C- and Multiangle Ku-Band Synthetic Aperture Radar Data for Bare Soil Moisture Estimation in Agricultural Areas

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A sensitivity analysis of C-band (5.3 GHz) and Ku-band (14.85 GHz) synthetic aperture radar (SAR) data to the bare soil moisture content of agricultural fields was conducted in this study. The C-band data were obtained with a 23° incidence angle, whereas the Ku-band data were obtained with 35°, 55°, and 75° incidence angles. The fields presented either a small-scale or an intermediate-scale periodic soil roughness components, associated with level-basin and furrow irrigation systems, respectively. For fields with a small-scale roughness component, the SAR data were sensitive to soil moisture, particularly at the C-band with a 23° incidence angle and Ku-band with a 35° incidence angle. For fields with a intermediate-scale roughness component, both C- and Ku-band data were nearly insensitive to soil moisture. By using a theoretical surface scattering model, this study also analyzed the effects of different soil roughness components [root mean square (RMS) height h*, correlation length, and periodic row structure] in the SAR data. For fields with RMS height <0.3 cm, a small variation in* h *(from 0.1 to 0.3 cm) provoked a significant variation in the SAR data (up to 8 dB).*

INTRODUCTION

Estimation of soil moisture in agricultural areas is important for improving yield forecasts, scheduling irrigations, and other farm management activities (Idso et al., 1975). Although conventional ground-based soil moisture measurement techniques, such as the neutron probe, time domain reflectometry, and gravimetric methods, are accurate and permit measurements of the entire soil profile, they are essentially point-based measurements at a specific time. On the other hand, remote sensing can provide indirect estimates over large areas with frequent repeat coverage. The microwave region (from 1 mm to 1 m wavelength) has been the most favorable spectral region for surface soil moisture studies (Schmugge, 1985; Engman and Chauhan, 1995). There is a large contrast between the dielectric constant ε of liquid water (~80) and dry soil (3–5) within this spectral range, which makes the synthetic aperture radar (SAR) data sensitive to soil moisture content (Ulaby et al., 1986; Engman and Chauhan, 1995).

For a bare soil surface, the radar backscattering process is controlled by the dielectric property of the soil, which is related to the soil moisture content, and the soil random surface roughness (Ulaby et al., 1978; Bernard et al., 1982; Dobson and Ulaby, 1986; Bertuzzi et al., 1992). One way to minimize the soil roughness influence is to use the copolarized ratio technique; that is, the ratio between HH and VV polarized waves. Autret et al. (1989) and Chen et al. (1995) reported that SAR data derived from this technique are almost completely independent of soil roughness. However, these types of data have been collected by sensors mounted on airplanes or trucks and are available only at restricted experimental sites. No current spacecraft system has dual-polarization capability.

Another way to minimize the influence of soil roughness is to use data from sensors operating with a frequency and incidence angle around 5 GHz (C-band) and 10°, respectively (Ulaby and Batlivala, 1976; Ulaby et al., 1978). However, to obtain high spatial resolutions (magnitude of tens of meters), satellites currently carrying SAR

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systems are configured with incidence angles larger than the mentioned value: 23° for the European Remote Sensing (ERS-1, ERS-2) satellites and 38° for the Japanese Earth Remote Sensing (JERS-1) satellite. The exception is the Canadian Remote Sensing (RADARSAT) satellite, which operates at 10–60° range of incidence angle.

Ulaby et al. (1978) showed that, depending upon the combination of frequency and incidence angle, the range of the radar backscattering coefficients $\sigma°$ due to variations in surface roughness can vary up to 22 dB. In general, for smooth, bare soil surfaces with low soil moisture contents, $\sigma°$ decreases rapidly with increasing incidence angle, particularly at angles close to nadir ($<10°$); conversely, for rough surfaces, $\sigma°$ decreases gradually with increasing incidence angles. In addition, the concept of smooth and rough surface is frequency-dependent. For instance, a soil surface appears rougher for sensors operating at 14.85 GHz (Ku-band) than for those operating at 5 GHz (C-band). The presence of periodic row or furrow structures in some agricultural sites can also exert considerable angular effects in the radar scattering process (Batlivala and Ulaby, 1976; Ulaby and Bare, 1979; Beaudoin et al., 1990). Thus, the sensitivity of the SAR data to soil moisture is sensor- and site-specific. In other words, to obtain improved soil moisture estimates, the effects of soil roughness for a given sensor configuration and field condition need to be addressed by using either experimental data or theoretical/semiempirical models.

The objective of this study were: a) to investigate the sensitivity of the C-band SAR data acquired at 23° incidence angle and the Ku-band SAR data acquired at three incidence angles (35°, 55°, and 75°) to the bare soil moisture content over agricultural fields with different periodic row structures (these sensor configurations were chosen because of their availability on existing aircraft and satellite platforms); and b) by using the theoretical surface scattering model developed by Ulaby et al. (1982a), to investigate the sensitivity of SAR data to the following soil roughness components in the SAR data: root mean square (RMS) height h, correlation length L, and periodic row structure.

EXPERIMENTAL DESIGN

Site Description

The study site was at the University of Arizona's Maricopa Agricultural Center (MAC), a 770 hectare research and demonstration farm located south of Phoenix (33.08°N latitude, 111.98°W longitude), Arizona. Sandy loam, sandy clay loam, and clay loam are the predominant soil surface textures at the farm (Post et al., 1988). The major crop types consist of alfalfa grown year-round with seven to eight harvests per year; cotton, grown during the summer; and wheat, grown during the winter (Moran et al., 1997). Furrow and level-basin are the predominant irrigation systems.

The terrain was flat so that the geometric distortions in the radar data due to topographic effects were negligible. The rectangular-shaped fields are oriented in either north–south (N–S) or east–west (E–W) directions. Each field was subdivided into smaller areas defined as "borders." All fields selected contained the following structures produced by different tillage practices (Fig. 1): a) a small-scale, periodic pattern associated with planting row structures with level-basis irrigation systems; or b) an intermediate-scale, periodic pattern with furrow irrigation systems. These periodic structures were randomly perturbed by the presence of soil clods.

Synthetic Aperture Radar (SAR) Data

A set of airborne, 16-bit magnitude SAR images acquired on 30 January 1996, provided by the Sandia National Laboratories (SNL) in Albuquerque, New Mexico, were analyzed in this report. The sensor operated at 14.85 GHz (Ku-band) frequency, three incidence angles (35°, 55°, and 75°). VV polarization, and 2-m nominal spatial resolution. The radar look-direction was N72°E. Another 16-bit amplitude SAR image acquired by the ERS-2 satellite on 31 January 1996 was also analyzed. This satellite operates at 5.3 GHz (C-band) frequency, 23° incidence angle, VV polarization, and 30 m nominal spatial resolution.

