THE USE OF SAR/TM SYNERGY FOR ESTIMATING SOIL MOISTURE CONTENT OVER A SEMI-ARID RANGELAND

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Abstract. The C-band ERS-1 SAR data were combined with the Landsat TM data to improve the soil moisture estimates in a semiarid region. The SAR data were compared with the soil moisture measurements at three conditions: a) without any correction for soil roughness and vegetation effects; b) corrected for soil roughness effects; and c) corrected for both soil roughness and vegetation effects. The soil roughness effects were taken into account by using a dry season SAR image. The vegetation influence was considered by using an empirical relationship between SAR and leaf area index data, the latter being derived from TM images. Results indicated that the contribution of soil roughness and vegetation in the radar backscatter were significant and they must be taken into account to obtain accurate soil moisture estimations.

Keywords: Radar Remote Sensing; Soil Moisture; SAR/TM synergy.

1 Introduction

Soil moisture content needs to be measured consistently on a spatially distributed basis because it plays a critical role in hydrologic processes and energy fluxes at local, regional, and global scales by controlling the distribution of rainfall into runoff, evapotranspiration and infiltration (Benallegue et al., 1995; Dubois et al., 1995). Although ground-based techniques to measure soil moisture such as the gravimmetric method, neutron probe, and Time Domain Reflectrometry present accurate measurements, they are labor-intensive and represent point-based information of a terrain. As a result, this variable is often neglected in hydroclimatical and agricultural models.

Attempts have been made to derive spatially-based soil moisture content information from synthetic aperture radar (SAR) data. Many studies (Bernard et al., 1982; Benallegue et al., 1994; Cognard et al., 1995, among others) have obtained a simple linear correlation between soil moisture content and SAR data in long wavelengths (e.g., C-band at 5 cm or L-band at 21 cm). However, these and other promising results were obtained either from bare soil fields or from agricultural fields with flat surfaces and wide ranges of surface soil moisture contents. When sites of variable vegetation cover and soil roughness are included in the regression, we often find a considerable dispersion in the regression. The primary objective of this study was to develop a practical approach to account for both soil roughness and vegetation effects in the C-band SAR data to improve the estimation of rocky soil moisture content over a semiarid rangeland.

2 Experiment

The study area is located at the Walnut Gulch Experimental Watershed (31.72° N, 110.00° W), a representative site of shrub- and grass-dominated rangelands found in the southwestern part of the United States (**Figure 1**). The surface soils (0-5 cm) are predominantly sandy loams and gravelly loamy sands, with 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, and grass-dominated in the esteam part.

Seven European Remote Sensing (ERS-1) SAR images were acquired in 1992 as part of the Walnut Gulch Watershed remote sensing (WG'92) experiment conducted by the U.S. Department of Agriculture (Moran et al., 1996) and another single image was obtained in 1994 during the wet season (Day of Year –

DOY 206, **Table 1**). These images, obtained at a 30 m nominal spatial resolution and 12 m pixel spacing, were georreferenced to the Universal Transverse Mercator coordinate system (Zone 12, 1927 North American Datum, Clarke 1866), and calibrated, that is, corrected for topographic effects by accounting for the real backscatter area of each pixel using a digital elevation model (Beaudoin et al., 1994). Radar backscatter coefficients (σ^o; units = dB) were extracted from these preprocessed images using the equation proposed by Laur (1992):

$$\sigma^o = 10\log\left[\frac{\overline{DN}^2 + STD^2}{K}\right]$$

where $\overline{DN}$ = average digital number of the site (average of at least 50 pixels per site);

STD = standard deviation of DN; and

K = sensor calibration constant.

Regarding the Landsat TM data, eight images obtained during the WG'92 experiment were analyzed (**Table 1**). The TM digital numbers were transformed to surface reflectance values in three steps (Moran et al.,1992, 1996; Washburne, 1994): a) acquisition of the incident solar illumination data from sunrise to solar noon in the same day of the Landsat overpasses, using a solar radiometer, to account for the atmospheric effects in the TM digital numbers; b) generation of at-satellite radiance values for a given series of surface reflectance values by using the Herman-Browning radiative transfer code; and c) generation of TM reflectance images from values derived from the radiative transfer code and from Landsat TM sensor calibrations. All TM images were also georeferenced to the UTM coordinate system.

