Parameter Sensitivity of Soil Moisture Retrievals From Airborne L-Band Radiometer Measurements in SMEX02

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***Abstract*—Over the past two decades, successful estimation of soil moisture has been accomplished using L-band microwave radiometer data. However, remaining uncertainties related to surface roughness and the absorption, scattering, and emission by vegetation must be resolved before soil moisture retrieval algorithms can be applied with known and acceptable accuracy using satellite observations. Surface characteristics are highly variable in space and time, and there has been little effort made to determine the parameter estimation accuracies required to meet a given soil moisture retrieval accuracy specification. This study quantifies the sensitivities of soil moisture retrieved using an L-band single-polarization algorithm to three land surface parameters for corn and soybean sites in Iowa, United States. Model sensitivity to the input parameters was found to be much greater when soil moisture is high. For even moderately wet soils, extremely high sensitivity of retrieved soil moisture to some model parameters for corn and soybeans caused the retrievals to be unstable. Parameter accuracies required for consistent estimation of soil moisture in mixed agricultural areas within retrieval algorithm specifications are estimated. Given the spatial and temporal variability of vegetation and soil conditions for agricultural regions it seems unlikely that, for the single-frequency, single-polarization retrieval algorithm used in this analysis, the parameter accuracy requirements can be met with current satellite-based land surface products. We conclude that for regions with substantial vegetation, particularly where the vegetation is changing rapidly, any soil moisture retrieval algorithm that is based on the physics and parameterizations used in this study will require multiple frequencies, polarizations, or look angles to produce stable, reliable soil moisture estimates.**

***Index Terms*—Microwave radiometry, parameter space methods, sensitivity, soil moisture, vegetation.**

I. Introduction

RESULTS from many previous studies (cf. [1]) suggest that, within protected microwave frequencies, the optimal frequency for remote sensing of soil moisture is L-band ($\sim$1.4 GHz) taking into account the greater emitting depth and lesser roughness and vegetation effects at this long wavelength. Although there is no operational satellite-borne L-band radiometer today, plans are underway to deploy two by 2010—Soil Moisture and Salinity Mission (SMOS) [2] and Hydrosphere State Mission (HYDROS) [3]. Many recent experiments in the U.S. and Europe have demonstrated success in mapping the spatial distribution of near-surface moisture with ground-based and aircraft-borne radiometers at various wavelengths [4]–[10]. The focus in these experiments has typically been on correlating daily changes in observed microwave brightness temperatures with *in situ* soil moisture. Despite the advantages and successes at L-band, there are remaining uncertainties that must be resolved, or at least quantified, before soil moisture retrieval algorithms can be applied with known and acceptable accuracy over large land areas using satellite observations. These issues include surface roughness and the absorption, scattering, and emission by vegetation. These surface characteristics are highly variable in space and time and there has been little effort made to determine the parameter estimation accuracies required to meet a given soil moisture retrieval accuracy specification.

The objective of this paper is to carefully examine and quantify the sensitivities of soil moisture retrieved via a single-channel, single-polarization algorithm to the key model parameters describing the land surface. Although many current algorithms based on multiple frequencies or polarizations are more complex and perhaps more accurate, we feel that it is important to understand sensitivities, retrieval performance and limitations for this simple model at each frequency and polarization in order to apply such algorithms appropriately. The analysis has been performed for corn and soybean sites in the midwestern United States; these field conditions represent typical grain-producing regions in the U.S. and globally. By quantifying model sensitivities, we are able to make inferences about how input parameter uncertainties will translate into soil moisture estimation errors when this type of model is applied in similar conditions.

II. Measurements and Methods

A. SMEX02 Experiment Description

SMEX02 (Soil Moisture Experiments in 2002) was conducted in central Iowa from June 24–July 12, 2002 to validate remote sensing algorithms and observations made by a satellite-based passive microwave instrument and an aircraft-based microwave sensor, Passive and Active L- and S-band Radiometer (PALS). This agricultural region was selected in part so that microwave remote sensing algorithms could be tested in a simple landscape consisting primarily of two crops, corn and soybeans, with large homogeneous fields. Although individual fields in SMEX02 were quite uniform in vegetation cover, there was a large contrast in vegetation conditions between the two crops. In addition, there was a substantial increase in vegetation

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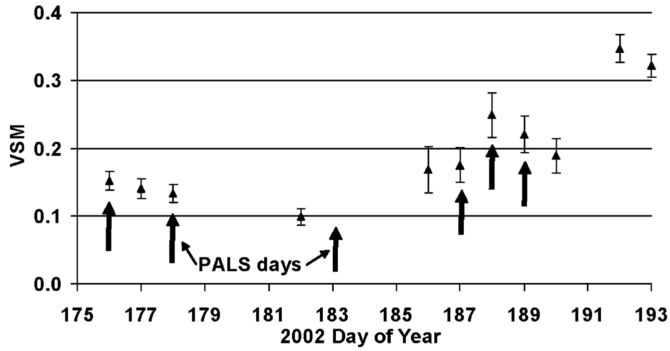

Fig. 1. Time series of all-site means of 0–6 cm volumetric soil moisture. Vertical bars represent ±2 standard errors for the daily mean.