All images were georeferenced to the Universal Transverse Mercator coordinate system (zone 12, 1927 North American Datum, Clarke 1866). Radar backscattering coefficients ($\sigma°$) were extracted using the following equations:

$$\sigma° \text{ (dB, C-band)} = 10 \log(DN^2 + STD^2) - K_1, \quad (1)$$

$$\sigma° \text{ (dB, Ku-band)} = 10 \log[(DN * K_2)^2], \quad (2)$$

where DN is the average digital number for each border; STD is the standard deviation, and K_1 and K_2 are the calibration constants (63.8 dB and 0.001426 dB, respectively). The averages and standard deviations for the C- and Ku-band $\sigma°$ calculations were obtained using at least 40 pixels and 2000 pixels per border, respectively.

Ground-Based Measurements

A field survey was conducted on 30 January 1996, to record border-by-border qualitative estimates of the soil moisture and soil roughness conditions. The percent of crop cover was also registered. Based on this survey, the following fields were selected for ground truth measurements (Fig. 2): a) fields with planting row structures: 18 (borders 1, 15, and 16); 23 (borders 6, 7, 8, and 9); 26 (borders 1, 5, 9, and 13); and 34 (all 16 borders); b) furrowed fields: 13 (borders 1, 2, 3, and 4); 21 (borders 1, 2, 5, and 6); 27 (borders 3 and 5); and 31 (borders 1 and 2).

These fields were characterized by bare soil or near-bare soil (less than 5% of wheat cover) conditions and various soil roughness structures. The borders were selected

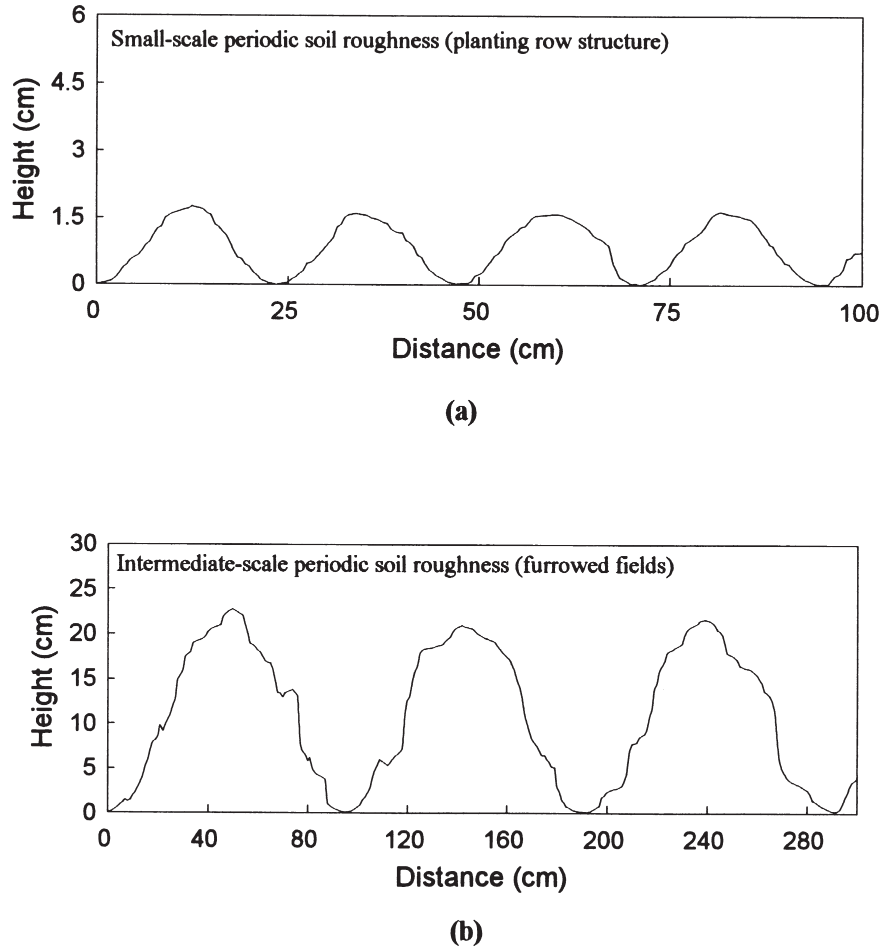


Figure 1. Schematic soil surface roughness components of Maricopa Agricultural Center fields: a) small-scale periodic roughness; b) intermediate-scale periodic roughness.

taking into consideration the soil moisture variability within the field. Soil samples for gravimetric soil moisture measurements within the top 2 cm were collected in these fields during the Ku-band overpass. Because of the high homogeneity of the soil moisture condition within each border in the fields with planting row structures, one sample per border was collected at the center of the border. For the fields with furrow structures, three samples located at the bottom, middle, and top of the furrows were collected and averaged for one reading. Volumetric soil moisture contents (*Mv*) were derived by assuming an average bulk density of 1.4 g/cm^3 for the farm (D. F. Post, personal communication, 1996). This value is in the range of MAC's bulk densities found by Post et al. (1988) for 0–30 cm depth (from 1.40 g/cm^3 to 1.45 g/cm^3).

Surface soil roughness was measured during the following days from the Ku-band overpass using a roughness meter consisting of a row of 100 equally spaced pins (Simanton et al., 1978). The device was aligned in the same radar look-direction (N72°E). Figure 3 shows an example of roughness sampling in fields with N–S planting row structure and E–W rough furrow structure, respectively. A total of 16 measurements per field were made for those with planting row structures. For furrowed fields, 32 measurements were collected per field: that is, two per border, one at the top of the furrow and another at the bottom of the furrow. The lines formed by 100 point readings were digitized in a Geographic Information System software package (Arc/Info) to calculate the roughness indices.

Theoretical Surface Backscattering Model at the MAC

The theoretical surface backscattering model used in this study is validated for randomly perturbed periodic surfaces and was developed by Ulaby et al. (1982a). The backscattering coefficients are derived by assuming that the scattering process is caused exclusively by the random part of the surface (Ulaby et al., 1986). The periodic component modulates the local slope a of the superimposed random component. Radar backscattering coefficients $\sigma°(\theta)$ are calculated by

$$\sigma°(\theta)=\frac{1}{T}\int_0^T \sigma°(\theta_1)\ \sec(a)\ dy, \qquad (3)$$

where θ is the incidence angle of the sensor, T is the one spatial period of the row structure (row spacing) in the direction y, and θ_1 is the local incidence angle. In

