WATER RESOURCES RESEARCH, VOL. 34, NO. 6, PAGES 1491–1498, JUNE 1998

Relation between ERS-1 synthetic aperture radar data and measurements of surface roughness and moisture content of rocky soils in a semiarid rangeland

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Abstract. Surface roughness and soil moisture content control the distribution of rainfall into runoff, evapotranspiration, and infiltration. Satellite radar data have the potential to provide spatial and multitemporal estimates of these variables, depending upon the sensor configuration and field condition. The relation between the European Remote Sensing Satellite (ERS-1) synthetic aperture radar (SAR) data and measurements of surface roughness and moisture content of rocky soils in a semiarid rangeland in southeast Arizona was analyzed in this study. A dry and a wet season C band SAR image were acquired and corrected for topographic effects. Field soil roughness and moisture content data were obtained from 47 sampling sites. An intensive soil moisture sampling campaign was also conducted at three sites to determine the number of samples necessary to estimate soil moisture content with 10% accuracy. Dry and wet season SAR data were found to be correlated (r^2 = 0.80 and 0.59, respectively) with root-mean-square (RMS) height measurements, while SAR data from the wet season image were poorly correlated with soil moisture. The results indicated that C band SAR data are promising for estimation of surface roughness in semiarid rangelands. However, they are less promising for soil moisture estimation, unless the effects of soil roughness and vegetation are removed. The acquisition of an adequate number of soil moisture samples to obtain representative soil moisture measurements is also a key issue in the validation of soil moisture retrieval from SAR data. In the study area, at least 17 samples per hectare were needed to obtain soil moisture estimates with 10% accuracy.

1. Introduction

One of the major goals in hydrology is to understand and quantify the processes that control hydrologic storages and fluxes at local, regional, and global scales [*Moran et al.*, 1994]. Soil roughness and soil moisture content play a critical role in these hydrologic processes. They control the distribution of rainfall into runoff, evapotranspiration, and infiltration, which must be considered in water and energy balances [*Moore and Larson*, 1979; *Benallegue et al.*, 1995; *Dubois et al.*, 1995]. Thus these variables need to be measured consistently on a spatially distributed basis.

Although ground-based techniques such as the pin-based roughness meter developed by *Simanton et al.* [1978] or the ultrasonic profiler developed by *Robichaud and Molnau* [1990] can provide accurate estimates of surface roughness, they are labor intensive and essentially represent point-based information of a terrain. This is also valid for ground-based soil moisture measurement techniques such as the gravimetric method, neutron probe, and time domain reflectometry. The highly intermittent character of precipitation and the heterogeneity of evapotranspiration, topography, and soil physical and chemical properties such as texture, porosity, and structure create large spatial and temporal variations in soil moisture [*Wei*, 1995]. As a result, this important variable is often neglected in hydrologic, climatic, and agricultural models.

Many researchers [*Bertuzzi et al.*, 1992; *Rao et al.*, 1993; *Benallegue et al.*, 1995; *Engman and Chauhan*, 1995; *Taconet et al.*, 1996] have studied the potential of remotely sensed data to estimate surface roughness and soil moisture contents, mainly at centimeter wavelengths (microwave spectral region), with the aim of obtaining multitemporal information of these variables over large areas. Experiments with truck-, aircraft-, and spacecraft-mounted microwave sensors have shown good predictions of soil moisture within the top 5 cm. However, these results were obtained either from agricultural fields with homogeneous crop cover and surface roughness, flat surfaces, and wide ranges of soil moisture or from watersheds located mostly in temperate climates with a high range (10–40%) of volumetric soil moisture content [*Bernard et al.*, 1982; *Benallegue et al.*, 1994; *Cognard et al.*, 1995]. In sandy soils of semiarid regions, where the volumetric soil moisture content hardly exceeds 20%, soil moisture retrieval from microwave remotely sensed data can be difficult. If the site contain a high percent of rock fragments, soil roughness retrieval seems more indicated. Data collected at 6-cm wavelength (C band) by *Jackson*

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Paper number 98WR00032.
0043-1397/98/98WR-00032$09.00