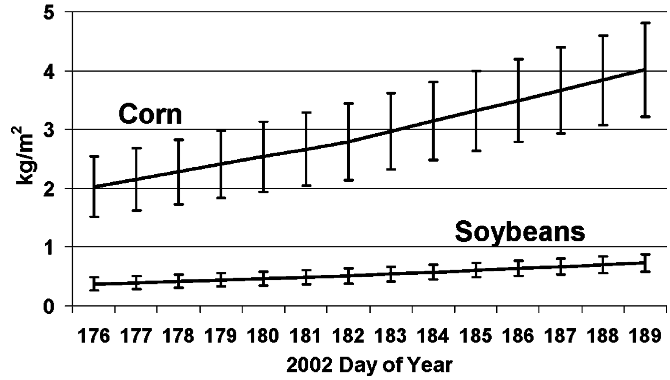

Fig. 2. Time series of vegetation water content means for corn and soybean land cover segments, derived from remotely sensed vegetation indices. Vertical bars represent the standard deviations of the remotely sensed estimates.

density and coverage during the 19-day experiment. Ground sampling teams collected data on a near-daily basis at field, watershed and regional scales for validation efforts. In this study, we utilize *in situ* data collected within the small-scale intensive sampling domain of about 10 × 20 km centered over the Walnut Creek watershed as well as PALS brightness temperature data collected over a slightly larger area (see Section II-C).

Land cover was classified using Landsat Enhanced Thematic Mapper scenes from May 14, July 1, and July 17, 2002. A tassel cap transformation was performed on the July 1 image and a standard NDVI with red and near-infrared bands was computed using the May 14 and July 17 images. The three output bands of the tassel cap transformation and the two NDVI images were utilized with equal weight in a segmentation-based supervised classification with 11 classes. The two dominant classes, corn and soybeans, make up over 80% of the area covered by PALS observations. A segmentation process was used to cluster individual pixels into groups (objects) based on scale and similarity criteria defined by the image analyst. The typical corn or soybean segment dimension is 500–800 m. The classification was verified to be 100% accurate at 31 study sites in the PALS mapping area.

B. *In Situ Soil Moisture and Vegetation Conditions*

Volumetric soil moisture content (VSM) was measured on 11 mornings during the experiment, usually between 8:30 and 11:30 LDT, at 31 observation sites as indicated by the triangles in Fig. 1. During the first nine days of the experiment, soils in the watershed were very dry. On June 25 (day 176), near-surface (0–6 cm) VSM, averaged over all observation sites, was about 0.15. Over the following week, VSM decreased to about 0.10. Light rainfall was distributed sporadically around the watershed on July 4–5 (days 185–186), elevating mean VSM to about 0.17. On July 6 (day 187), more significant rainfall occurred over the watershed and the mean VSM increased to almost 0.25 on July 7 (day 188). Even heavier rain fell on July 10 (day 191), resulting in VSM values approaching 0.35. The uncertainty in the mean VSM across all sites is also indicated in Fig. 1 in the form of ±2 standard errors for each daily mean. During the early dry period, the daily standard errors were approximately 0.01 VSM. The scattered rains on days 185–186 increased the standard errors to about 0.02 VSM. With the more widespread and heavy rainfalls on days 187 and 191, variability decreased to levels similar to those of the dry period.

For each soil moisture site in the study area, vegetation properties including vegetation water content, plant height and fractional vegetation cover were estimated from remotely sensed normalized difference water index (NDWI) on June 23 (day 174), July 1 (182), and July 8 (189) [11], [12]. Fig. 2 shows the daily mean vegetation water contents for corn and soybean land cover segments. Linear interpolation was used between the observations to create the continuous time series shown here and used in the VSM retrievals. During the 13-day period of days 176–189, the vegetation grew very rapidly. Over this period, mean vegetation water content for soybean fields increased from about 0.37 to 0.73 kg/m^2, and for corn sites increased from about 2.0 to 4.0 kg/m^2. The vertical bars in Fig. 2 indicate the daily standard deviations, also interpolated between observations days, of the estimated vegetation water contents for each crop. The root mean square error of the remotely sensed estimates with respect to *in situ* observations at the field sites is approximately 0.7 kg/m^2 [12].

Surface roughness was measured at several locations at each SMEX02 field site using the "grid scanning" and "slope scanning" methods [13]. The two methods gave very similar results, with measured roughness values ranging from 0.5–1.5 cm with a mean of about 0.9 cm. The mean roughness was 1.0 cm for corn sites and 0.7 cm for soybean sites.

C. *PALS*

1) Instrument Description: The PALS passive and active microwave instrument operates at L-band (1.41 GHz radiometer and 1.26 GHz radar) and S-band (2.69 GHz radiometer and 3.15 GHz radar) with dual polarization [14]. During SMEX02 the instrument was flown on a C-130 aircraft with the antennas viewing out the rear door directed downward behind the aircraft at an incidence angle of 45°. The instrument is nonscanning, thus a single-footprint track is sampled along the flight path. In this study, we performed separate soil moisture retrievals with L-band horizontally and vertically polarized brightness temperatures.