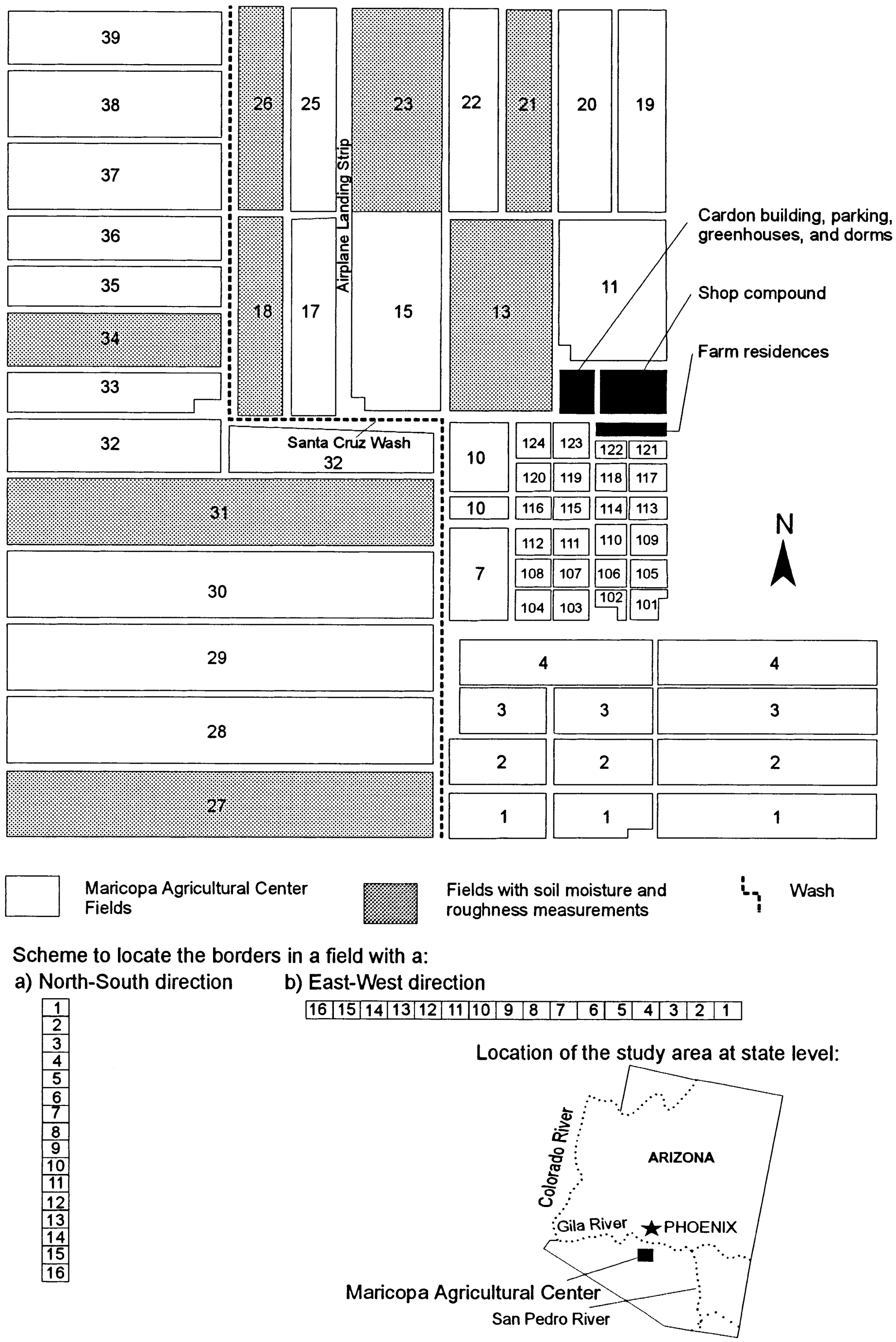


Figure 2. Maricopa Agricultural Center map with fields selected for ground truth measurements.

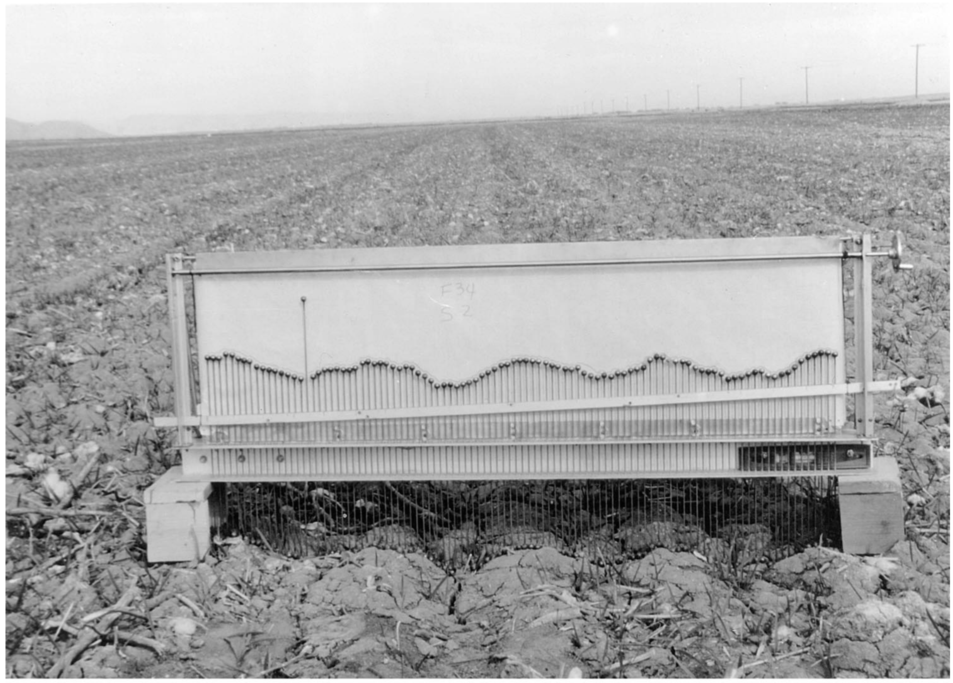
practice, $\sigma^\circ(\theta)$ is obtained by calculating a certain number of local backscattering coefficients $\sigma^\circ(\theta_1)$ over a differential segment dy and integrating them along a spatial period T. The term $\sigma^\circ(\theta_1)$ accounts for the scattering from the random component and the term $\sec(\alpha)$ accounts for the periodic component of the soil surface. The angles α and θ_1 are calculated by each segment dy as follows:

$$\alpha=\arctan\left[\frac{dR(y)}{dy}\right], \tag{4}$$

$$\theta_1=\theta-\alpha, \tag{5}$$

where $dR(y)$ is the relative height of the periodic component at a distance dy.

The integral equation model (IEM) developed by Fung and Chen (1992) was used to estimate $\sigma^\circ(\theta_1)$ values. The input data for the model are the wavelength λ, type of polarization, incidence angle of the sensor, dielectric constant ε, RMS height h, autocorrelation function $\rho(x')$, type of autocorrelation function, and correlation length L of the soil surface. Dielectric constants



(a)

(b)

Figure 3. Examples of soil roughness measurements: a) Field 34, border 2, with approximately north–south planting row structure; b) Field 21, border 2, with approximately east–west furrow structure.

were derived from the following relation (Topp et al., 1980; Topp and Davis, 1985):

$$M_v = -0.0530 + 0.0292\varepsilon - 0.00055\varepsilon^2 + 0.0000043\varepsilon^3, \quad (6)$$

where M_v is the volumetric soil moisture content. This equation has been validated for a wide range of mineral soils and various soil moisture conditions (Altese et al., 1996).