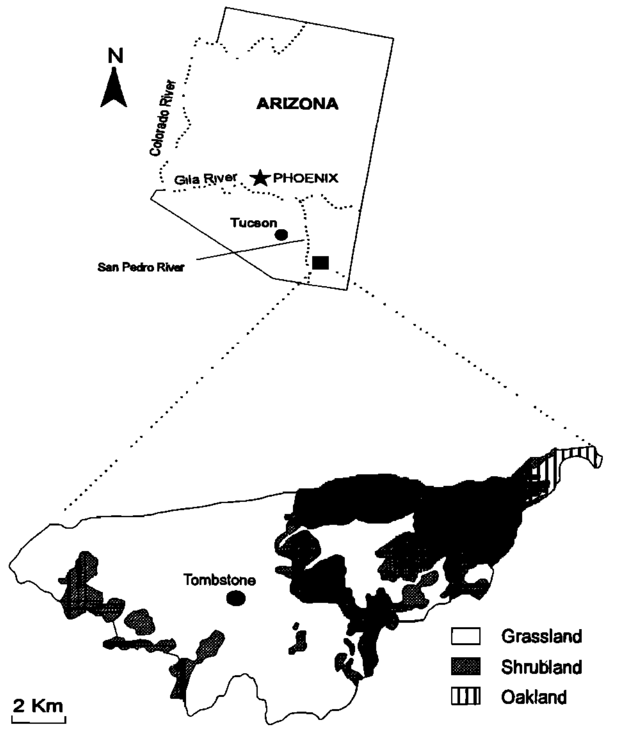


Figure 1. Map of the Walnut Gulch Experimental Watershed (31.72°N, 110.00°W) showing its geographical location in the State of Arizona.

et al. [1992] showed that the presence of rocks made this (and shorter) wavelength useless as soil moisture sensors.

The objective of this study was to analyze the relation between the C band (5.3 GHz) radar backscattered energy and measurements of surface roughness and moisture content of rocky soils from the Walnut Gulch Experimental Watershed (31.72°N latitude, 110.00°W longitude), located in a semiarid rangeland near Tombstone, Arizona (Figure 1).

2. Backscattering Models

The microwave spectral region has been the most promising spectral region for indirect estimation of soil roughness and moisture measurements. However, the retrieval of these variables from microwave sensors requires a suitable inversion algorithm. There are two classes of algorithms, known as "theoretical" and "empirical" or "semiempirical" models. The theoretical models [e.g., *Fung and Ulaby*, 1978; *Ulaby et al.*, 1990; *Fung et al.*, 1992] simulate volume scattering within a canopy and provide site-independent relations between a given radar configuration and different surface parameters, including surface roughness and soil moisture content. However, a large number of variables and parameters involved in these models makes their inversion difficult [*Prevot et al.*, 1993a].

A simpler, semiempirical model, known as "water-cloud" was developed by *Attema and Ulaby* [1978], *Bouman* [1991], and *Prevot et al.* [1993a, b], where the radar backscattering coefficient σ^0 ($m^2 m^{-2}$) of a canopy is described in terms of the contribution from vegetation σ^0_{veg} and soil σ^0_{soil} layers:

$$\sigma^0 = \sigma^0_{veg} + \tau^2\sigma^0_{soil} \quad (1)$$

where τ^2 ($m^2 m^{-2}$) is the two-way attenuation of the vegetation layer, given by *Prevot et al.* [1993a, b] as

$$\tau^2 = \exp\left[\frac{-2Bm_\nu}{\cos\alpha}\right] \quad (2)$$

where B is a constant related to the type and structure of canopy for a given radar configuration, m_ν is the vegetation water content, and α is the incidence angle of the sensor. Although semiempirical or empirical models are simple, they require a large amount of field data to generate general statistical laws [*Oh et al.*, 1992].

The scattering contribution of vegetation volume (σ^0_{veg}) is obviously significant at sites with high levels of biomass, such as tropical and temperate forests [*Le Toan et al.*, 1992]. For agricultural sites with lower level of biomass, such as sites with wheat and corn, some authors working with C band SAR data with incidence angle around 20° [e.g., *Taconet et al.*, 1996] have reported σ^0_{veg} as negligible. In semiarid regions, the contribution of σ^0_{veg} may not be negligible because of their typically low soil moisture contents. Volumetric soil moisture content in these regions barely exceeds 20%, so that the contribution of soil moisture in the backscattering process is expected to be low as well.

The soil contribution σ^0_{soil} (= decibels) is usually expressed as a function of its roughness and volumetric soil moisture content h_ν [*Ulaby et al.*, 1978; *Dobson and Ulaby*, 1981; *Bernard et al.*, 1982; *Bruckler et al.*, 1988; *Prevot et al.*, 1993a, b]:

$$\sigma^0_{soil} = C + h_\nu \quad (3)$$

where C is a roughness dependent parameter and D is a constant.

Based on these three functions and unit conversion, (1) can be rewritten as

$$\sigma^0 = \sigma^0_{veg} - \frac{B'm_\nu}{\cos\alpha} + C + Dh_\nu \quad (4)$$

where

$$B' = \left[\frac{20}{\ln 10}\right]B$$

Equation (4) shows the following relationships between scattering process and surface biophysical parameters: (1) decrease or increase of σ^0 with an increase of vegetation water content (depending upon the biomass level and wavelength), for a given sensor incidence angle α; (2) increase of σ^0 with an increase of soil surface roughness, controlled by the C parameter; and (3) increase of σ^0 with an increase of soil moisture content (h_ν).