During SMEX02, PALS was flown over the watershed study area on eight days (June 25, 27, July 1, 2, 5, 6, 7, and 8) although data on July 1 and July 5 were incomplete. Flights were

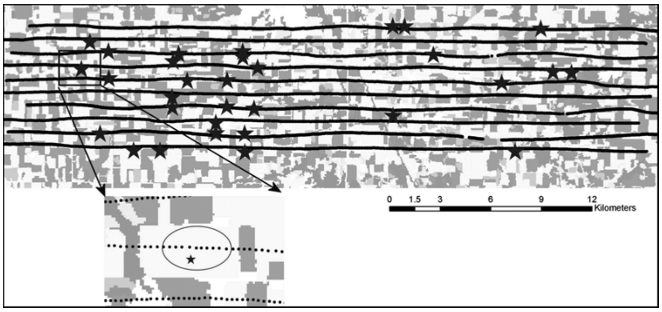

Fig. 3. PALS flight lines for July 7 overlaid on the land cover segments. Stars show the locations of sampling sites. Inset: location of individual PALS observations and an example of a 95% power PALS footprint corresponding to the observation at the center of the footprint.

made from approximately 8:30 to 10:30 A.M. LDT except from 10:00 to 12:00 A.M. LDT on July 7. Fig. 3 shows the flight lines flown on July 7 along with the field sampling locations. PALS was flown at an average altitude of about 1160 m with little variation. Instrument calibration flights were conducted in addition to the data flights and the absolute calibration accuracy was determined to be within 2 K (E. Njoku, 2003, personal communication).

Observed brightness temperatures on June 25 for both corn and soybeans appear to be anomalously high compared with other days. $T_{\rm BH}$ and $T_{\rm BV}$ were 6–9 K higher on June 25 than on June 27 and nearly identical to July 2 in spite of the fact that on the two later days soil moisture was lower and vegetation more dense, implying higher brightness temperatures. Surface temperatures were about 4 K higher on June 25, explaining part of the discrepancy. Nonetheless, calculations with a forward radiative transfer model indicate that the June 25 $T_{\rm B}$'s were 5–10 K too high relative to June 27 and July 2. For these reasons, we have excluded June 25 from further analysis.

2) PALS Observations: PALS brightness temperature observations, like those of any microwave sensor, represent the convolution of the various land cover elements within the sensor footprint. The extent of the footprint is a function of sensor altitude and look angle among other engineering factors. Conventionally, a footprint represents the extent from which half of the total power is returned. For the purpose of this study, we have extended the footprint to represent 95% of the energy returned to the sensor (Fig. 3). Due to the relative sizes of the footprints and a typical land cover segment, most PALS footprints contain a mixture of land cover types and thus cannot be considered to represent a single land cover type. However, the footprint midpoints for a few observations are located near the center of large fields so that at least 95% of the footprint is contained within a land cover segment. Because the $T_{\rm B}$ variability within a corn or soybean segment is significantly less than the variability between crops, such observations provide excellent estimates of the $T_{\rm B}$ for each crop type. Such observations are referred to as pure observations [15].

Because vegetation water contents of soybeans and corn were significantly different, the resulting L-band microwave brightness temperatures of corn and soybeans (based on the mean of all pure observations for each crop type) were also significantly different (Table I). Following the rains of July 4–6, PALS vertical and horizontal (subscripts V and H) polarization T_B decreased for both crop types. The decrease in soybean $T_{\rm BH}$ from July 2 to July 7 was much greater (58 K) than that for corn (18 K). The $T_{\rm BH}$ differences between crop types were much greater on wet days (corn 44 K higher than soybeans on July 7) than on dry days (corn 5 K higher than soybeans on July 2). These differences were found to be statistically significant. Comparatively, the $T_{\rm BH}$ variability among pure observations *within* each crop type was much less than the differences *between* crops (Table I). Similar trends can also be seen in $T_{\rm BV}$, although the between-crop and temporal differences were much smaller. The temporal range of $T_{\rm BV}$ was 280–291 K for corn and 260–291 K for soybeans. Differences between $T_{\rm BV}$ and $T_{\rm BH}$ were smaller for corn due to the depolarizing effect of the vegetation. For soybean fields, the polarized emission of the bare soil contributed to larger $T_{\rm BV} - T_{\rm BH}$ differences [7].

D. Soil Moisture Retrieval Algorithm

1) Description of Algorithm: The inverse retrieval algorithm used in this study is summarized in [1] and described more completely in [16]. The theory behind microwave remote sensing of soil moisture is based on the large contrast between the dielectric properties of liquid water (~80) and dry soil (<4). The brightness temperature of an emitter of microwave radiation is related to the physical temperature of the source through the emissivity such that

$$T_{\rm B} = (1 - R) \bullet T_{\rm eff} = e \bullet T_{\rm eff} \quad (1)$$

where R is the reflectivity from the surface, $T_{\rm eff}$ is the effective radiating temperature of the surface, and $e = (1 - R)$ is the effective emissivity, which depends on the dielectric constant of the medium [17]. $T_{\rm eff}$ is parameterized similar to [18] in terms of the soil surface temperature T_s and "deep" soil temperature $T_{\rm d}$ as

$$T_{\rm eff} = T_d + C(T_s - T_d) \quad (2)$$

where C is an empirical parameter weighting the relative contributions of the surface and deep soil to $T_{\rm eff}$. Although C in principle depends on soil moisture, it is impractical in this algorithm to consider this dependence. We estimated the C parameter utilizing the output of the forward radiative transfer model simulations performed using detailed soil profile measurements for both crops on all days of the study. The C parameter was calculated from the model output by multiplying the relative contributions of the total microwave energy for each soil layer by the linear weights used to interpolate surface temperature in the radiative transfer model. From this analysis we determined that, at L-band and for a soil depth of 10 cm, the appropriate values of C ranged from 0.88–0.96 for dry to wet conditions. We used a constant value of 0.92 in all soil moisture retrievals in this study. This is much higher than the value of 0.25 determined in [18]. We evaluated the impact of the differences in the C parameter by comparing soil moisture retrievals using both values. The resulting differences in $T_{\rm eff}$ range from 1.5 K in wet conditions to 7.8 K under dry conditions when the soil temperature gradients were stronger. The impact on retrieved soil moisture ranged from 0.005–0.055 VSM, with the greater impact being for corn.