Leaf area index (*LAI*) values were calculated from all Landsat TM scenes by using the following relationship proposed by Baret (1995):

$$LAI = -\frac{\log[(A - MSAVI)/B]}{K}$$

where *MSAVI* is defined as (Qi et al., 1994):

$$MSAVI = (2\rho_{NIR} + 1 - [(2\rho_{NIR} + 1) * 2 - 8(\rho_{NIR} - \rho_{RED})] * 0.5)/2$$

where ρ_{NIR} and ρ_{RED} are the surface reflectances in the near infrared and red spectral regions, respectively. For arid and semiarid regions, Qi et al. (1994) found the following values for *K*, *A*, and *B*: 0.67, 0.82, and 0.78, respectively.

Gravimetric samples for soil moisture content were collected at the Meteorological-Energy flux (MF) stations 1, 3, 5, and 6 in 1992 (**Table 1**). Six replicates of each sample were averaged to one reading. Volumetric soil moisture contents were derived using previously measured bulk densities (1.44 ~1.83 g/cm^3) (Troufleau et al., 1997). Soil moisture measurements were also made on the same day of the ERS-1 SAR overpass in 1994 at 21 validation sites in the shrub-dominated part of the watershed (three replicates). Dry bulk density data were obtained for each site by the excavation method (Blake and Hartge, 1986), allowing the calculation of volumetric soil moisture contents.

3 Approach

Investigation Sites

The MF sites 1, 2, 3, 7, and 8, located in the shrub-dominated part of the watershed (**Figure 1**), were selected to investigate the use of SAR/TM synergism to correct the effects of vegetation in the SAR data, in order to obtain an improved estimation of soil moisture content from radar data in the watershed. The MF sites 4, 5, and 6, located in the eastern, grass-dominated side of the watershed, were not included in the analysis because of the limited number of available SAR images. The analysis was performed in four steps:

1) analysis of relationship between SAR and TM data, by comparing the multitemporal values of σ^o and LAI simultaneously;
2) correction of the topographic effects in the radar backscattering signals. The technique involved a subtraction ($\sigma^o - \sigma^o_{dry}$); that is, the σ^o from a given image was subtracted by the σ^o from a dry season image. The assumption in this step was that the soil roughness is the only important parameter in the backscattering process in a dry season image. The coefficients derived from this subtraction is referred as σ^o_1 hereafter.
3) finding of an empirical relationship between σ^o_1 and LAI. This relation corresponds to the linear regression equation obtained by considering the σ^o_1 and LAI from four MF sites above mentioned; and
4) correction of the vegetation effects on σ^o_1 In this step, we calculated the residuals of radar backscattering coefficients (σ^o_2) for the MF sites by subtracting the measured and the estimated σ^o_1 values. The measured σ^o_1 values refer to the SAR signals obtained from the subtraction of σ^o from a dry season image (step 2), while the estimated σ^o_1 values refer to the SAR signals calculated from the empirical σ^o_1 –LAI relation.

Validation Sites

To validate the approach described above, the SAR and soil moisture data acquired in 1994 in the shrub-dominated part of the watershed by Sano et al. (1998) were analyzed applying the same methodology used for the investigation sites. In other words, the soil moisture contents measured during the 1994 ERS-1 SAR overpass were compared with the radar backscattering coefficients at three steps: 1) without any correction; 2) partially corrected for soil roughness; and 3) fully corrected for soil roughness and vegetation effects. The σ°_l-LAI relation obtained from the investigation sites were applied to account for the vegetation effects. The LAI value for each validation site was derived by linearly interpolating the LAI values obtained in DOYs 194 and 226 (1992). These 1992 dates were the two closest days in relation to the 1994 overpass (**Table 1**).

