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SOIL MOISTURE EVALUATION USING SYNTHETIC APERTURE RADAR (SAR) AND OPTICAL REMOTE SENSING IN SEMIARID RANGELAND

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1. INTRODUCTION

Knowledge of distributed surface soil moisture content (~5cm depth) is important for many hydrologic applications including mapping rainfall events, monitoring differential drying patterns, and assessing water availability for plant growth. Surface soil moisture can also be used to parameterize soil water simulation models that estimate soil moisture content with depth in the plant rooting zone. Though the demand for distributed soil moisture information is high, the means for obtaining such information are few. Conventional measurement techniques (e.g., gravimetric and time-domain reflectometry (TDR)) are generally point-based, and require on-site operators and tedious post-processing. Such sensor attributes are not conducive to measurement of regional soil moisture conditions on a frequent basis.

There is some evidence that satellite-based Synthetic Aperture Radar (SAR) sensors could provide a regional assessment of surface soil moisture content (θ_s) (Engman and Chauhan, 1995). Theoretically, SAR backscatter (σ^o, dB) detected by orbiting satellite-based sensors (e.g., ERS-2 SAR) is directly related to θ_s; in practice, σ^o is also highly influenced by topographic features, vegetation density, and variations in small-scale surface roughness. Thus, it is difficult to convert SAR images directly into maps of regional θ_s for heterogeneous terrain. Previous studies have suggested that the accuracy of SAR-based θ_s estimates could be improved by combining data from optical sensors (e.g., surface reflectance and temperature) to discriminate the SAR signal response to vegetation (Moran et al., 1997).

In this project, we designed an experiment to study the link between ERS-2 SAR C-band backscatter to soil moisture, while minimizing the influence of other conditions. That is, we focused our study on flat, uniformly-vegetated sites, and planned to monitor the variations in soil moisture and vegetation cover over time. By choosing flat sites, we avoided the effects of topography; and by monitoring the sites over time (rather than multiple sites over space), we minimized the influence of variations in small-scale roughness conditions. Furthermore, by measuring vegetation density on a monthly basis at each site, we were able to quantify changes in vegetation that might influence SAR σ^o.

In addition, we ordered an image from a satellite-based optical sensor concurrent with each SAR scene acquisition. Images were obtained from the Landsat Thematic Mapper (TM) sensor which measures surface reflected radiance in six wavelengths (from 0.45 to 2.35 µm) and measures surface temperature in a single spectral waveband covering 10.42 to 11.66 µm.

The objectives of this work were to:

1. investigate the sensitivity of ERS-2 C-band SAR backscatter measurements to soil moisture content in a semi-arid rangeland with sparse vegetation cover; and

2. test an approach based on both optical (Landsat TM) and radar (ERS-2 SAR) measurements to improve regional estimates of soil moisture content .

2. APPROACH

The basic approach for the use of SAR/optical synergism for estimation of soil moisture content was developed by Sano (1997). He proposed a semi-empirical approach which accounted for both soil roughness and vegetation effects on the SAR signal, and greatly improved the relation between SAR backscatter and soil moisture content in a semiarid region. In this approach, the effects of soil roughness were taken into account by taking the difference between the SAR backscatter from a given image and the backscatter from a "dry season" image (σ^o-σ^o_{dry}). The vegetation influence was corrected by using an empirical relationship between (σ^o- σ^o_{dry}) and green leaf area index (GLAI), where the latter was derived from the optical data.

This approach is illustrated hypothetically in Figure 1. Sano (1997) found that the vertical distance between a given point and the line defining the (σ^o- σ^o_{dry})/GLAI relation was independent of surface roughness and vegetation density, and directly related to the soil

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moisture content of the site. That is, in Figure 1, though the values of $(\sigma^o-\sigma^o_{dry})$ for points A-C increase from A (2 dB) to B (5 dB) to C (6 dB), the soil moisture conditions are related to the length of the vertical arrow; thus, the soil moisture content of B is greatest and A least, with C intermediate. Sano (1997) found that this approach worked well for estimating soil moisture conditions for sparsely-vegetated (GLAI<1), semi-arid sites in Arizona. However, he admitted that his validation of this approach was questionable because the small number of soil moisture samples (3/site) didn't properly characterize each site.