3. Experimental Design

3.1. Study Area

The Walnut Gulch Experimental Watershed has been operated by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) since 1954. The predominant textures of surface soils (0–5 cm) are sandy loams and gravelly loamy sands, with a small quantity of organic matter and a rock content around 30% [*Gelderman*, 1970; *Kustas and Goodrich*, 1994]. The vegetation is a mixed shrub/grass rangeland; that is, shrub-dominated in the western part of the watershed, while the eastern part is dominated by grass (Figure 1).

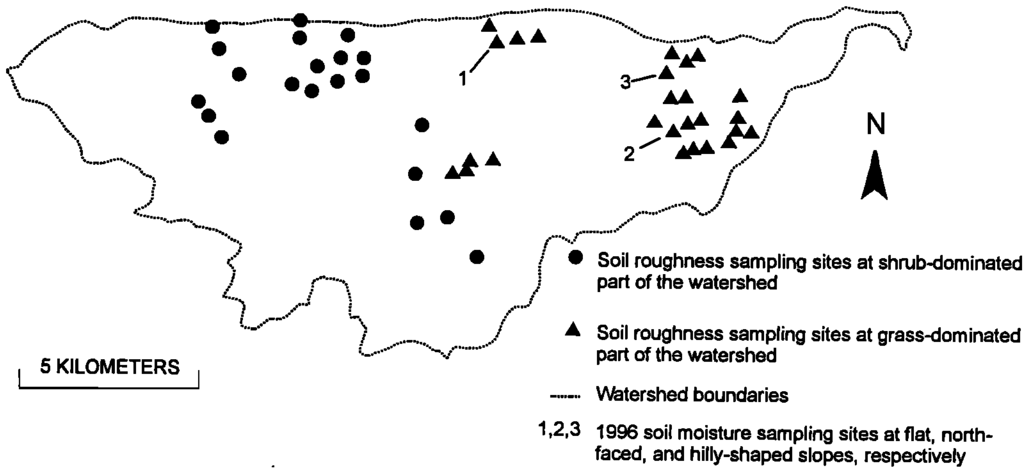


Figure 2. Walnut Gulch Experimental Watershed boundaries with location of soil moisture sampling sites.

3.2. Radar Images

This study was based on the analyses of two European Remote Sensing Satellite (ERS-1) synthetic aperture rada (SAR) images acquired by the European Space Agency (ESA). The ERS-1 satellite carries a SAR sensor operating at 5.3 GHz (C band), *VV* polarization, 23° incidence angle, 100-km swath width, and 12.5-m pixel spacing. One wet season image was acquired in late July 1994 (day of year (DOY) 206). This date was chosen to obtain a scene with high field soil moisture content during the satellite overpass. Normally, about two thirds of the rainfall in the watershed occurs as high intensity, convective thunderstorms during the "monsoon" season in July and August. The mean annual precipitation typically ranges from 250 to 500 mm yr^{-1}. On the basis of the records from 89 rain gages located in the watershed, the first storms associated with the 1994 summer monsoon season (DOY 204 and 205) produced an average precipitation of 10.3 mm (standard deviation = 3.1 mm). Another image previously acquired in the middle of May 1992 (DOY 116) as part of the remote sensing experiment conducted in the Walnut Gulch watershed (WG'92) [*Moran et al.*, 1996] was also analyzed. This image was obtained in the dry season, when the surface was dry and covered with senescensed vegetation. An average of 2.62% of volumetric soil moisture content was obtained from four sites (six replicates) in the grass-dominated part of the watershed.

These images corresponded to the standard Precision Image (PRI) products, which were corrected for antenna elevation, gain pattern, and range spreading loss [*Cognard et al.*, 1995]. They were also georeferenced to the universal transverse Mercator (UTM) coordinate system (Zone 12, 1927 North American Datum, Clarke 1866), corrected for topographic effects, and calibrated, that is, corrected to account for the real backscattering area of each pixel, using a digital elevation model [*Beaudoin et al.*, 1994]. The elevation model was derived from topographic maps at 1:24,000 scale with a contour interval of 6.1 m Radar backscatter coefficients (σ^0, in decibels) were extracted from these preprocessed images using the following equation [*Laur*, 1992]:

$$\sigma^0 = 10 \log \left[\frac{(\overline{\mathrm{DN}}^2 + \mathrm{STD}^2)}{K} \right] \qquad (5)$$

where DN is digital number, STD is standard deviation, and K is system calibration constant.

In this study, we used approximately 200 pixels per site to obtain the average DN values. *Bruniquel* [1996] showed that with this number of pixels, σ^0 values are expected to be within a confidence interval smaller than 1 dB. In fact, all sites presented confidence intervals smaller than 0.8 dB.