While these differences might be fairly significant if we were interested in the absolute values of retrieved VSM, they do not substantively affect our parameter space or sensitivity analyses presented in Section III.

Compensation for energy attenuation by vegetation is based on the relationship between the vegetation transmissivity (γ) and optical depth (τ) [19]

$$\gamma = \exp\left(-\frac{\tau}{\cos\theta}\right) \tag{3}$$

and the optical depth is parameterized in terms of the vegetation water content (W_c) and an empirical parameter B

$$\tau = \mathrm{B} \bullet W_c. \tag{4}$$

According to [20], the B parameter depends on frequency, polarization, and incidence angle. An expression for the bare rough soil surface reflectance R_{br} can be derived from (1) in [19] in terms of the transmissivity and the single-scattering albedo (ω)

$$R_{\mathrm{br}} = \frac{R + \omega(\gamma - 1)}{\gamma\left[\gamma - \omega(\gamma - 1)\right]}. \tag{5}$$

Correction for the amount of scattering that takes place due to roughness of the soil surface uses the simple statistical model of [21], which treats the soil surface height as having a Gaussian distribution with variance σ^2. The microwave reflectance of a bare smooth surface is thus given by

$$R_o = R_{\mathrm{br}} \exp(\mathrm{h} \bullet \cos^2\theta) \tag{6}$$

where

$$h = 4\sigma^2 \left(\frac{2\pi}{\lambda}\right)^2 \tag{7}$$

and $\lambda =$ wavelength. This single-parameter roughness correction is very simple and is certainly not adequate under all conditions. More elaborate models incorporate information on the correlation length scale for surface roughness and even allow roughness to vary as a function of soil moisture [22].

Reflectivity is described by the Fresnel equation that defines the behavior of electromagnetic waves at a smooth dielectric boundary. For horizontal and vertical polarized waves (H, V) at nonnadir incidence (θ), the Fresnel reflectivity may be derived from electromagnetic theory [23] as

$$R(H,\theta) = \left|\frac{\cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}}\right|^2 \tag{8}$$

$$R(V,\theta) = \left|\frac{\varepsilon_r\cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\varepsilon_r\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}}\right|^2 \tag{9}$$

where ε_r is the real part of the complex dielectric constant, or relative permittivity, of the emitter. Because the contribution of the imaginary part of the dielectric constant is relatively small, inversion of (8) and (9) is simplified by considering only the real part of ε_r. Application of the Fresnel equation requires remote observations of reflectivity and assumptions that the dielectric and temperature properties of the soil are uniform throughout the emitting layer, that emissivity is related principally to the relative permittivity, and that the soil depth emitting the energy being measured is known. By inverting the Fresnel equation, we obtain a "retrieved" relative permittivity of the emitting layer ($\varepsilon_{\mathrm{H,ret}}$ or $\varepsilon_{\mathrm{V,ret}}$) in terms of the observed reflectivity at each polarization. For H-pol we obtain from (8)

$$\varepsilon_{\mathrm{H,ret}} = \sin^2\theta + \cos^2\theta\left(\frac{\sqrt{R_H}+1}{\sqrt{R_H}-1}\right)^2 \tag{10}$$

and for V-pol from (9)

$$\varepsilon_{\mathrm{V,ret}} = \frac{\mathrm{a}^2 + \mathrm{a}(\mathrm{a}^2 - 4\mathrm{b}^2\cos^2\theta\sin^2\theta)^{\frac{1}{2}}}{2\mathrm{b}^2\cos^2\theta} \tag{11}$$

where $a = R_{\mathrm{V}}^{1/2} + 1$ and $b = R_{\mathrm{V}}^{1/2} - 1$. Volumetric soil moisture content is determined from $\varepsilon_{\mathrm{H,ret}}$ or $\varepsilon_{\mathrm{V,ret}}$ by inverting the soil dielectric mixing model of Dobson [24] using known dielectric properties of soil, water, and air.

2) Input Data: The soil moisture retrieval algorithm requires the following inputs: brightness temperature (T_{BV} or T_{BH}), surface temperature, deep soil temperature, vegetation water content (W_c), soil surface roughness (σ), vegetation B parameter, and single-scattering albedo (ω). Of these, the first four are temporally variable and are supplied by remote and *in situ* daily measurements whereas the last three are "fixed" parameters. Although these three parameters are not strictly constant, we assumed initially that they vary on time scales long enough to consider them constant for the 13-day period between the first and last PALS flight days. Surface roughness may increase significantly due to tillage operations [25] or from extended drought which may lead to soil cracking. On the other hand, rainfall may decrease soil surface roughness. The vegetation B parameter and single-scattering albedo are generally treated as functions of land cover type, although the latter may increase as the vegetation becomes more dense [20].