The parameters h, $\rho(x')$, and L are related to the random soil roughness and were obtained from the height measurements using a device developed by Simanton et al. (1978). Because of the presence of the periodic components in these measurements, the random components were separated from the periodic components using the Fourier and the inverse Fourier transforms. The RMS height h corresponded to the standard deviation of heights relative to a reference surface. The autocorrelation function for a spatial displacement $x'=(j-1)\,\Delta_x$, where j is an integer$\geq$1, is given by (Ulaby et al., 1982b)

$$\rho(x')=\frac{\sum_{i=1}^{N+1+j} z_i z_{j+i-1}}{\sum_{i=1}^{N} z_i^2}, \qquad (7)$$

where z_i is the height z at a point i.

The surface correlation length L is defined as the displacement x' for which $\rho(x')$ is equal to 1/e, that is,

$$\rho(L)=\frac{1}{e}\,. \qquad (8)$$

Fields 23 and 34 (planting row structures oriented approximately perpendicular to the radar beam direction) were selected to investigate the performance of the theoretical model for the sensor configurations analyzed in this study. Data from furrowed fields were not analyzed because the IEM model used in this study was an approximation of the complete, but complex version. This approximate version is valid only for surfaces with small to moderate RMS heights or for low to medium frequencies (Altese et al., 1996). The following assumptions were made for the modeling: a) the influence of sparse vegetation cover (<5% cover by wheat) in the radar backscattering process are negligible and b) the influence of soil volumetric scattering was also considered negligible since SAR systems operating at high frequencies have a short penetration capability into the soils (~2 cm). The sensor configuration with the best performance was used to investigate the sensitivity of $\sigma°$ to different soil roughness components in the scattering process. The criteria used to define the best performance was the mean absolute difference (*MAD*):

$$MAD=|\sigma°_{\mathrm{ESTIMATED}}-\sigma°_{\mathrm{MEASURED}}|, \qquad (9)$$

where $\sigma°_{\mathrm{ESTIMATED}}$ refers to the $\sigma°$ estimated by the model and $\sigma°_{\mathrm{MEASURED}}$ refers to the $\sigma°$ measured by the SAR systems.

RESULTS AND DISCUSSION

Field Data

Tables 1 and 2 summarize the field data obtained for this study. All fields were either bare soils or near bare soils with a maximum of 5% wheat cover. The volumetric soil moisture content ranged from 8% to 42%. The row spacing and amplitude for the fields with small scale row structures were 23.6 cm and 1.7 cm, respectively; for the intermediate-scale furrowed fields, the furrow spacing and amplitude were 95 cm and 22 cm, respectively.

Table 1. Field Data from Maricopa Agricultural Center Acquired on 30 and 31 January 1996: Fields with Planting Row Structure

Field	*Border*	*Row Direction*	*Crop Cover*	*Volumetric Soil Moisture (%)*
18	1	E–W	Wheat (<3%)	42
	15			10
	16			14
23	6	N–S	Wheat (<5%)	36
	7			35
	8			13
	9			10
26	1	E–W	Wheat (<1%)	10
	5			11
	9			8
	13			10
34	1	N–S	Wheat (<1%)	24
	2			20
	3			15
	4			15
	5			15
	6			14
	7			14
	8			20
	9			20
	10			24
	11			29
	12			31
	13			36
	14			34
	15			32
	16			35

Sensitivity of Measured SAR Backscatter to Soil Moisture

Figure 4 presents the scatterplot between radar backscattering coefficient $\sigma°$ and % volumetric soil moisture con-

Table 2. Field Data from Maricopa Agricultural Center Acquired on 30 and 31 January 1996: Furrowed Fields

Field	*Border*	*Furrow Direction*	*Crop Cover*	*Volumetric Soil Moisture Content (%)*
13	1	E–W	Bare soil	8
	2			8
	3			7
	4			8
21	1	E–W	Wheat (<5%)	25
	2		Wheat (<5%)	20
	5		Bare soil	8
	6		Bare soil	8
27	3	E–W	Wheat (<1%)	34
	5			20
31	1	N–S	Bare soil	24
	2			11