Table 1. Description of Physical Characteristics of the Elgin-Stronghold and Luckyhills-McNeal Soil Units

Parameters	Elgin-Stronghold Complex	Luckyhills-McNeal Complex
Soil Classification	Paleargid (Elgin) Calciorthid (Stronghold)	Calciorthid (Luckyhills) Haplargid (McNeal)
Slope, %	8–15	3–8
Landform	fan terraces	fan terraces
Soil color	dark brown (0–25 cm)	pale brown (Luckyhills, 0–5 cm) strong brown (McNeal, 0–2.5 cm)
Texture	very gravelly sandy loam (0–2.5 cm)	very gravelly sandy loam (0–2.5 cm)

From *Breckenfeld* [1993].

3.3. Ground-Based Measurements

Soil samples for gravimetric moisture measurements within the top 5 cm (three replicates) were collected on the same day of the 1994 satellite overpass under two different surface conditions (Figure 2). One set of 26 sites was located in the eastern, grass-dominated part of the watershed, over the very gravelly sandy loam, Elgin-Stronghold Complex soil unit [*Breckenfeld*, 1993]. Another set of 21 sites was located at the western, shrub-dominated part of the watershed, a very gravelly sandy loam, Luckyhills-McNeal complex soil unit. These soil types represent the most extensive soil mapping units in the grass-dominated and shrub-dominated areas in the watershed (Table 1). Dry bulk density data were also obtained for each sampling point (three replicates) by the excavation method [*Blake and Hartge*, 1986], allowing the calculation of volumetric soil moisture.

Soil surface roughness measurements were made using a roughness meter developed by *Simanton et al.* [1978], which measures 100 heights of soil surface per meter. Three plots each, having an area of 1 m × 2 m, were randomly selected per site. The roughness meter, aligned approximately every 20 cm

Table 2. Field Data for Grass-Dominated Sites in the Walnut Gulch Experimental Watershed

Sampling Point	UTM E-W	UTM N-S	Soil Series	Soil Moisture,[a] g g^{-1}	Bulk Density,[a] g cm^{-3}	RMS Height,[a] cm	Biomass, g m^{-2}	Rock Fragment, %	Slope, %	Gravel, %	Clay, %	Sand, %
1	3510114	594807	Stronghold	9.25 (0.03)	1.51 (0.07)	0.92 (0.29)	383.58	33				
2	3509502	593841	Elgin	6.43 (0.30)	1.70 (0.03)	0.77 (0.37)	165.46	35	9	27	17	55
3	3509299	593712	Stronghold	9.59 (0.26)	1.72 (0.06)	0.85 (0.41)			5	22	17	65
4	3509169	593339	Stronghold	7.78 (0.11)	1.70 (0.09)	0.81 (0.47)			10	33	16	62
5	3513632	593886		4.91 (0.19)	1.58 (0.11)	0.92 (0.36)	762.38	26				
6	3513164	594205	Stronghold	6.65 (0.08)	1.51 (0.04)	1.73 (0.50)	509.78	29	6	15	14	56
7	3513343	594762	Stronghold	5.09 (0.15)	1.64 (0.04)	1.48 (0.37)			7	48	15	58
8	3512910	595573	Stronghold	7.16 (0.18)	1.54 (0.07)	1.53 (0.33)	219.63	34	4	37	14	60
9	3511418	599037	Stronghold	8.07	1.63 (0.09)	0.67 (0.19)	389.58	30	7	25	17	60
10	3511174	599609	Stronghold	8.28	1.57 (0.05)	1.16 (0.88)	335.54	28	10	28	18	60
11	3511438	599982	Elgin	3.00	1.66 (0.03)	0.79 (0.42)			9	20	20	60
12	3511473	600226	Elgin	1.76	1.50 (0.13)	0.74 (0.39)			12	46	13	65
13	3510801	600186	Elgin	4.72	1.62 (0.01)	0.89 (0.58)			12	38	27	58
14	3510637	599997	Stronghold	6.74	1.81 (0.13)	1.43 (0.40)			7	26	15	63
15	3510846	600609	Elgin	2.57	1.54 (0.08)	1.64 (0.59)			12	36	18	60
16	3511114	601225	Elgin	3.64	1.43 (0.07)	1.30 (0.56)			10	35	18	65
17	3511313	601499	Elgin	3.52	1.75 (0.04)	1.58 (0.37)	184.50	22	7	25	18	60
18	3511438	601399	Stronghold	1.80	1.41 (0.03)	1.12 (0.45)			15	20	12	67
19	3511299	601718	Stronghold	2.33	1.50 (0.10)	1.82 (0.42)			13	18	15	60
20	3512114	599395	Stronghold	3.31	1.31 (0.01)	0.68 (0.27)			15	30	18	62
21	3512174	599743	Elgin	2.46	1.38 (0.14)	1.15 (0.49)			5	15	39	36
22	3512433	601325	Elgin	3.36	1.44 (0.04)	0.83 (0.29)			10	46	28	56
23	3512861	599166	Stronghold	1.70	1.48 (0.10)	1.08 (0.40)			15	39	15	57
24	3513234	599708	Stronghold	1.13	1.57 (0.14)	1.16 (0.40)			15	46	12	60
25	3513483	599305	Stronghold	1.00	1.35 (0.11)	0.92 (0.44)	188.61	33	15	36	15	59
26	3513453	599982	Stronghold	1.82	1.44 (0.06)	1.99 (0.60)	268.54	33	12	34	15	65