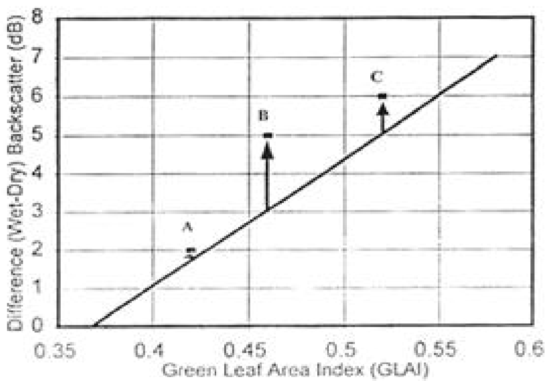

Figure 1. A graphic illustration of the SAR/optical approach for evaluating surface soil moisture developed by Sano (1997). The vertical distance of points A-C from the solid line is related directly to soil moisture content.

3. **EXPERIMENT**

Three sites were chosen in the Upper San Pedro River Basin (USPB) in southeast Arizona for investigation of the SAR/optical approach for monitoring surface soil moisture content. The sites were characterized by level terrain and uniform vegetation cover (over a 300 x 300 m area), and were named by the dominant vegetation type: Tobosa, Sacaton and Creosote. The Tobosa site is located in a swale which supports a mix of tobosa grass (*Hilaria mutica*) and Creosote (*Larrea tridentata*) shrubs. The Sacaton site is dominated by big sacaton (*Sporobolus wrightii*) with some tobosa grass. The Creosote site is on a flat mesa and is characterized by scattered creosote shrubs (*Larrea tridentata*) with very few grasses or annual forbs.

In this study, we requested 10 ERS-2 SAR scenes covering our study site during late 1996 and throughout 1997. The dates of these overpasses were selected to correspond closely with the dates of overpasses of the Landsat-5 satellite (Table 1). During each ERS-2 overpass, we visited all three sites and made 49 gravimetric measurements of soil moisture content to 5cm depth over a target area of 90 x 90 m within the larger uniform area of 300 x 300 m.

We also measured vegetation cover, biomass, height, and leaf area every three weeks to record seasonal changes. Leaf area was measured in situ using a LICOR LAI2000 plant canopy analyzer, and these measurements were verified in the laboratory by direct measurements of sampled leaf area using a LICOR LI3000 leaf area meter. In contrast to the GLAI estimates made by Sano (1997), the LAI2000 measures plant area index (PAI). For the period from January through June, PAI was primarily standing, dry grasses and desiccated creosote shrubs.

Table 1. Dates of acquisitions of Landsat TM and ERS-2 SAR image pairs and dates of collection of supporting data at the Sacaton (S), Tobosa (T) and Creosote (C) sites.

Landsat TM	ERS-2 SAR	Vegetation Sampling	Soil Moisture
†11/12/96	†11/3/96		
¤1/15/97	†1/12/97		1/12/97
¤2/16/97	†2/16/97		2/26/97
†3/20/97	†3/23/97	S: 3/20/97 T: 4/3/97 C: 4/8/97	3/23/97
†4/21/97	†4/27/97	T: 4/14/97 S: 4/21/97 C: 5/5/97 T: 5/12/97	4/21/97
†6/9/97	†6/1/97	S: 6/2/97 C: 6/9/97 T: 6/16/97	6/1/97
*7/11/97	*7/6/97	C: 7/14/97 S: 7/21/97 T: 7/28/97	7/6/97
*8/12/97	*8/10/97	C: 8/4/97 S: 8/9/97 T: 8/19/97	8/10/97
*9/13/97	*9/14/97	C: 8/26/97 S: 9/2/97 T: 9/8/97	8/14/97
10/5/97	10/19/97	C: 10/6/97 S:10/14/97 T: 10/20/97	10/19/97

* Ordered † Received
¤ Not ordered due to cloudy weather

During each TM overpass, we visited the sites and made measurements of surface reflectance and temperature over large areas for comparison with the TM measurements. We also deployed a solar radiometer and arranged for the launch of a radiosonde balloon to measure atmospheric conditions for eventual atmospheric correction of the TM image to obtain estimates surface reflectance and temperature. On several occasions, we deployed a radiometer aboard a small aircraft to measure surface reflectance and temperature at fine resolution (1-2 m) to provide us with local estimates of vegetation vigor for validation of our satellite-based analysis.

In southeast Arizona, the majority of the precipitation and the maximum vegetation greenness is achieved in late July and August. Thus, the experiment was designed to continue through October 1997, when the vegetation had passed maximum density and was beginning to senesce.

4. RESULTS

At the time of this writing, we had only received and processed four SAR scenes (1/12/97, 2/16/97, 3/23/97 and 6/1/97) and one TM scene (3/20/97). With only one TM scene, it was impossible to use spectral data to determine seasonal variations in GLAI values to investigate the use of SAR/optical synergy. Instead, we used the field measurements of PAI to conduct the analysis, and we will follow up later with analysis of the forthcoming TM scenes. Furthermore, the following results are based on only four SAR scenes, three of which didn't cover the Tobosa site. Therefore, results are preliminary and may change with the analysis of all ten SAR scenes at a later date.