Values of the input temperatures and vegetation water content used in the retrieval algorithm are shown in Table I. We used the means of the PALS pure observations for each land cover type for the brightness temperature inputs. Vegetation water content estimates were derived from aircraft-based remotely sensed NDWI. Soil temperature means were calculated each day for each crop type using the *in situ* observations from the 21 corn and 10 soybean sites. The surface temperatures represent an infrared measurement of the soil surface, whereas for the deep soil temperature we used the mean of the measured 10-cm soil temperatures for each crop [26]. Due to more complete shading by the corn canopy, the surface and deep temperatures were typically slightly lower than for the soybean sites. The July 2 soil temperatures shown in Table I were actually measured on July 1 as there were no *in situ* measurements made on July 2. Soil moisture and meteorological conditions were very similar on the two days, so we do not believe that this is a significant source of error. As discussed in Section II-B, vegetation water content increased dramatically, more than doubling for each crop between June 25 and July 8.

TABLE I

VALUES OF INPUT VARIABLES USED IN THE SOIL MOISTURE RETRIEVAL ALGORITHM. $T_{\rm BH}$, $T_{\rm BV}$ = pure H, V-POLARIZED BRIGHTNESS TEMPERATURES, T_s = surface temperature, $T_{\rm d}$ = deep soil temperature, AND W_c = vegetation water content. STANDARD DEVIATIONS ARE SHOWN BELOW THE MEANS FOR EACH QUANTITY. THE PALS INCIDENCE ANGLE WAS 45°

Date	Corn					Soybeans				
	T_{BH}(K)	T_{BV}(K)	T_s(K)	T_d(K)	W_c (kg/m^2)	T_{BH} (K)	T_{BV} (K)	T_s(K)	T_d(K)	W_c (kg/m^2)
June 25	279.9	290.8	307.9	298.8	2.02	277.6	291.0	311.7	300.1	0.37
	2.0	1.5	4.6	1.1	0.44	1.7	1.2	5.1	1.6	0.10
June 27	272.9	285.3	304.2	297.3	2.28	268.0	284.0	307.4	298.2	0.42
	6.1	3.9	6.7	1.3	0.46	11.3	6.7	8.3	2.0	0.10
July 2	282.1	290.6	304.4	298.7	2.97	277.5	291.0	307.0	300.4	0.54
	1.4	1.0	3.4	~ 1.4	0.52	2.2	1.2	4.8	1.4	0.11
July 6	271.6	285.0	301.6	298.1	3.67	242.6	275.2	305.0	298.8	0.67
	7.7	5.2	2.2	0.8	0.54	8.0	3.9	5.4	1.4	0.11
July 7	264.2	280.2	299.2	296.9	3.84	219.9	260.0	299.5	297.3	0.70
	5.9	4.1	2.6	1.3	0.56	10.7	8.4	4.3	1.2	0.12
July 8	270.7	284.2	301.0	297.8	4.02	230.4	267.9	302.4	298.3	0.73
	5.1	3.8	3.2	0.9	0.59	12.6	10.1	3.4	0.9	0.12

III. MODEL SENSITIVITIES AND PARAMETER SPACE ANALYSIS

In this study, we examined the sensitivity of retrieved moisture to the model input parameters by performing a suite of retrievals based on a set of parameter combinations that spans a three-dimensional parameter space. Here "sensitivity" refers to the change in retrieved soil moisture per change in the parameter. Most of the results presented here represent a view of the parameter space in one or two dimensions. The analysis was conducted for each of the five days for which PALS data are available, and for hypothetical homogeneous land areas representative of the corn and soybean fields within the study domain. Our original hypothesis was that, for each crop, there would be day-to-day consistency between the regions within the parameter space that produce soil moisture retrievals that agree well with *in situ* observations. This hypothesis is tested by analyzing the daily parameter spaces for each crop. The emphasis is on horizontal polarization, but some results for V-pol are also presented.

In order to evaluate soil moisture retrieval sensitivity and temporal consistency, we first present retrieval algorithm results for various combinations of surface roughness and vegetation B parameter. In these retrievals, σ was varied from 0.2–2.0 cm in intervals of 0.2; the corresponding roughness h values ranged from 0.01–1.38. B ranged from 0.07–0.16 in intervals of 0.01. The suite of retrievals was repeated for single-scattering albedo values of 0.00, 0.03, 0.06, and 0.09. These ranges were guided by previous studies [6], [7], [20], [22], [25], [27] and adjusted in some cases based on preliminary analysis. We have also performed retrievals for a hypothetical "mixed pixel" region of corn and soybeans to more realistically evaluate soil moisture estimation issues in a mixed agricultural region, such as the SMEX02 study area. Comparisons of the retrieved and observed soil moisture values across the parameter space help identify the parameter combinations that yield accurate moisture estimates for each day and crop. By fixing two parameters and allowing the third to vary, we evaluate the sensitivity of retrieved VSM to a given parameter.