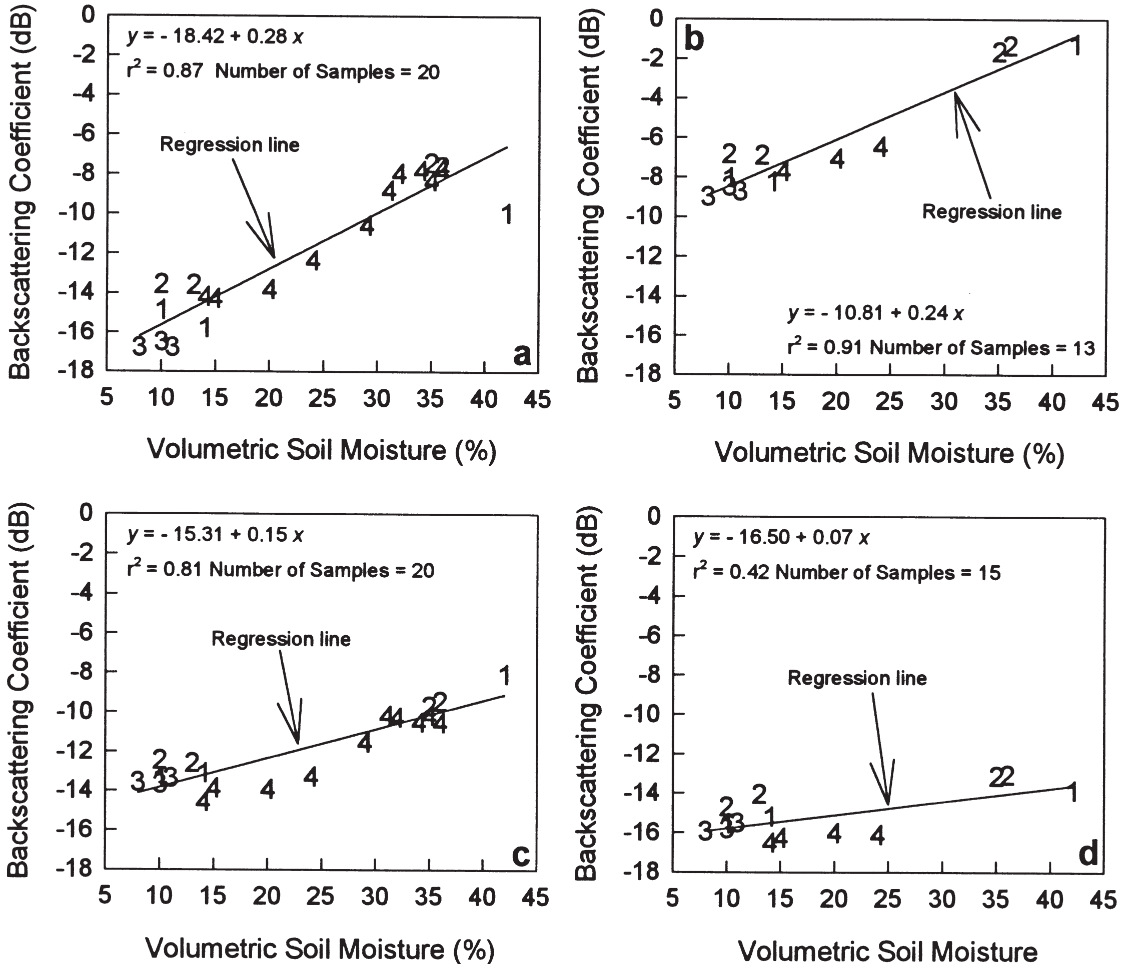


Figure 4. Scatterplot between SAR data and % volumetric soil moisture content for fields with planting row structure: a) the C-band with a 23° incidence angle; b) the Ku-band with a 35° incidence angle; c) the Ku-band with a 55° incidence angle; and d) the Ku-band with a 75° incidence angle. 1=Field 18; 2=Field 23; 3=Field 26; 4=Field 34.

tent M_v for fields with a planting row structure. The test of significance for the correlation coefficients indicated that the correlations were significant at 0.01 critical value. The highest slope (28.18) for the C-band at a 23° incidence angle indicated that this configuration was the best to estimate soil moisture. Among the Ku-band configurations, the 35° incidence angle was the best (slope= 23.71, r^2=0.91, for a confidence level of 95%), whereas the 75° incidence angle was nearly insensitive to the soil moisture. Despite an overall positive trend, the Ku-band at a 55° incidence angle was nearly insensitive to soil moisture when the latter was smaller than 25%.

Figure 5 shows the scatterplot between $\sigma°$ and M_v from the furrowed fields. The backscattering coefficients from all borders with the same soil moisture contents within the same field were averaged. The $\sigma°$ was insensitive to soil moisture for all sensor configurations, most likely because of the dominant influence of the soil roughness [presence of both periodic roughness and large soil clods, with a diameter higher than 15 cm (see Fig. 2)] in the backscattering process. The influence of furrow direction can be easily seen in the sensor configurations with relatively low incidence angles: C-band with a 23° incidence angle and Ku-band with a 35° incidence angle. In these configurations, the N–S oriented furrow structure of Field 31 presented the highest $\sigma°$ values, regardless of soil moisture content.

Performance of the Theoretical Model: Comparison with the Experimental Data

In this section, the performance of the theoretical model was verified by comparing the $\sigma°$ derived by the model with the experimental data from Fields 23 and 34. The small-scale, periodic roughness pattern of these fields was found to be described by a cosine wave function with period T=23.6 cm and amplitude A=1.7 cm; that is,

$$y=1.7\cos\left(\frac{2\pi}{23.6}x+\pi\right)+1.7, \tag{10}$$

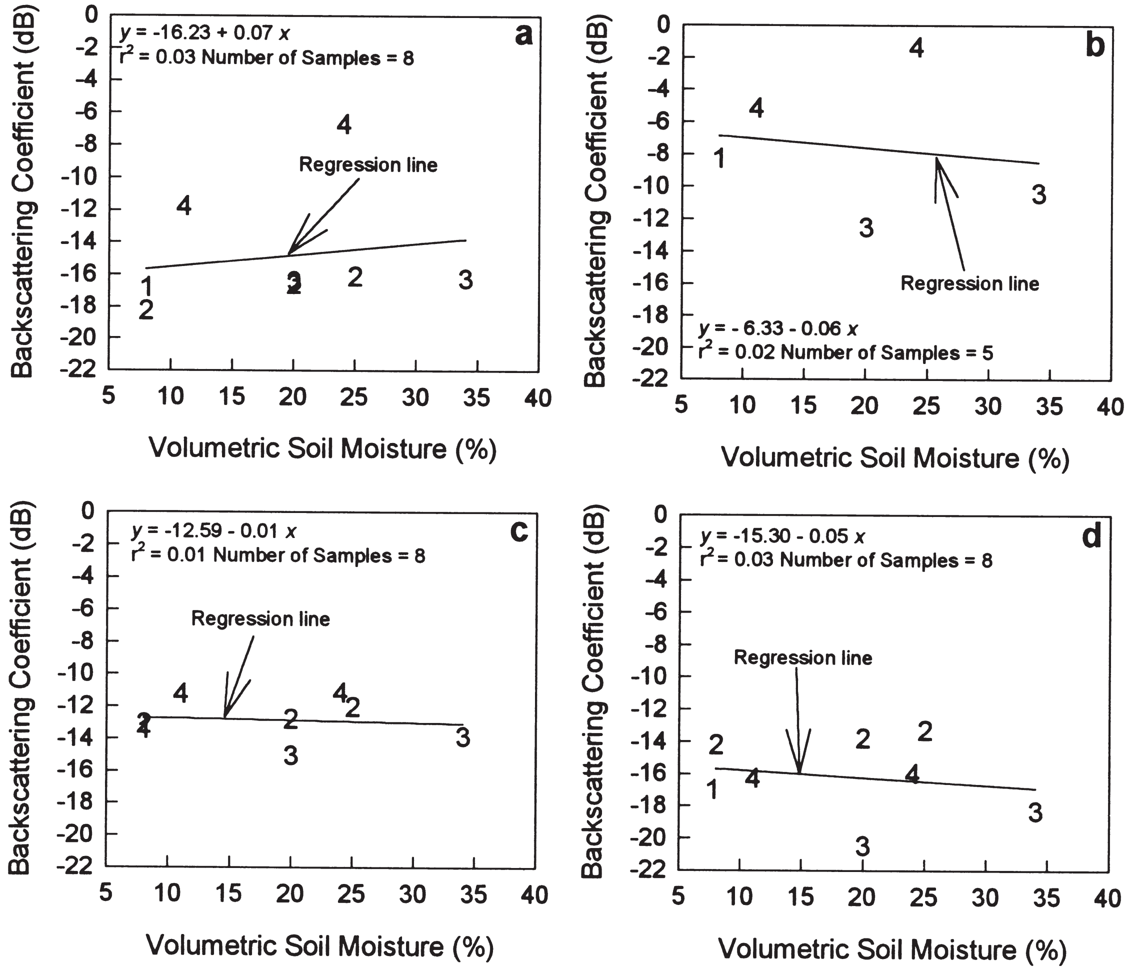


Figure 5. Scatterplot between SAR data and % volumetric soil moisture content for furrowed fields: a) the C-band with a 23° incidence angle; b) the Ku-band with a 35° incidence angle; c) the Ku-band with a 55° incidence angle; and d) the Ku-band with a 75° incidence angle. 1=Field 13; 2=Field 21; 3=Field 27; 4=Field 31.

