapted from Batlivala and Ulaby, 1977b).

direction modulation function of corn stubble is presented in Figure 13. The estimated measurement precision of M(dB) is about 1 dB.

(a) At 1.1 GHz, the like-polarized (HH and VV) M(dB) increases from about 0-1 dB at nadir to a peak in the 20°-40° range and then decreases as θ increases to 60°.

(b) Since, theoretically, σ^0 should be independent of row direction at nadir, the observed value of M(dB) at $\theta = 0°$ provides an estimate of the measurement uncertainty of M(dB) at other angles. This uncertainty is between 0 and 1.5 dB. In almost all cases, the cross-polarized value of M(dB) is within this measurement uncertainty. Thus, it can be concluded that, within the measurement precision of M(dB), the cross-polarized scattering coefficient is independent of look direction at all angles and frequencies.

(c) For corn and soybeans, $M(\text{dB}) \simeq 0$ dB at 4.25 GHz (Figures 14b and 15b) for all polarizations. For wheat, on the other hand, M(dB) is between 2 and 3 dB in the 10° to 20° range (Figure 16). This difference in behavior between wheat and the other two crops is due either to the corresponding difference in row spacing (see Table 1) or to differences in the soil moisture content between the perpendicular and parallel look direction measurement conditions, since the two measurements were made on consecutive days.

We close this section with a presentation of M(dB) of a soybean field as a function of crop height at 1.1 GHz (Figure 17). As would

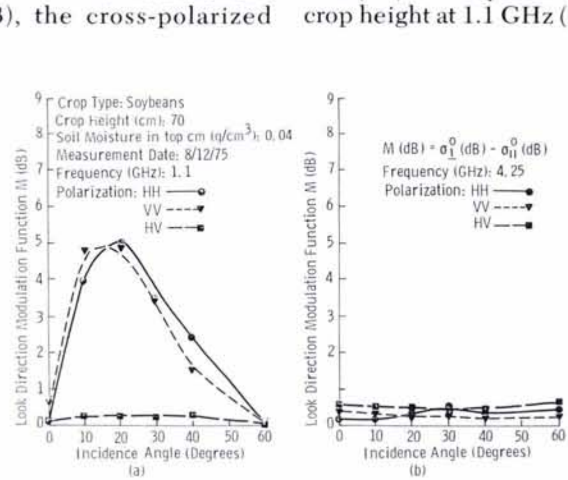

FIG. 15. Comparison of the angular response of the look direction modulation function of a soybean field for HH, HV, and VV polarizations at (a) 1.1 GHz and (b) 4.25 GHz (adapted from Batlivala and Ulaby, 1977b).

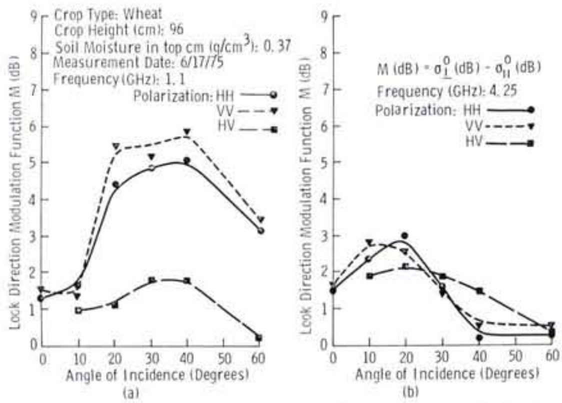

FIG. 16. Comparison of the angular response of the look direction modulation function of a wheat field for HH, HV, and VV polarizations at (a) 1.1 GHz and (b) 4.25 GHz (adapted from Batlivala and Ulaby, 1977b).

be expected, accompanying the increase in crop height is an increase in the vegetation attenuation and, hence, a decrease in the magnitude of M(dB). This behavior supports the hypothesis that the observed dependence of σ^0(dB) on look direction in the 1-4 GHz region is in response to the soil spatial anisotropy and not to the vegetation anisotropy.

Concluding Remarks

The experimental data presented in the previous section support the following conclusions:

(a) The like-polarized $M(\text{dB}) \simeq 0$ dB at all angles for $f \geq 4$ GHz. Below 4 GHz, M(dB) can be as large as 10 dB depending on crop type, crop height, frequency, and angle.

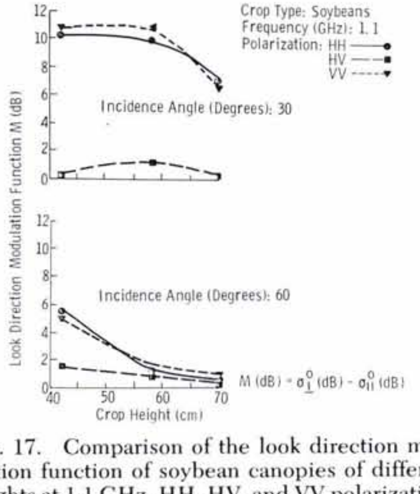

FIG. 17. Comparison of the look direction modulation function of soybean canopies of different heights at 1.1 GHz, HH, HV, and VV polarizations at incidence angles of (a) 30 degrees and (b) 60 degrees.

(b) The cross-polarized σ^0(dB) is independent of look direction $M(\text{dB}) \simeq 0$) at all angles and across the entire 1-18 GHz region.

(c) The vegetation backscatter component is independent of look direction, $\sigma^0_{\parallel_v} \simeq \sigma_{\perp}{}^0{}_v$, and likewise the vegetation attenuation is approximately the same in both directions. These observations lead to the conclusion that, electromagnetically, the vegetation canopy appears isotropic in the horizontal plane.

(d) In terms of remote sensing applications such as soil moisture estimation and crop identification, frequencies above 4 GHz should be used to avoid the look direction ambiguity problem.

(e) The experimental results presented here and their conclusions are applicable to agricultural areas where dry farming practices are used. If irrigation ditches or dikes are present, these results may not be applicable.

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