Due to fortunate weather conditions, we obtained an excellent range of soil moisture conditions for our study (see notes in Table 2). During the June SAR overpass, the soil moisture conditions at all sites were extremely dry, and the late summer greenup of the vegetation had not yet occurred. Consequently, we designated it as the "dry" scene and subtracted the June SAR backscatter (σ^o_{dry}) from the backscatter measured on the January, February and March dates to account for the contribution of surface roughness to the SAR signal.

The PAI estimated *in situ* with the LAI2000 plant canopy analyzer compared relatively well with the leaf area of the sampled vegetation measured in the laboratory with the LI3100 leaf area meter (Qi et al., 1997). Measurements with the LAI2000 showed that the PAI of the Sacaton site was significantly greater than that of the Creosote and Tobosa sites, with average values for June of 1.2, 0.39 and 0.35, respectively. Since there was no greenup of vegetation during this period, there was no significant change in site PAI. In summary, for this analysis, the PAI was primarily dry biomass; it was different from site to site, but not different from date to date.

Table 2. Volumetric soil moisture content (%) in 1997 at three sites in the Upper San Pedro River Basin, Arizona.

Date	Volumetric Soil Moisture (m^2/m^2)			Notes
	Sacaton	Creosote	Tobosa	
1/12/97	28.2±5.1	9.0±1.4	19.3±6.1	It snowed in early January, and the snow had melted by the time of the ERS-2 overpass. Thus, the soil conditions at all three sites (and throughout the region) were near saturation.
2/26/97	13.2±5.7	3.4±0.9	8.0±3.8	It rained several times in February, resulting in wet (but not saturated) soil conditions.
3/23/97	7.3±4.3	1.1±0.8	3.7±1.1	There was minimal rain in March and April, and the soil conditions were moderately dry.
4/21/97	5.9±2.2	1.2±0.8	3.1±1.5	
6/1/97	3.5±1.3	0.9±0.2	3.3±1.1	During the hot months of June and July, the soil at all sites was very dry, the grass was brown, and no annuals were present.
7/6/97	3.1±1.1	0.7±0.2	2.2±0.6	
8/1/97	27.6±7.3	8.7±1.7	13.1±7.5	A large storm proceeded the August overpass, resulting in high soil moisture conditions in combination with peak vegetation greenness.
9/14/97	13.8±5.0	3.8±1.1	7.0±2.6	A small storm proceeded the September overpass.

Following the work of Sano (1997), we derived a relation between $(\sigma^o-\sigma^o_{dry})$ and PAI using SAR $(\sigma^o-\sigma^o_{dry})$ values from the March image and the January-to-June average PAI values for the Creosote and Sacaton sites (Figure 2).

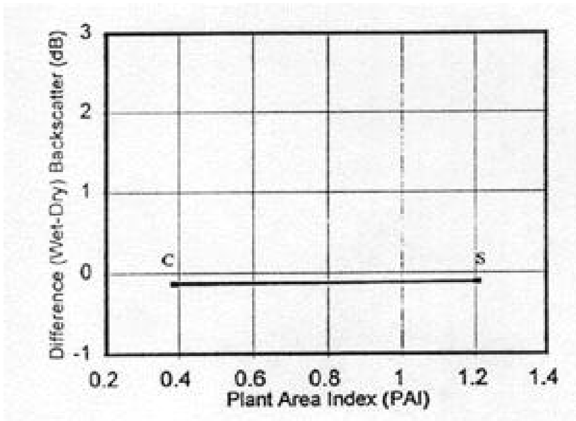

Figure 2. The relation between measured plant area index (PAI) and the difference between the SAR backscatter from the March and June images $(\sigma^o-\sigma^o_{dry})$ for the Creosote (C) and Sacaton (S) sites. These results showed that $(\sigma^o - \sigma^o_{dry})$ was independent of differences in the PAI of standing brown vegetation.

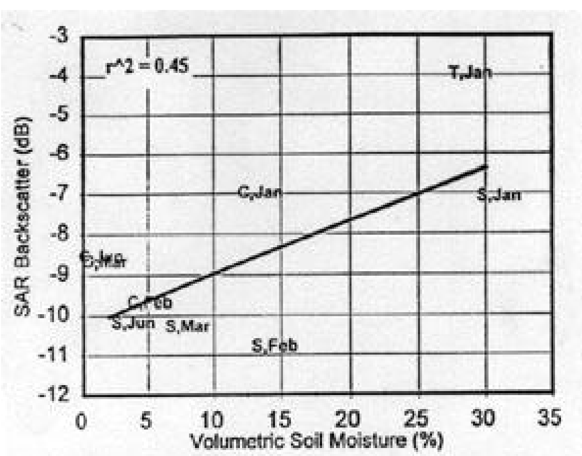

Figure 3. The relation between C-band SAR backscatter and surface (5cm) soil moisture content for three sites [labeled S (Sacaton), C (Creosote) and T (Tobosa)] and four dates in January, February, March and June.