Sixteen different values of a, one at each dy=1.5 cm, were calculated to estimate $\sigma°(\theta_1)$ [see Eq. (3)]. An example of ground profiles sampled by the roughness meter, its periodic components split from the random component using a Fourier and inverse Fourier transform, and its sinusoidal function modeled by Eq. (10) are shown in Figures 6a, 6b, and 6c, respectively. Regarding the random roughness component, the calculated autocorrelation function for the MAC data set was found to be closer to an exponential function, with a correlation length L=5 cm and 6 cm for Fields 23 and 24, respectively. Previous studies (Fung et al., 1992; Oh et al., 1992) also showed that an exponential function was applicable to bare soil surfaces. Table 3 indicates the dielectric constant ε and the RMS height h values obtained from Fields 23 and 34. An average RMS height h of 0.3 cm for both fields was used to calculate $\sigma°(\theta)$. The $\sigma°(\theta)$ for the seven borders (10–16) of Field 34 for 35° and 75° incidence angle were not generated because measured SAR data were unavailable.

The model presented an overall underestimation for the Ku-band and an overestimation for the C-band (Fig. 7). The lowest mean absolute difference (*MAD*) was found for Ku-band with a 55° incidence angle (*MAD*= 2.6 dB), while the highest value was found for Ku-band with a 75° incidence angle (*MAD*=5.5 dB). The C-band with a 23° incidence angle and the Ku-band with a 35° incidence angle presented intermediate differences (*MAD*=3.67 and 4.10, respectively).

The high sensitivity of the SAR signal to the soil roughness, especially for relatively smooth surfaces (Altese et al., 1996) made the inversion procedure difficult. A small error in the RMS height measurement affect the $\sigma°$ derivation significantly. For instance, the *MAD* for Ku-band with a 55° incidence angle can be reduced by its half value (from 2.6 dB to 1.3 dB) if we use h=0.4 cm, instead

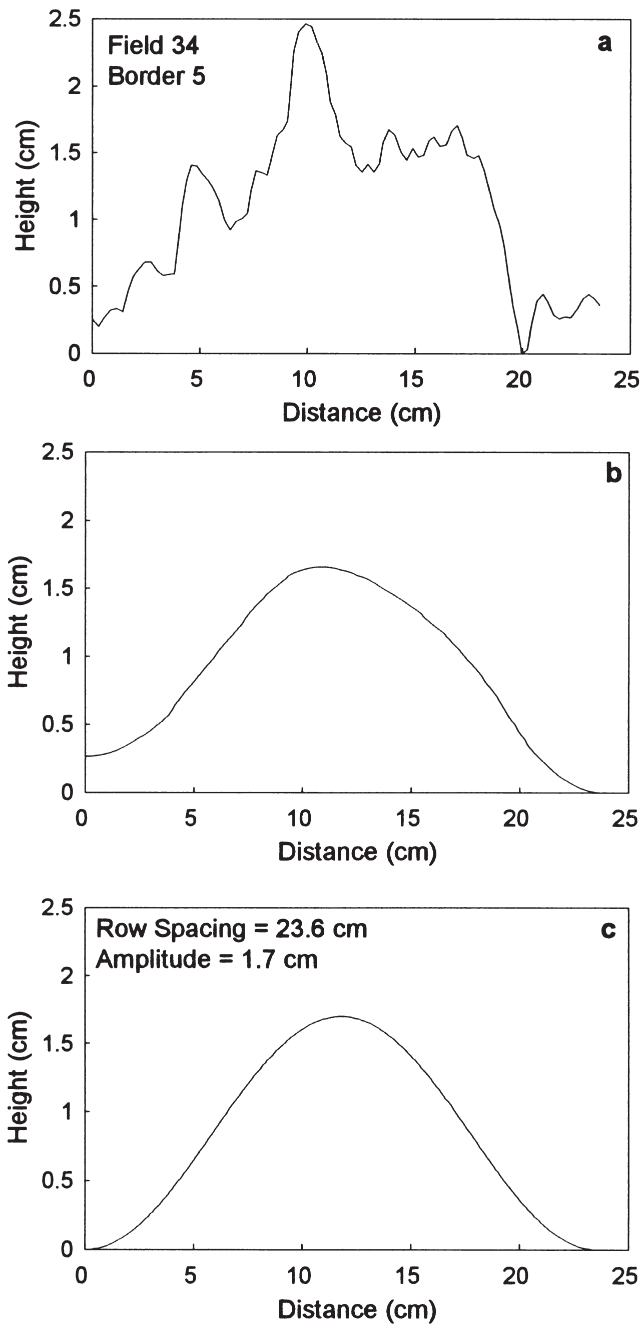


Figure 6. Example of a) ground profile sampled in the field, b) its periodic roughness component, and c) its sinusoidal function. Data from Field 34, border 5.

of 0.3 cm. Therefore, the accuracy of the RMS height measurements is the key issue to obtain an accurate soil moisture retrieval from inversion procedures.

Sensitivity of the Ku-Band SAR Signal to Different Soil Roughness Components

The Ku-band with 35°, 55°, and 75° incidence angles were used to investigate the sensitivity of $\sigma°$ to the different soil roughness components (RMS height, correlation

Table 3. Dielectric Constant and RMS Height Data Calculated for Fields 23 and 34

Field	*Border*	*Dielectric Constant*	*RMS Height (cm)*
23	5	21	0.3
	6	20	0.3
	7	7	0.2
	8	6	0.3
34	1	13	0.2
	2	11	0.3
	3	8	0.4
	4	8	0.3
	5	8	0.2
	6	8	0.3
	7	8	0.3
	8	11	0.2
	9	11	0.2
	10	13	0.4
	11	16	0.3
	12	17	0.3
	13	21	0.5
	14	20	0.3
	15	18	0.3
	16	20	0.3

length, and periodic row spacing). The results are shown in Tables 4, 5, and 6. We can notice the following:

1. The sensitivity of Ku-band $\sigma°$ to the RMS height h was significant, particularly for fields with h <0.3 cm. A variation of h from 0.1 to 0.3 cm provoked a variation in $\sigma°$ of ~9 dB; a range of volumetric soil moisture from 5% to 45% (dielectric constant range from 3.8 to 30.8) is required to provoke the same magnitude of $\sigma°$ variation due to soil moisture. The RMS height influence decreased significantly when h was higher than 0.3

Figure 7. Scatterplot between modeled and measured radar backscattering coefficients.