SS albedo = 0.03 <-- Roughness (cm) -->

	Veg-B	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
July 2	0.07	0.006	0.008	0.010	0.014	0.019	0.026	0.034	0.045	0.058	0.076
	0.08	0.011	0.013	0.016	0.020	0.025	0.032	0.040	0.052	0.067	0.086
	0.09	0.016	0.018	0.021	0.025	0.031	0.038	0.048	0.060	0.076	0.098
	0.10	0.022	0.024	0.027	0.031	0.037	0.045	0.055	0.069	0.087	0.111
	0.11	0.028	0.030	0.033	0.037	0.044	0.052	0.064	0.078	0.098	0.125
	0.12	0.034	0.036	0.039	0.044	0.051	0.061	0.073	0.089	0.111	0.141
	0.13	0.041	0.043	0.046	0.052	0.059	0.070	0.083	0.101	0.126	0.160
	0.14	0.048	0.050	0.054	0.060	0.068	0.080	0.094	0.115	0.142	0.181
	0.15	0.056	0.058	0.063	0.069	0.078	0.091	0.107	0.130	0.161	0.206
	0.16	0.064	0.067	0.072	0.079	0.089	0.103	0.121	0.147	0.183	0.236
June 27	0.07	0.027	0.029	0.032	0.037	0.043	0.052	0.063	0.077	0.097	0.123
	0.08	0.032	0.034	0.037	0.042	0.049	0.058	0.070	0.086	0.107	0.136
	0.09	0.037	0.039	0.043	0.048	0.055	0.065	0.078	0.095	0.118	0.150
	0.10	0.043	0.045	0.049	0.054	0.062	0.072	0.086	0.105	0.130	0.166
	0.11	0.049	0.051	0.055	0.061	0.069	0.081	0.096	0.116	0.144	0.184
	0.12	0.055	0.057	0.062	0.068	0.077	0.089	0.106	0.128	0.159	0.204
	0.13	0.062	0.064	0.069	0.076	0.086	0.099	0.117	0.141	0.176	0.226
	0.14	0.069	0.072	0.077	0.084	0.095	0.110	0.129	0.156	0.195	0.252
	0.15	0.077	0.080	0.085	0.094	0.105	0.121	0.143	0.173	0.217	0.283
	0.16	0.085	0.089	0.095	0.104	0.116	0.134	0.158	0.192	0.241	0.318
July 7	0.07	0.072	0.075	0.080	0.088	0.099	0.114	0.135	0.163	0.204	0.265
	0.08	0.087	0.090	0.096	0.105	0.118	0.136	0.160	0.194	0.245	0.324
	0.09	0.103	0.107	0.114	0.125	0.140	0.161	0.191	0.233	0.298	0.402
	0.10	0.122	0.127	0.136	0.148	0.166	0.192	0.229	0.283	0.367	0.513
	0.11	0.145	0.151	0.161	0.176	0.199	0.230	0.277	0.347	0.463	
	0.12	0.173	0.180	0.192	0.211	0.239	0.279	0.340	0.436		
	0.13	0.207	0.216	0.231	0.255	0.290	0.343	0.425			
	0.14	0.250	0.261	0.280	0.311	0.358	0.430	0.548			
	0.15	0.305	0.319	0.345	0.386	0.451					
	0.16	0.378	0.397	0.433	0.492						
		0.01	0.06	0.12	0.22	0.34	0.50	0.68	0.88	1.12	1.38

<-- Roughness h -->

Fig. 4. H-pol parameter space for corn with single-scattering albedo $= 0.03$. Values shown are the retrieved VSM for each roughness/B-parameter combination. Values highlighted in dark gray are within ± 0.04 VSM of the mean of the observations at the corn sites. Cells shaded light gray indicate values below 0.02 VSM and are considered unrealistically low. Cells with no values represent unrealistically high soil moisture whereby retrieved values are greater than the soil porosity.

A. Corn

1) Parameter Space Analysis: Soil moisture values for corn conditions retrieved using $T_{\rm BH}$, a single-scattering albedo of 0.03, and all combinations of roughness and vegetation B parameter are shown in Fig. 4 for July 2, June 27, and July 7. In this and other parameter space representations, VSM observations for July 1 are used to define the valid soil moisture ranges for July 2. Soil moisture during this period was very low and stable and we do not believe this to be a large source of error, but any drying that occurred from July 1 to July 2 would shift the valid regions slightly to the left. The first two days were