4 Results

Investigation Sites

Figure 2 shows a temporal pattern (from April to November, 1992) of both LAI and σ° at MF sites 1, 2, 3, 7, and 8. Because the ERS-1 and Landsat satellite overpasses were not coincident, LAI values were linearly interpolated at the ERS-1 overpasses by using two adjacent LAI values. The assumption was that the soil drying was uniform and that there was no rain during the two TM overpasses. For MF sites 1, 2, and 7, we can notice a good degree of similarity between LAI and σ° particularly from DOY 160 to DOY 290. The reason for the small temporal σ° variation of MF sites 3 and 8 needs to be investigated.

Therefore, we used the σ° values from MF sites 1, 2, and 7 to derive the empirical LAI and σ°_l relation for the investigation sites (**Figure 3**). All multitemporal σ° values (from DOY 135 to DOY 291) were subtracted from the DOY 170 σ°, since the lowest backscattering coefficients for all MF sites were found on this date. **Figure 3** also shows a consistently higher σ°_l values for MF 2, in comparison with MF 1 and MF 7 with similar LAI values. This suggests a higher soil moisture contents for the MF 2, so that this site was not included in the derivation of σ°_l –LAI relation. The obtained linear regression equation was:

$$\sigma^\circ_l\,(\mathrm{dB}) = -10.69 + 148.58\,\mathrm{LAI}$$

Validation Sites

The SAR and field data from 21 investigation sites in the shrub-dominated part of the watershed is shown in **Table 2**. **Figure 4a** shows the linear relationship between SAR backscattering coefficients and volumetric soil moisture content for the validation sites, without any correction for soil roughness and vegetation effects. The correlation was poor ($r^2 = 0.09$). When only soil roughness is corrected by using the subtraction technique, the soil moisture and SAR backscattering correlation was worse ($r^2 = 0.06$, **Figure 4b**). Consequently, correction for soil roughness without considering vegetation effects may not improve soil moisture estimation in arid and semiarid regions.

When both soil roughness and vegetation effects were corrected for, the soil moisture and SAR backscatter correlation was substantially improved (**Figure 4c**). The relatively high r^2 and slope values (0.66 and 0.30, respectively, if we do not include Sites 3, 4, and 5, which probably presented some laboratory or field experimental error) indicate that the techniques used in this study to account for roughness and vegetation effects were successful. However, the correlation is still lower than expected or lower than those obtained from other regions such as in agricultural areas or in temperate regions ($r^2 > 0.80$, e.g., Bernard et al., 1992). The reason for this low correlation can be the spatial variability of soil moisture in the study area, which was discussed in details by Sano et al. (1998).

5 Concluding Remarks

In this study, we used a microwave and optical synergism to improve the soil moisture content estimation using C-band ERS-1 SAR data in a semiarid region. The following were the major findings:

a) the C-band radar backscattering coefficients were highly, positively correlated with leaf area index derived from Landsat TM data. This indicates that the sparse vegetation in semiarid regions does contribute significantly to the radar backscatter observed with SAR systems. This was mainly due to low soil moisture contents in the semiarid regions (< 20%). In other words, the contribution from soil moisture in the backscattering process in semiarid regions is not significantly higher than that from vegetation, so that the influence of vegetation becomes significant in a multitemporal radar data analysis.

b) the techniques used in this study to account for soil roughness and vegetation effects allowed us to obtain improved soil moisture estimates and, upon validation, it may become an easy way to correct for effects of these two parameters without using multipolarization or multifrequency SAR data.

c) the σ°-LAI relation obtained from the investigation sites (MF sites) performed well for some of the validation sites; nevertheless, future research involving more multitemporal data and more vegetation types needs to be conducted to obtain a more generical relationship.

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Table 1. Dates for the Acquisition of Remotely Sensed and Soil Moisture Data for the WG'92 Experiment.

Day of Year, 1992	Landsat TM	ERS-1 SAR	Soil Moisture Sampling
114	yes		yes
116		yes	
130			yes
135		yes	
146			yes
162	yes		yes
170		yes	
178	yes		yes
194	yes		
210			yes
226	yes		yes
240		yes	
258			yes
274	yes		yes
275		yes	
290			yes
291		yes	
306	yes		
310		yes	
326	yes		
206[a]		yes	yes

[a] Image acquired in 1994

Table 2. Synthetic Aperture Radar and Field Data from the 21 Validation Sites Located in the Shrub-dominated Part of the Walnut Gulch Experimental Watershed (1994 data).