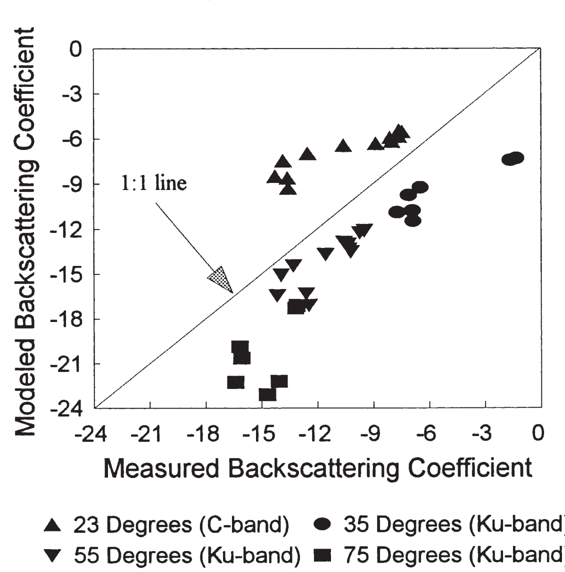


Table 4. Influence of a) RMS Height h, b) Correlation Length L, and c) Periodic Row Structure in the Surface Scattering Process for the Ku-Band with a 35° Incidence Angle

a) Soil Moisture (%)	Dielectric Constant	RMS Height (cm)[a]				
		h_1=0.1	h_2=0.3	h_3=0.5	h_2-h_1	h_3-h_2
5	3.8	−23.19	−14.67	−12.16	8.52	2.51
10	5.8	−20.83	−12.27	−9.70	8.56	2.57
15	8.1	−19.40	−10.82	−8.21	8.58	2.61
20	10.6	−18.44	−9.85	−7.22	8.59	2.63
25	13.4	−17.72	−9.12	−6.48	8.60	2.64
30	16.6	−17.13	−8.53	−5.88	8.60	2.65
35	20.4	−16.63	−8.03	−5.37	8.60	2.66
40	25.0	−16.19	−7.58	−4.92	8.61	2.66
45	30.8	−15.78	−7.17	−4.50	8.61	2.67
(Highest−lowest) difference	27.0	7.41	7.50	7.66		

b) Soil Moisture (%)	Dielectric Constant	Correlation Length (cm)[b]				
		L_1=4	L_2=6	L_3=8	L_1-L_2	L_2-L_3
5	3.8	−13.23	−14.67	−15.79	1.44	1.12
10	5.8	−10.83	−12.27	−13.39	1.44	1.12
15	8.1	−9.38	−10.82	−11.94	1.44	1.12
20	10.6	−8.41	−9.85	−10.97	1.44	1.12
25	13.4	−7.68	−9.12	−10.24	1.44	1.12
30	16.6	−7.09	−8.53	−9.65	1.44	1.12
35	20.4	−6.58	−8.03	−9.15	1.45	1.12
40	25.0	−6.14	−7.58	−8.70	1.44	1.12
45	30.8	−5.72	−7.17	−8.29	1.45	1.12
(Highest−lowest) difference	27.0	7.51	7.50	7.50		

Soil Moisture (%)	Dielectric Constant	Contribution (dB) from Soil Clods (S_1)	Contribution (dB) from Soil Clods and Row Structures (S_2)	S_2-S_1
5	3.8	−16.24	−14.67	1.57
10	5.8	−13.76	−12.27	1.49
15	8.1	−12.26	−10.82	1.44
20	10.6	−11.26	−9.85	1.41
25	13.4	−10.5	−9.12	1.38
30	16.6	−9.9	−8.53	1.37
35	20.4	−9.37	−8.03	1.34
40	25.0	−8.91	−7.58	1.33
45	30.8	−8.49	−7.17	1.32
(Highest−lowest) difference	27.0	7.75	7.50	

[a] Correlation length=6 cm.
[b] RMS height=0.3 cm.
[c] Calculated from the integral equation model.
[d] Calculated from the Ulaby et al. (1982a) model.

cm ($\sigma°$ variation of ~3 dB for a variation in h from 0.3 to 0.5 cm).

2. The sensitivity of Ku-band $\sigma°$ to the soil moisture was independent of roughness condition. A variation of ~8–10 dB was found for a soil moisture variation from 5% to 45%, regardless of soil roughness condition.
3. The sensitivity of the Ku-band $\sigma°$ to the correlation of length L was lower than the sensitivity to the soil moisture or RMS height. The $\sigma°$ variation due to an increment of 2 cm in L was <1.7 dB.
4. The sensitivity of Ku-band $\sigma°$ to the periodic row structure was also lower than the sensitivity to soil moisture or RMS height. The effect of periodic planting row structures in the $\sigma°$ derivation was <1.5 dB.

For the entire range of dielectric constant from 3.8 to 30.8, the lowest variations in both RMS heights (h_2-h_1 and h_3-h_2 values in Tables 4, 5, and 6) and correlation lengths (L_1-L_2 and L_2-L_3 values in Tables 4, 5, and 6) was found for the 35° incidence angle, although the 55° incidence angle also presented quite similar variations. This result indicates that, regarding the optimal inci-

Table 5. Influence of a) RMS Height h, b) Correlation Length L, and c) Periodic Row Structure in the Surface Scattering Process for the Ku-Band with a 55° Incidence Angle

a) Soil Moisture (%)	*Dielectric Constant*	*RMS Height (cm)*[a]				
		h_1=*0.1*	h_2=*0.3*	h_3=*0.5*	h_2-h_1	h_3-h_2
5	3.8	−29.29	−20.75	−18.08	8.54	2.67
10	5.8	−26.67	−18.06	−15.23	8.61	2.83
15	8.1	−25.02	−16.36	−13.43	8.66	2.93
20	10.6	−23.90	−15.20	−12.20	8.70	3.00
25	13.4	−23.03	−14.31	−11.26	8.72	3.05
30	16.6	−22.32	−13.58	−10.50	8.74	3.08
35	20.4	−21.70	−12.95	−9.83	8.75	3.12
40	25.0	−21.14	−12.38	−9.24	8.76	3.14
45	30.8	−20.62	−11.85	−8.69	8.77	3.16
(Highest−lowest) difference	27.0	8.67	8.90	9.39		

b) Soil Moisture (%)	*Dielectric Constant*	*Correlation Length (cm)*[b]				
		L_1=*4*	L_2=*6*	L_3=*8*	L_1-L_2	L_2-L_3
5	3.8	−19.04	−20.75	−21.99	1.71	1.24
10	5.8	−16.35	−18.06	−19.29	1.71	1.23
15	8.1	−14.65	−16.36	−17.59	1.71	1.23
20	10.6	−13.49	−15.20	−16.43	1.71	1.23
25	13.4	−12.60	−14.31	−15.54	1.71	1.23
30	16.6	−11.87	−13.58	−14.81	1.71	1.23
35	20.4	−11.24	−12.95	−14.18	1.71	1.23
40	25.0	−10.37	−12.38	−13.61	2.01	1.23
45	30.8	−10.14	−11.85	−13.08	1.71	1.23
(Highest−lowest) difference	27.0	8.90	8.90	8.91		

Soil Moisture (%)	*Dielectric Constant*	*Contribution (dB) from Soil Clods* (S_1)	*Contribution (dB) from Soil Clods and Row Structures* (S_2)	S_2-S_1
5	3.8	−21.32	−20.75	0.57
10	5.8	−18.56	−18.06	0.50
15	8.1	−16.82	−16.36	0.46
20	10.6	−15.62	−15.20	0.42
25	13.4	−14.71	−14.31	0.40
30	16.6	−13.96	−13.58	0.38
35	20.4	−13.31	−12.95	0.36
40	25.0	−12.73	−12.38	0.35
45	30.8	−12.19	−11.85	0.34
(Highest−lowest) difference	27.0	9.13	8.90	

[a] Correlation length=6 cm.
[b] RMS height=0.3 cm.
[c] Calculated from the integral equation model.
[d] Calculated from the Ulaby et al. (1982a) model.

dence angle for soil moisture retrieval, 35° presented the best performance among the three angles analyzed in this study. This result is in agreement with the empirical results of this article and with previous findings (e.g., Altese et al., 1996).