UTM, universal transverse Mercator.
[a] Numbers in parentheses represent coefficient of variation.

along the local contour line, gave us 3000 point readings per site. These points were connected to lines and digitized using a Geographical Information System (GIS) software package (Arc/Info) to calculate the average standard deviation (in centimeters). This average corresponded to the roughness index or to the root-mean-square (RMS) height variation of the site.

Percent rock fragment and dry biomass were also measured within a month, following the 1994 satellite overflight at 18 sites (10 in the grass-dominated areas and 8 in the shrub-dominated areas). The percent rock fragment was determined with the line-intercept transect method [*Canfield*, 1941]. Two lines with 100-m extensions were chosen randomly for each site. The percent rock fragment (more than 5 mm in diameter) was calculated from the following ground characteristics recorded at 1-m intervals along these transects: bare soil, rock fragment, grass, shrub, forb, and litter. Five 1 m × 0.5 m areas were selected along the transect, spaced by 20 m. All the green vegetation and litter within these areas were clipped, collected, oven dried at 60°C for 24 hours and weighed to determine the dry biomass (g m^{-2}).

The following additional soil physical and topographic data were also obtained for most of the sites: slope, percent gravel, percent clay, and percent sand. The slopes corresponded to the average of two soil scientist estimates in the field. They also determined the correct soil series for each site. The percent gravel was obtained by collecting 1 L of soil sample at 0–5 cm depth, removing the fine particles (<5 mm) by sieving, and estimating its remaining volume in a 1-L Erlenmeyer flask. The percent clay and percent sand were estimated in the laboratory by manipulating the soil samples in the hand. The soil texture was estimated by more than 40 students taking a Soil Morphology Classification, and Survey class offered by the University of Arizona (1996 fall semester). Tables 2 and 3 summarize the field data for grass- and shrub-dominated areas, respectively.

Another field soil moisture campaign was conducted on November 4, 1996 (DOY 309) at three sites located in the grass-dominated part of the watershed. Each site (sites 1, 2, and 3 in Figure 2 and 5, 6, 10, and 23 in Table 2) presented the following slopes: flat, north-faced slope, and hilly-shaped slope, respectively. The soil texture was very gravelly sandy loam (for other surface biophysical characteristics, see Table 2). Sixty-four gravimetric soil moisture samples were taken at a regular 20-m-spaced grid within a 100-m-radius area. The purpose of these measurements was to estimate the number n of samples required to obtain moisture content data with acceptable accuracy. The following data are required to calculate n: coefficient of variation CV (ratio of the standard deviation to the mean value) from the field measurements, confidence level, and the percent of maximum allowable error d, which indicates the expected closeness of the sample mean x to the population mean μ [*Warrick et al.*, 1996]. These parameters are related by

$$n = \frac{t^2(\mathrm{CV})^2}{d^2} \tag{6}$$

where t is a constant that depends on the confidence level and is obtained from a statistical table (t-test, degree of freedom = ∞). The assumption is that the soil moisture measurements for the study area have a normal distribution function.

4. Results and Discussion

4.1. Relation of C Band SAR Data to Soil Roughness

Figure 3 shows a good relation between the dry season C band SAR data and RMS height measurements (h) in the

Table 3. Field Data for Shrub-Dominated Sites in the Walnut Gulch Experimental Watershed