Sampling Point	UTM (East-West)	UTM (North-South)	Backscattering Coefficient (dB)	Soil Moisture (cm^3/cm^3)
1	3512550	585919	-9.39	8.13
2	3511915	586178	-8.56	9.58
3	3511214	586882	-8.67	7.74
4	3509980	586177	-9.18	3.93
5	3510284	585769	-8.29	6.25
6	3505697	593802	-9.99	10.00
7	3506746	594404	-8.97	8.01
8	3507806	593359	-8.99	5.41
9	3507567	592558	-8.19	7.90
10	3511154	588333	-7.86	9.30
11	3513025	588458	-7.92	18.78
12	3512517	588488	-8.11	15.90
13	3512751	589841	-7.78	15.11
14	3511811	589109	-8.73	11.59
15	3512092	589711	-9.47	11.67
16	3511383	589706	-8.88	9.51
17	3511000	589044	-9.29	11.58
18	3512040	590393	-9.61	11.15
19	3511716	590388	-8.49	9.31
20	3510398	592299	-10.08	10.94
21	3508993	592309	-9.00	7.77

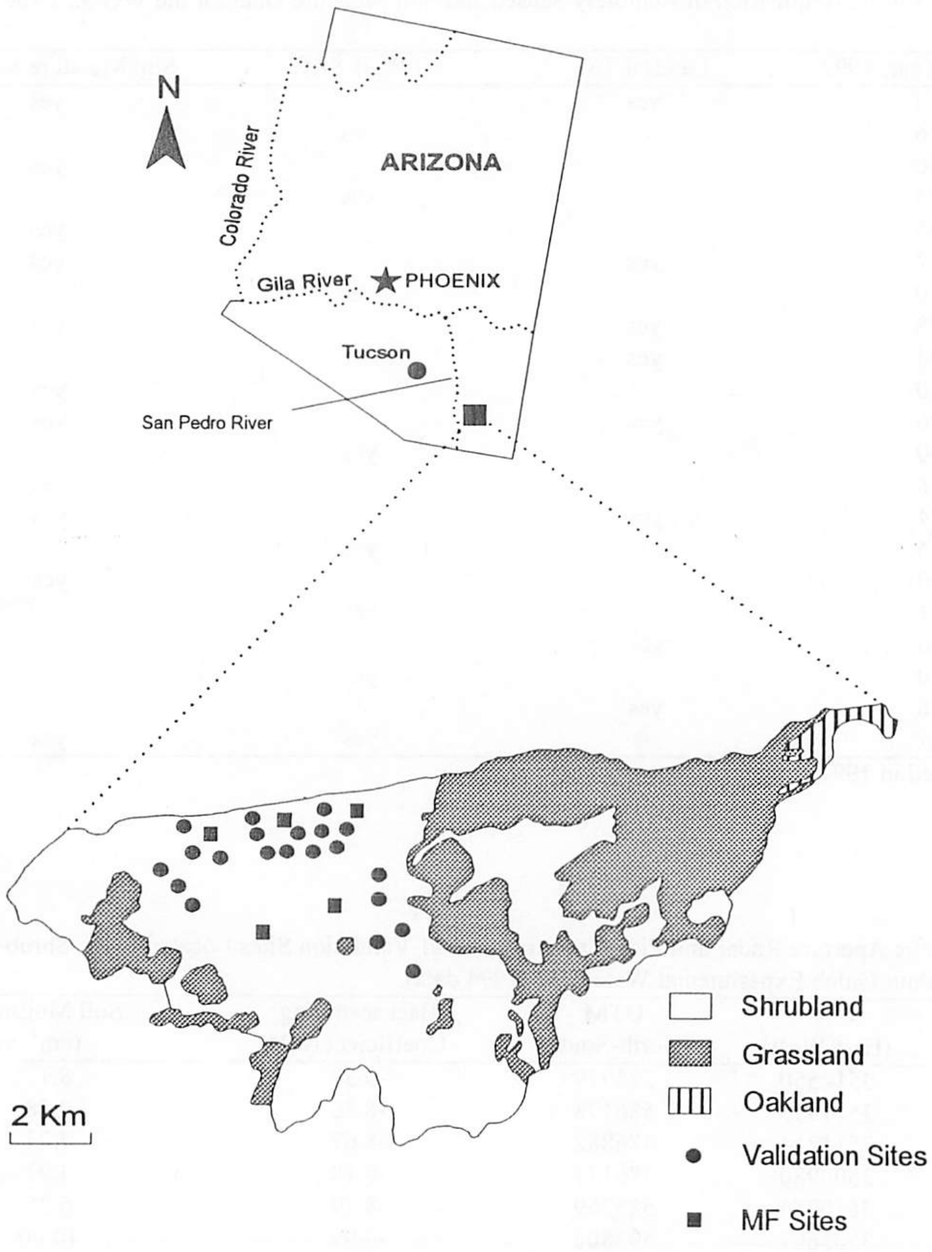

Fig. 1 – Map of the Walnut Gulch Experimental Watershed showing its location in the State of Arizona.