SS albedo = 0.06		<-- Roughness (cm) -->									
July 2	Veg-B	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
	0.07	0.000	0.000	0.000	0.004	0.009	0.015	0.022	0.031	0.043	0.058
	0.08	0.000	0.001	0.004	0.008	0.012	0.018	0.026	0.036	0.048	0.064
	0.09	0.003	0.005	0.007	0.011	0.016	0.022	0.030	0.040	0.053	0.070
	0.10	0.007	0.008	0.011	0.015	0.020	0.026	0.035	0.045	0.059	0.077
	0.11	0.010	0.012	0.015	0.019	0.024	0.031	0.039	0.050	0.065	0.084
	0.12	0.014	0.016	0.018	0.022	0.028	0.035	0.044	0.056	0.072	0.092
	0.13	0.018	0.019	0.022	0.026	0.032	0.040	0.049	0.062	0.078	0.101
	0.14	0.022	0.023	0.026	0.031	0.037	0.045	0.055	0.068	0.086	0.110
	0.15	0.026	0.027	0.031	0.035	0.041	0.050	0.061	0.075	0.094	0.120
	0.16	0.030	0.032	0.035	0.040	0.047	0.055	0.067	0.082	0.103	0.131
June 27	0.07	0.021	0.023	0.026	0.030	0.036	0.044	0.054	0.067	0.085	0.108
	0.08	0.025	0.026	0.030	0.034	0.040	0.048	0.059	0.073	0.092	0.117
	0.09	0.028	0.030	0.034	0.038	0.045	0.054	0.065	0.080	0.100	0.127
	0.10	0.033	0.035	0.038	0.043	0.050	0.059	0.071	0.087	0.108	0.138
	0.11	0.037	0.039	0.042	0.048	0.055	0.065	0.077	0.094	0.117	0.149
	0.12	0.041	0.043	0.047	0.053	0.060	0.071	0.084	0.103	0.127	0.162
	0.13	0.046	0.048	0.052	0.058	0.066	0.077	0.092	0.111	0.138	0.176
	0.14	0.051	0.053	0.058	0.064	0.072	0.084	0.100	0.121	0.150	0.192
	0.15	0.056	0.059	0.063	0.070	0.079	0.092	0.108	0.131	0.163	0.209
	0.16	0.062	0.065	0.069	0.077	0.086	0.100	0.118	0.142	0.177	0.228
July 7	0.07	0.058	0.061	0.066	0.072	0.082	0.094	0.112	0.135	0.168	0.216
	0.08	0.069	0.072	0.077	0.084	0.095	0.109	0.129	0.156	0.195	0.252
	0.09	0.080	0.084	0.089	0.098	0.110	0.126	0.149	0.181	0.227	0.298
	0.10	0.094	0.097	0.104	0.113	0.127	0.146	0.173	0.211	0.267	0.356
	0.11	0.109	0.113	0.120	0.131	0.147	0.170	0.201	0.247	0.317	0.432
	0.12	0.126	0.131	0.139	0.152	0.171	0.198	0.236	0.292	0.381	0.535
	0.13	0.146	0.152	0.162	0.177	0.199	0.231	0.278	0.349	0.466	
	0.14	0.170	0.177	0.188	0.207	0.234	0.273	0.332	0.424		
	0.15	0.198	0.206	0.221	0.243	0.276	0.326	0.402	0.527		
	0.16	0.233	0.242	0.260	0.288	0.330	0.394	0.496			
		0.01	0.06	0.12	0.22	0.34	0.50	0.68	0.88	1.12	1.38
		<-- Roughness h -->									

Fig. 5. Same as Fig. 4 except for single-scattering albedo $= 0.06$.

SS albedo = 0.03		<-- Roughness (cm) -->									
July 2	Veg-B	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
	0.07	0.093	0.095	0.098	0.103	0.109	0.116	0.126	0.139	0.155	0.175
	0.08	0.098	0.100	0.103	0.108	0.114	0.122	0.133	0.146	0.163	0.184
	0.09	0.103	0.105	0.109	0.113	0.120	0.129	0.140	0.154	0.172	0.194
	0.10	0.109	0.111	0.114	0.119	0.126	0.136	0.147	0.162	0.181	0.205
	0.11	0.114	0.116	0.120	0.126	0.133	0.143	0.155	0.171	0.191	0.216
	0.12	0.120	0.123	0.127	0.132	0.140	0.150	0.163	0.180	0.201	0.229
	0.13	0.127	0.129	0.133	0.139	0.148	0.158	0.172	0.190	0.212	0.242
	0.14	0.133	0.136	0.140	0.147	0.155	0.167	0.181	0.200	0.224	0.256
	0.15	0.141	0.143	0.148	0.155	0.164	0.176	0.192	0.212	0.238	0.272
	0.16	0.148	0.151	0.156	0.163	0.173	0.186	0.202	0.224	0.252	0.288
June 27	0.07	0.119	0.121	0.125	0.131	0.139	0.149	0.162	0.178	0.199	0.226
	0.08	0.124	0.127	0.131	0.137	0.145	0.155	0.169	0.186	0.208	0.237
	0.09	0.130	0.132	0.137	0.143	0.151	0.162	0.177	0.195	0.218	0.249
	0.10	0.136	0.138	0.143	0.149	0.158	0.170	0.185	0.204	0.229	0.261
	0.11	0.142	0.145	0.149	0.156	0.165	0.178	0.193	0.214	0.240	0.275
	0.12	0.148	0.151	0.156	0.163	0.173	0.186	0.203	0.224	0.252	0.289
	0.13	0.155	0.158	0.163	0.171	0.181	0.195	0.212	0.235	0.265	0.304
	0.14	0.162	0.166	0.171	0.179	0.190	0.204	0.223	0.247	0.279	0.321
	0.15	0.170	0.173	0.179	0.187	0.199	0.214	0.234	0.260	0.294	0.339
	0.16	0.178	0.182	0.188	0.196	0.209	0.225	0.246	0.273	0.310	0.359
July 7	0.07	0.152	0.155	0.160	0.167	0.177	0.190	0.207	0.229	0.258	0.297
	0.08	0.164	0.167	0.172	0.180	0.191	0.206	0.225	0.249	0.282	0.325
	0.09	0.177	0.180	0.186	0.195	0.207	0.223	0.244	0.272	0.308	0.357
	0.10	0.192	0.195	0.202	0.212	0.225	0.243	0.266	0.297	0.338	0.395
	0.11	0.208	0.212	0.219	0.230	0.245	0.265	0.291	0.326	0.373	0.438
	0.12	0.226	0.231	0.239	0.251	0.267	0.289	0.319	0.359	0.413	0.490
	0.13	0.246	0.251	0.260	0.274	0.292	0.318	0.352	0.397	0.461	
	0.14	0.269	0.275	0.285	0.300	0.321	0.350	0.389	0.442	0.517	
	0.15	0.294	0.301	0.313	0.330	0.354	0.387	0.433	0.496		
	0.16	0.324	0.331	0.344	0.364	0.392	0.431	0.484			
		0.01	0.06	0.12	0.22	0.34	0.50	0.68	0.88	1.12	1.38
		<-- Roughness h -->									