Sampling Point	UTM E-W	UTM N-S	Soil Series	Soil Moisture,[a] g g^{-1}	Bulk Density,[a] g cm^{-3}	RMS Height,[a] cm	Biomass, g m^{-2}	Rock Fragment, %	Slope, %	Gravel, %	Clay, %	Sand, %
1	3512550	585919	Luckyhills	5.42 (0.15)[a]	1.50 (0.05)	0.82 (0.46)			6	29	16	60
2	3511915	586178	Luckyhills	6.22 (0.16)	1.54 (0.01)	1.14 (0.51)	285.74	52	5	16	11	77
3	3511214	586882	Luckyhills	5.49 (0.11)	1.41 (0.02)	1.36 (0.31)			3	45	16	60
4	3509980	586177	Luckyhills	2.75 (0.28)	1.43 (0.14)	0.80 (0.35)			3	25	24	53
5	3510284	585769	Luckyhills	3.98 (0.20)	1.57 (0.03)	1.52 (0.47)	344.36	37	4	55	14	63
6	3505697	593802		6.29 (0.41)	1.59 (0.00)	0.72 (0.55)	329.40	49				
7	3506746	594404		5.34 (0.10)	1.50 (0.13)	1.45 (0.42)	627.18	37				
8	3507806	593359		3.58 (0.35)	1.51 (0.06)	0.81 (0.64)						
9	3507567	592558		5.34 (0.05)	1.48 (0.05)	1.32 (0.53)						
10	3511154	588333	Luckyhills	6.12 (0.08)	1.52 (0.14)	1.49 (0.29)			5	26	13	65
11	3513025	588458	Luckyhills	11.74 (0.14)	1.60 (0.08)	0.92 (0.74)			4	24	16	62
12	3512517	588488		10.46 (0.29)	1.52 (0.07)	1.17 (0.33)	543.42	38				
13	3512751	589841	McNeal	8.30 (0.13)	1.82 (0.13)	0.94 (0.59)			5	55	16	58
14	3511811	589109	Luckyhills	6.90 (0.03)	1.68 (0.09)	0.96 (0.47)			4	28	15	60
15	3512092	589711		7.78 (0.12)	1.50 (0.03)	0.90 (0.39)						
16	3511383	589706	Luckyhills	5.66 (0.06)	1.68 (0.14)	0.97 (0.42)	415.22	27	8	23	10	83
17	3511000	589044	Luckyhills	7.88 (0.10)	1.47 (0.10)	1.34 (0.38)				26	15	70
18	3512040	590393	Luckyhills	7.06 (0.05)	1.58 (0.07)	0.91 (0.39)	415.48	35	8	35	16	55
19	3511716	590388	Luckyhills	6.25 (0.11)	1.49 (0.12)	1.42 (0.32)			10		10	73
20	3510398	592299		6.67 (0.10)	1.64 (0.09)	0.64 (0.29)						
21	3508993	592309		4.60 (0.06)	1.69 (0.07)	1.00 (0.45)	450.44	42				

UTM, universal transverse Mercator.

[a] Numbers in parentheses represent coefficient of variation.

watershed. A variation of approximately 1.6 cm in RMS height (from 0.6 to 2.0 cm) induced a σ^0 variation of approximately 2.5 dB in the SAR data. The following general exponential relationship (i.e., including data from both grass- and shrub-dominated parts of the watershed) between these two parameters was obtained ($r^2 = 0.80$, with a level of significance $\alpha = 0.05$):

$$\sigma^0 = -8.48 - 8.71e^{(-1.96h)} \tag{7}$$

This relation confirms a previous finding from *Altese et al.* [1996], who also found an exponential correlation between these two parameters, indicating that the sensitivity of radar data to soil roughness is stronger at lower roughness conditions.

Figure 4 compares the wet season C band SAR data with the RMS height measurements. The exponential relation found for dry season backscatter coefficient is still valid, although with a higher dispersion of points for the wet season SAR data. This dispersion was probably provoked by the higher variation of soil moisture and perhaps by the higher vegetation water content found among the all sites during the 1994 satellite overpass. These higher soil moisture and vegetation water contents in the wet season σ^0 also shifted the exponential curve found for dry season σ^0 up to about 0.5 dB. As expected, the increase in the backscattering coefficient was higher for sites

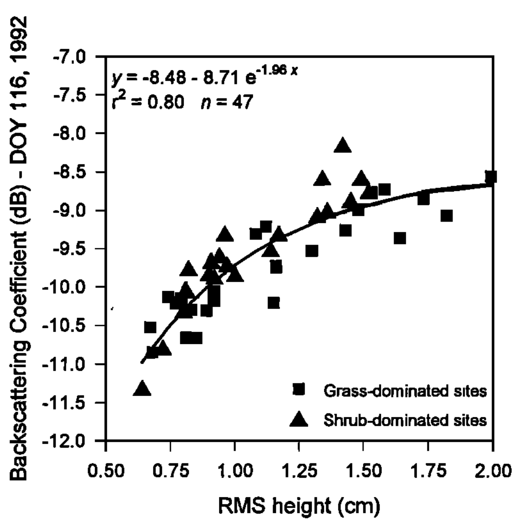
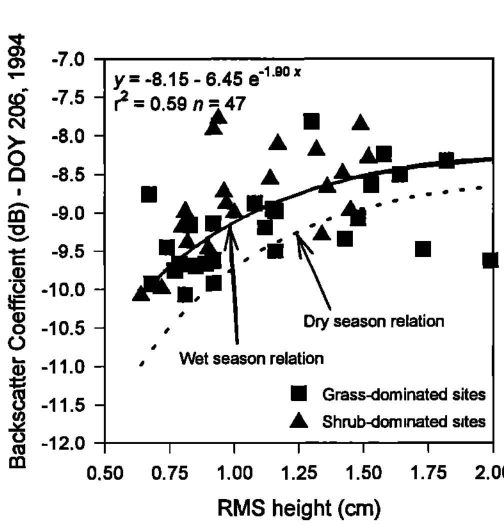


Figure 3. Scatterplot between 1992 dry season SAR image and soil roughness data in the Walnut Gulch Experimental Watershed.