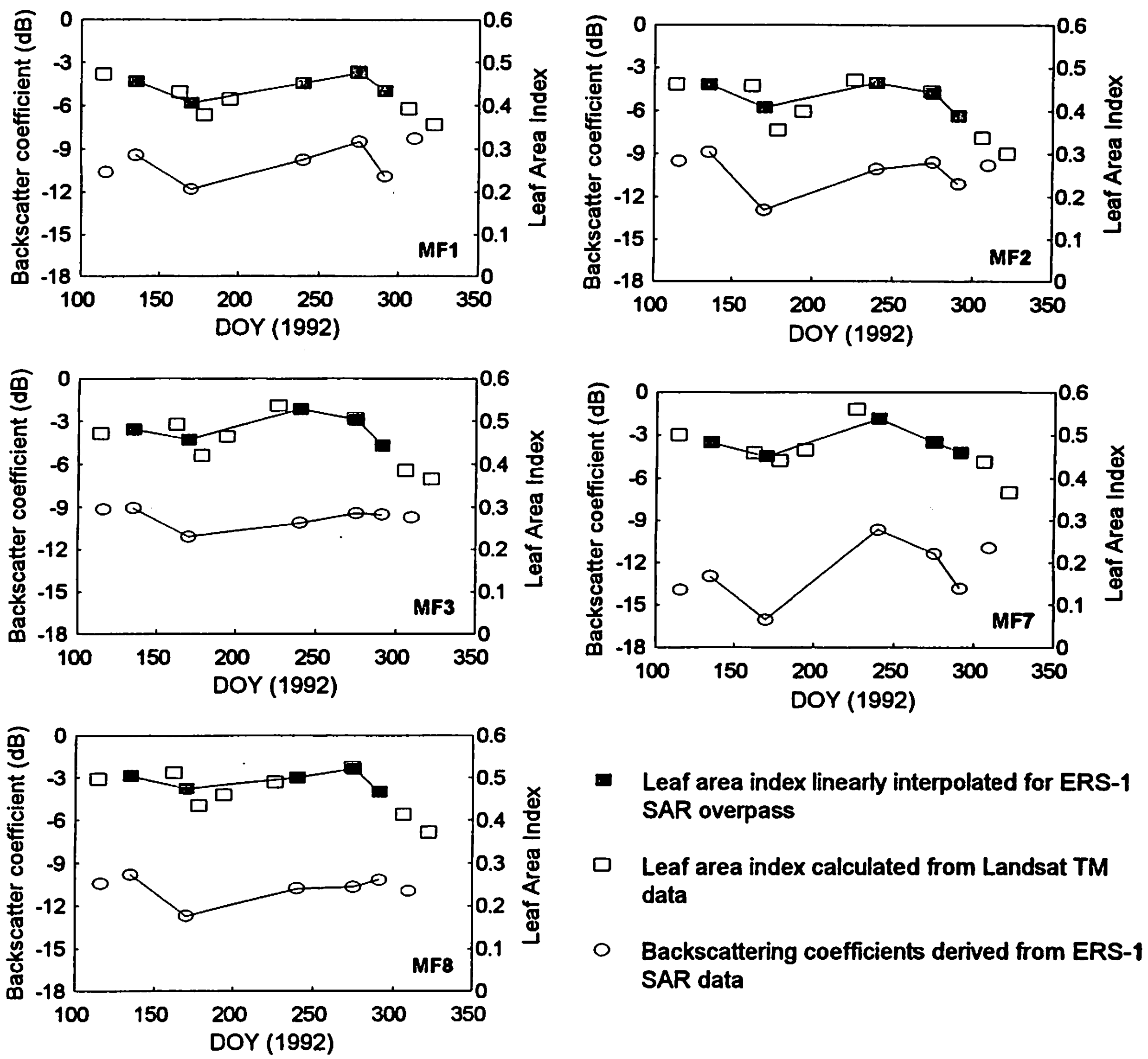

Fig. 2 – Temporal patterns of the backscattering coefficients and leaf area indices for Metflux stations 1, 2, 3, 7, and 8.

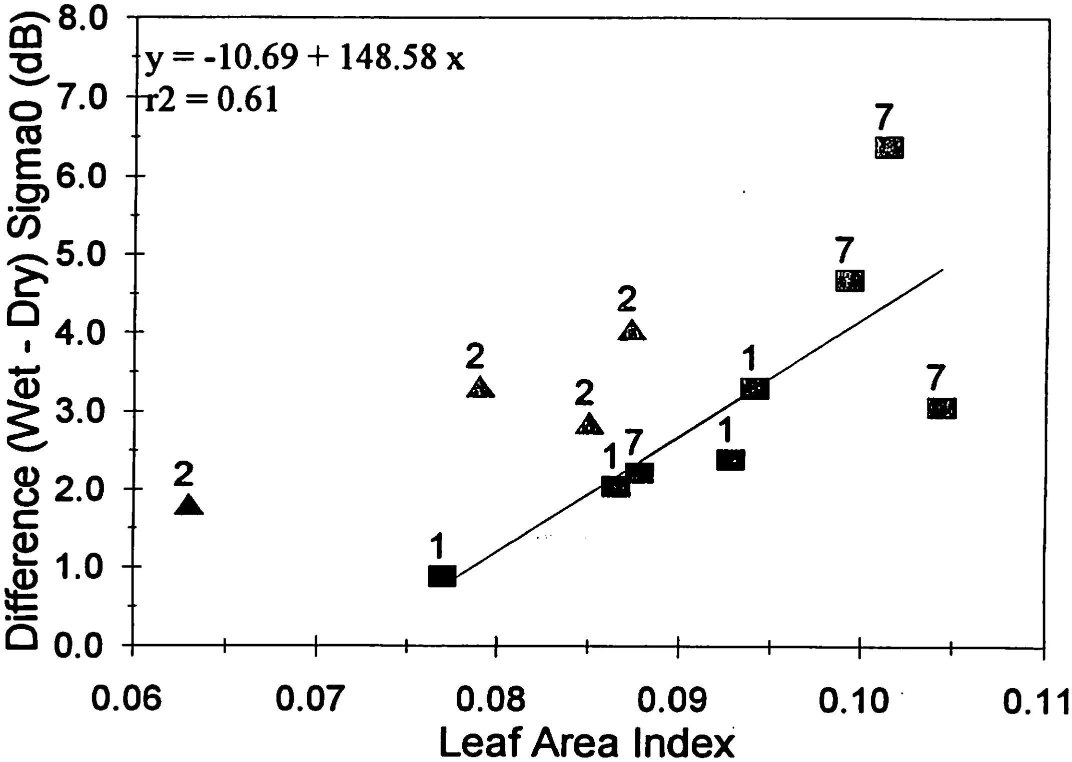

Fig. 3 – Scatterplot between radar backscattering coefficients and leaf area indices for MF stations 1, 2 and 7. Numbers above symbols represent MF sites. Data from MF 2 were not included in the regression analysis because of the probable high soil moisture content.