Based on only these two points, there was no significant variation in $(\sigma^o-\sigma^o_{dry})$ associated with the measured variation in PAI at the two sites. It appeared that the differences in standing brown vegetation biomass at these two sites were accounted for in the roughness correction. Consequently, in this analysis, the values of $(\sigma^o-\sigma^o_{dry})$ should be directly related to soil moisture conditions at the site, with no need for a PAI correction. We presume that a correction for changes in GLAI will be necessary when we include the scenes from July through October in this analysis.

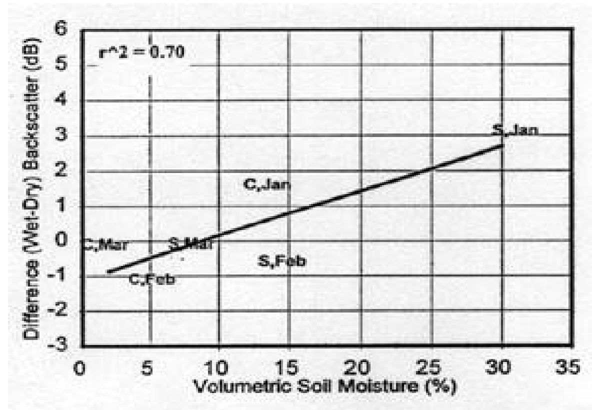

Figure 4. Same as Figure 3, except the SAR backscatter was normalized for differences in surface roughness by subtracting the June SAR backscatter signal from the backscatter signal of the other dates.

Results showed that measured C-band SAR backscatter (σ^o, dB) was poorly correlated (r^2=0.45) with surface soil moisture content (θ_s) at the three field sites (Figure 3). However, when the data were corrected for differences in surface roughness and standing brown vegetation biomass, there was a good correlation (r^2=0.70) between $(\sigma^o - \sigma^o_{dry})$ and θ_s (Figure 4). These results were similar to those obtained by Sano (1997).

5. **CONCLUDING REMARKS**

These preliminary results are encouraging, though not entirely conclusive. As expected, the correction for surface roughness conditions resulted in a substantial improvement in the correlation between the SAR signal and θ_s. However, an unexpected result was discovered with data from the February SAR scene. That is, the SAR backscatter related to the moderately-wet soil conditions in February was less than that for extremely-dry soil conditions in June (i.e., $\sigma^o-\sigma_{dry}<0$ in Figure 4). A possible explanation is that the SAR signal penetrated to a depth less than 5cm (the depth of our gravimetric measurements), and thus, the surface soil moisture conditions for February and June appeared similarly dry. If this were the case, then the 1 dB difference between the February and June measurements was due to some independent influence, such as sensor calibration, dew or something as yet unknown. It is also possible that the relation between $\sigma^o-\sigma^o_{dry}$ and θ_s is non-linear, making the SAR signal more sensitive to changes in wet than dry conditions. Further investigation will be conducted regarding this anomalous result.

In this preliminary analysis (limited to the dry season), it appeared that differences in standing brown vegetation (PAI<1.5) did not affect the SAR backscatter signal after the correction for roughness was applied. This result is significant for two reasons. First, it means that accurate estimates of soil moisture may be possible without a-priori information about standing dry biomass and dry litter. Second, it gives support to the use of an optical/SAR approach for mapping soil moisture because the optical data is sensitive to changes in GLAI rather than PAI.

Despite the good relation between σ^o-σ^o_{dry} and θ_s (Figure 4), the overall sensitivity of the SAR signal to changes in soil moisture was low. For the Sacaton site, a change in soil moisture of 25% resulted in a change in σ^o-σ^o_{dry} of only 3 dB. This is notable since 25% is the maximum soil moisture range expected for sandy loam soils in Arizona's semiarid rangeland.

The full set of ten ERS-2 SAR and eight Landsat TM images will allow further investigation of this SAR/optical approach for mapping regional soil moisture. The inclusion of a larger data set in this analysis will provide greater understanding of and confidence in the final results. Also, the forthcoming scenes will cover a period of increasing green vegetation at all three sites, and allow analysis of the use of optical data to normalize the effects of variations in green vegetation growth on the SAR signal.

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