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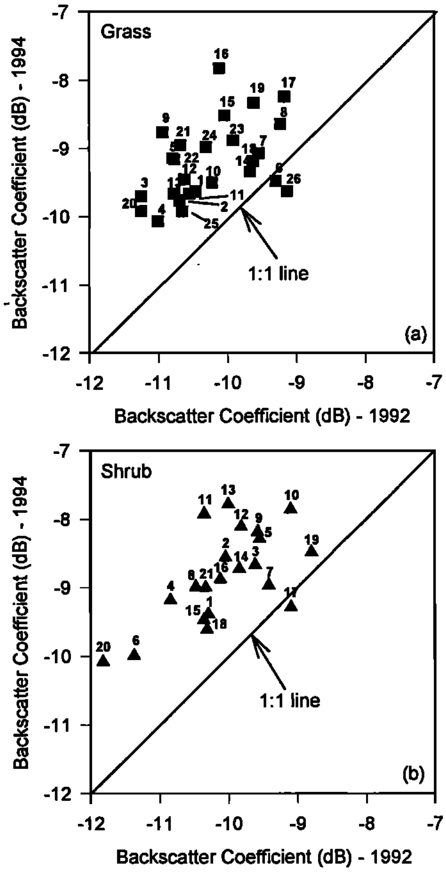

Figure 5. Scatterplot between 1994 wet season SAR image and 1992 dry season SAR image for (a) grass-dominated and (b) shrub-dominated sites. Numbers above the symbols represent the sampling sites.

with low RMS heights ($\Delta\sigma^0 \sim 1$ dB at $h = 0.6$ cm) than for those with high RMS heights ($\Delta\sigma^0 \sim 0.4$ dB at $h = 1.75$ cm). In the second case ($h = 1.75$ cm), the soil roughness effect in the SAR data is stronger than in the first case ($h = 0.6$ cm) so that the effect of soil moisture and vegetation water content is less pronounced.

4.2. Relation of C Band SAR Data to Soil Moisture

The sensitivity of the C-band SAR data to the variation in soil moisture content was analyzed by plotting the radar signals from the wet season against the signals from the dry season images (Figure 5). Most of the points are located above the 1:1 line, indicating that the backscattering coefficients of the wet season are higher than those of dry season. The average variation of σ^0 between these two dates was 1.0 dB (maximum = 2.3 dB) for grass-dominated sites and 1.2 dB (maximum = 2.4 dB) for shrub-dominated sites. As mentioned above, these higher backscattering coefficients for the wet season image were due to an overall higher soil moisture in the watershed and, perhaps, also due to a higher vegetation water content condition, especially at the shrub-dominated sites. The soil roughness remained essentially the same within the two dates. In contrast to agricultural fields, soil roughness does not change significantly over relatively short time periods in natural ecosystems.

When the wet season SAR data were compared with the volumetric soil moisture measurements, there was no significant correlation: $r^2 = 0.06$ for grass-dominated sites and $r^2 = 0.09$ for shrub-dominated sites. An analysis of partial correlation coefficients between 1994 SAR data and measurements of soil moisture and soil roughness (Table 4) also showed a low correlation between wet season SAR data and soil moisture content ($r^2 = -0.18$ for grass-dominated sites and $r^2 = 0.46$ for shrub-dominated sites), in comparison to the contribution of soil roughness ($r^2 = 0.45$ and 0.64, respectively). Partial correlation is the correlation between two variables with the effects of a third cancelled out [*Kline*, 1994]. The correlation between σ^0 and soil moisture was particularly very low for grass-dominated sites. *Jackson and Schmugge* [1991] and *Troufleau et al.* [1997] also found that grass-covered sites have an unusual behavior compared to other vegetation types. The accentuated accumulation of litter and stubble on the grass-covered soil surfaces seems to hold a significant amount of water from a rainfall event, masking the relation between SAR data and the underlying soil moisture content.

These low correlations between wet season SAR data and soil moisture contents can be explained by a dominant role played by soil roughness in the backscattering process, even in the wet season SAR image (see Figures 3 and 4), and/or an inaccurate soil moisture data. The soil moisture sampling time interval in this experiment was relatively large (from 8:00 A.M. to 5:00 P.M. local time), because of the poor road conditions and limited number of personnel available. Soil samples taken early in the morning or late in the afternoon may have presented moisture contents significantly different from that recorded by the sensor, specially because of the high rate of evaporation in Arizona's summer season and high rate of infiltration in the sandy soils of the watershed.