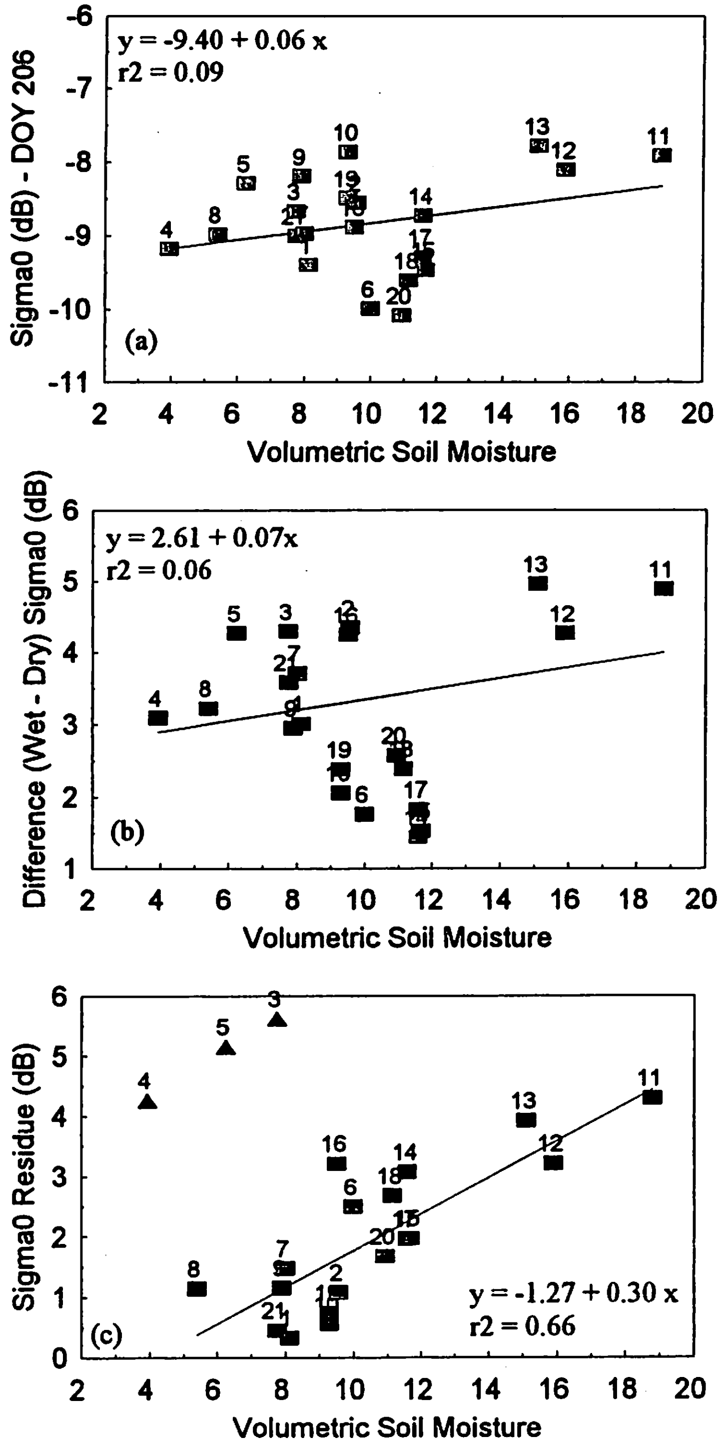

Fig. 4 – Scatterplot between radar backscattering coefficients and soil moisture content for validation sites (a) without any correction for soil roughness and vegetation effects; b) correcting for soil roughness effects; and (c) correcting for both soil roughness and vegetation effects. Sigma0 = radar backscattering coefficient. Sites 3, 4, and 5 were not included in the regression analysis due to a probable experimental or field measurement error).