CONCLUDING REMARKS

Results of this investigation showed different effects of periodic structures of agricultural fields on estimation of soil moisture from single frequency and single like-polarization radar backscattering coefficients, depending upon the sensor configuration. For fields with small-scale, periodic roughness, the highest correlations between $\sigma°$ and volumetric soil moisture content were found for SAR configurations of C-band with a 23° incidence angle (r^2=0.87; slope=0.28) and Ku-band with a 35° incidence angle (r^2=0.81; slope=0.24). An increase in these correlations would be expected if the data set were categorized by row direction (perpendicular and parallel to the radar look direction), that is, if the $\sigma°$ response due to the row tillage geometry (0.3–1.6 dB, Tables 4, 5, and 6)

Table 6. Influence of a) RMS Height h, b) Correlation Length L, and c) Periodic Row Structure in the Surface Scattering Process for the Ku-Band with a 75° Incidence Angle

a) Soil Moisture (%)	*Dielectric Constant*	*RMS Height (cm)*[a]				
		h_1=*0.1*	h_2=*0.3*	h_3=*0.5*	h_2-h_1	h_3-h_2
5	3.8	−36.03	−26,82	−22.93	9.21	3.89
10	5.8	−33.16	−24.07	−20.48	9.09	3.59
15	8.1	−31.25	−22.18	−18.62	9.07	3.56
20	10.6	−29.89	−20.81	−17.24	9.08	3.57
25	13.4	−28.82	−19.72	−16.13	9.10	3.59
30	16.6	−27.92	−18.81	−15.18	9.11	3.63
35	20.4	−27.12	−17.99	−14.34	9.13	3.65
40	25.0	−26.39	−17.25	−13.57	9.14	3.68
45	30.8	−25.69	−16.54	−12.83	9.15	3.71
(Highest−lowest) difference	27.0	10.34	10.28	10.1		

b) Soil Moisture (%)	*Dielectric Constant*	*Correlation Length (cm)*[b]				
		L_1=*4*	L_2=*6*	L_3=*8*	L_1-L_2	L_2-L_3
5	3.8	−25.07	−26.82	−28.07	1.75	1.25
10	5.8	−22.32	−24.07	−25.32	1.75	1.25
15	8.1	−20.43	−22.18	−23.42	1.75	1.24
20	10.6	−19.06	−20.81	−22.05	1.75	1.24
25	13.4	−17.97	−19.72	−20.97	1.75	1.25
30	16.6	−17.06	−18.81	−20.05	1.75	1.24
35	20.4	−16.25	−17.99	−19.24	1.74	1.25
40	25.0	−15.50	−17.25	−18.49	1.75	1.24
45	30.8	−14.79	−16.54	−17.78	1.75	1.24
(Highest−lowest) difference	27.0	10.28	10.28	10.29		

Soil Moisture (%)	*Dielectric Constant*	*Contribution (dB) from Soil Clods* (S_1)	*Contribution (dB) from Soil Clods and Row Structures* (S_2)	S_2-S_1
5	3.8	−28.01	−26.82	1.19
10	5.8	−25.34	−24.07	1.27
15	8.1	−23.33	−22.18	1.15
20	10.6	−21.81	−20.81	1.00
25	13.4	−20.58	−19.72	0.86
30	16.6	−19.53	−18.81	0.72
35	20.4	−18.58	−17.99	0.59
40	25.0	−17.71	−17.25	0.46
45	30.8	−16.87	−16.54	0.33
(Highest−lowest) difference	27.0	10.28	10.29	

[a] Correlation length=6 cm.
[b] RMS height=0.3 cm.
[c] Calculated from the integral equation model.
[d] Calculated from the Ulaby et al. (1982a) model.

were accounted for (Bradley and Ulaby, 1981). However, it was not possible to perform this kind of analysis in this study because of the limited number of soil moisture sampling sites.

For furrowed fields, the SAR data from all configurations analyzed in this study were insensitive to soil moisture content. The relatively large, randomly distributed soil clods and the intermediate-scale periodic roughness of the furrowed fields most likely played a major role in the radar backscattering process. Beaudoin et al. (1990) reported that, in C-band, the effects of random roughness associated with soil clods is never less than 2 dB. Regarding the furrow direction, its influence in the SAR data was evident for radar configurations with low incidence angles (C-band with a 23° incidence angle and Ku-band with a 35° incidence angle). This is in agreement with Batlivala and Ulaby (1976) and Ulaby et al. (1982a,b), who found a high variation in $\sigma°$ due to row direction for relatively small incidence angles.

This study also indicated that the estimation of soil moisture from furrowed fields using SAR data operating at a single like-polarization (VV) and a single frequency

(5.3 GHz or 14.85 GHz) seems to be difficult. Some authors (e.g., Bradley and Ulaby, 1981) found that the cross-polarization radar soil moisture response was nearly unaffected by field row tillage patterns. Thus, the sensitivity of radar backscattering coefficients to the soil moisture from furrowed fields similar to those analyzed in this study in a cross-polarized configuration needs to be investigated.

The analysis of the theoretical model showed that the sensitivity of the SAR signal to the soil roughness, particularly for fields with RMS height <0.3 cm, was very high. In such roughness condition, the inversion of σ° to the soil moisture is not reliable without an accurate information of soil roughness. Research to determine the number of soil roughness samples necessary to obtain accurate RMS heights needs to be conducted. Results from this study and from Altese et al. (1996) suggest that an accuracy of ± 0.01 cm in RMS height calculation should be considered.

The IEM used in this study was an approximate model of its complete version. The complete version describes the backscattering process without any limitation on roughness or frequency, whereas the approximate version is valid for surfaces with small to moderate RMS heights or for low to medium frequencies (Altese et al., 1996). Despite of its complexity, the complete version of IEM should be considered in future to investigate the influence of different soil roughness parameters in MAC furrowed fields or in any other farm with similar field conditions.

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