An insufficient number of soil samples for moisture content may have also contributed to the low correlation between wet season σ^0 and soil moisture. The high spatial variability of soil moisture is another difficult issue of soil moisture estimation from SAR data in a semiarid region. The optimal number of soil samples to obtain an accuracy of 10% in the watershed is discussed below.

4.3. Optimal Number of Soil Samples

Table 5 indicates the optimal number of soil samples to obtain a maximum allowable error $d = 0.1$ for three grass-dominated sites with three different slopes (flat, north-faced slope, and hilly-shaped slope), considering a confidence level of 99%. This value of d can be considered as the maximum acceptable error for hydrologic applications, which requires soil moisture measurements with an accuracy within a few percent [*Houser*, 1996]. As mentioned, each site corresponded

Table 4. Partial Correlation Coefficients for Grass- and Shrub-Dominated Sites of the Walnut Gulch Experimental Watershed

	SAR	Soil Moisture	RMS Height
	Grass-Dominated Sites		
SAR	1.00		
Soil moisture	−0.18	1.00	
RMS height	0.45	−0.08	1.00
	Shrub-Dominated Sites		
SAR	1.00		
Soil moisture	0.46	1.00	
RMS height	0.64	−0.39	1.00

Table 5. Coefficients of Variation and Number of Samples Required to Obtain 10% Accuracy of Soil Moisture Content for Three Sites with Different Slopes and for a 99% Confidence Interval

Site	Coefficient of Variation	Number of Samples
Flat	0.15	60
North-faced slope	0.17	77
Hilly-shaped slope	0.27	193

to an area (circle) with 100-m radius (approximately 3.14 hectares). It is evident that the number of samples was strongly dependent upon the slope. For relatively flat surfaces it is necessary to obtain 60 soil moisture samples to achieve an accuracy of 10% (about 17 samples per hectare), whereas for a hilly-shaped slope, the number increased to 193 (about 62 samples per hectare).

Considering that these values were derived using data obtained in the winter season, the number of samples would be even higher in the monsoon season because of the higher rate of evaporation. In other words, these optimal numbers of samples can be strongly season and site specific. The spatial variability of soil moisture at a given site depends not only on the slope, but also on other parameters, such as vegetation density, soil textural class, and amount of precipitation. *Rao and Ulaby* [1977] also obtained different n values for random and stratified sampling methods. Thus additional analyses at other sites in the watershed are recommended.

5. Concluding Remarks

In this study, the relation between dry and wet season C band SAR data and measurements of soil roughness and moisture content of rocky soils in the semiarid Walnut Gulch Experimental Watershed, Tombstone, Arizona was investigated. Dry and wet season C band SAR data were found to be correlated with soil roughness measurements. A variation of 1.4 cm in RMS height provoked a variation of about 2.5 dB in the dry season σ^0, whereas the variation between dry and wet season σ^0 provoked a variation of only about 0.5 dB. Thus the soil roughness retrieval from a dry season C band SAR data appears to be promising. On the other hand, the estimation of soil moisture from a wet season C band appears to be difficult, unless techniques to correct SAR data for the effects of soil roughness and vegetation are applied, as well as an adequate number of soil moisture samples are collected.

Future research should focus on investigation of the actual effect of the rock fraction in the C band scattering process in the watershed. In a dry season C band SAR image (with soil moisture and vegetation water content ~0), the actual contribution of soil surface roughness (surface scattering) and percent rock fraction (volume scattering) need to be determined. The importance of σ^0_{veg} in the C band backscattering process also needs to be addressed. An analysis of a multitemporal data sets acquired simultaneously in optical and microwave spectral regions appears to be a good approach.

Acknowledgments. Special thanks are due to J. Epiphanio, L. Accioly, F. Rahman, C. Unkrich, G. de Lira, and K. Batchily for helping us with the field work; to D. F. Post and D. Breckenfeld for checking the soil units and collecting the soil morphology data from most of the field sites; to S. Marsh and J. Qi for reviewing the manuscript; and to A. W. Warrick and S. Musil for permitting us to use their Soil Physics Laboratory at the University of Arizona for soil moisture measurements. We also greatly appreciated the cooperation of people from USDA Southwest Watershed Research Center, Tucson, Arizona: M. Weltz for his orientation in vegetation sampling techniques, D. Goodrich for providing the orthophotos of the watershed, and R. Simanton for allowing the use of the roughness meter. The assistance of personnel at the ARS Walnut Gulch Experimental Watershed facility in Tombstone, Arizona, was also very important. This work was partially supported by the NASA-EOS Interdisciplinary Research Program in Earth Sciences (NASA IDP-88-086), National Science Foundation (grant INT-9314872), and NASA Landsat Team (grant S-41396-F).

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(Received March 11, 1997; revised December 30, 1997;
accepted December 31, 1997.)