Fig. 6. Same as Fig. 4 except for V-pol.

dry, with July 2 being the driest, and the third was the wettest of the five PALS observation days. Not shown are the parameter spaces for the two moderately wet days, July 6 and July 8, but these are very similar to July 7. In these matrices, values highlighted in dark gray are within ± 0.04 VSM of the mean of the observations at the corn sites. This tolerance was chosen to match the HYDROS soil moisture estimation accuracy requirement for vegetation water content values < 5 kg/m^2 [3]. Cells shaded light gray indicate values below 0.02 VSM and are considered unrealistically low. Cells with no values represent unrealistically high soil moisture whereby retrieved values are greater than the soil porosity. Ideally, the valid (dark gray) regions within parameter spaces for each day would be very similar. However, in Fig. 4, the valid parameter regions for the days appear quite different, as the lower sensitivity of retrieved soil moisture to the two parameters under dry conditions (June 27 and July 2) causes the valid regions to be much larger than for the wet conditions (July 7), where higher sensitivity results in a narrow valid region. Nonetheless, there is considerable overlap in the regions for all five days, encompassing completely the valid region of July 7.

The parameter space representations for corn for $\omega = 0.06$ are shown in Fig. 5. For a given T_{BH}, increasing ω results in a lower VSM than determined for $\omega = 0.03$ (Fig. 4). Consequently, the valid parameter regions shift toward higher roughness or B values to offset the albedo effect. Again, for all days there is a substantial intersection in the valid regions that includes most of the July 7 valid region for $\sigma \geq 1.0$ cm.

Fig. 6 illustrates the parameter space for corn when T_{BV} is used to retrieve VSM with $\omega = 0.03$. The valid parameter regions for the dry days are characterized by much lower σ or B values than for the wet day, and there is no overlap of valid regions for all days. This is also true using T_{BV} with other values of single-scattering albedo. This lack of consistency between days at V-pol is unexplained at this time.

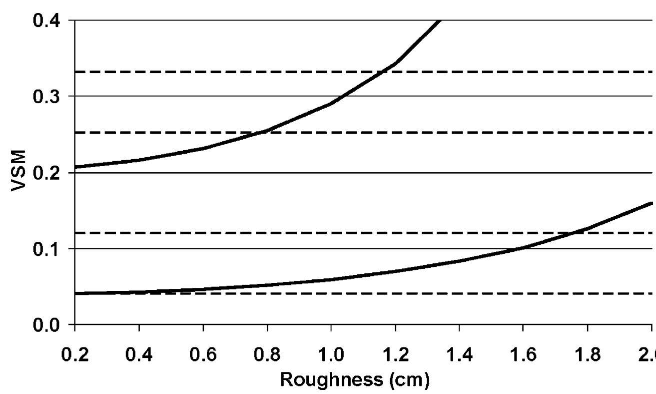

Fig. 7. Sensitivity to surface roughness of VSM retrieved using T_{BH} for corn with single-scattering albedo $= 0.03$ and B $= 0.13$. The upper and lower curves correspond to July 7 and July 2, respectively. The dashed lines indicate the observed mean ± 0.04 VSM for each day.

2) Sensitivities of Retrieved VSM to Model Parameters: Based on the suite of soil moisture retrievals performed, we examine the VSM retrieval sensitivity to each of the model parameters. For each crop and each polarization, the reference point around which sensitivity analyses were performed represents a parameter combination that is as close as possible to a best fit solution for all five PALS days. The sensitivity analyses presented here are for illustrative purposes only, with the focus being on the change in VSM as a function of the model parameters rather than the retrieved VSM values in an absolute sense. For H-pol, the sensitivity to surface roughness for corn is illustrated for July 2 and July 7 in Fig. 7 by fixing B at 0.13 and ω at 0.03. This combination of B and ω is just one of numerous combinations that could be used to illustrate model sensitivity, but it does result in intersection with the valid parameter region for certain σ values on the two days shown, as can be seen in Fig. 7. For the two days, retrieved VSM is shown for σ ranging from 0.2–2.0 cm,

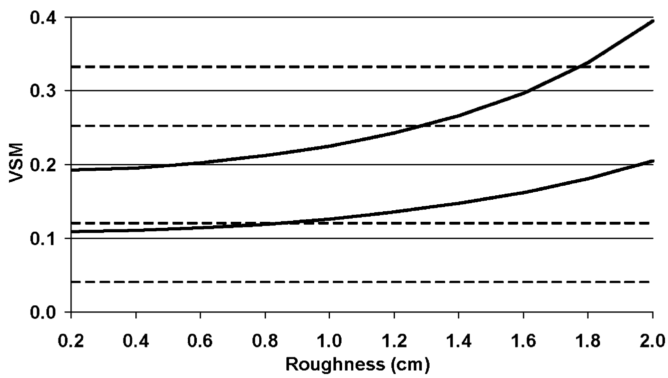

Fig. 8. Sensitivity to surface roughness of VSM retrieved using T_{BV} for corn with single-scattering albedo $= 0.03$ and B $= 0.10$. The upper and lower curves correspond to July 7 and July 2, respectively. The dashed lines indicate the observed mean ±0.04 VSM for each day.

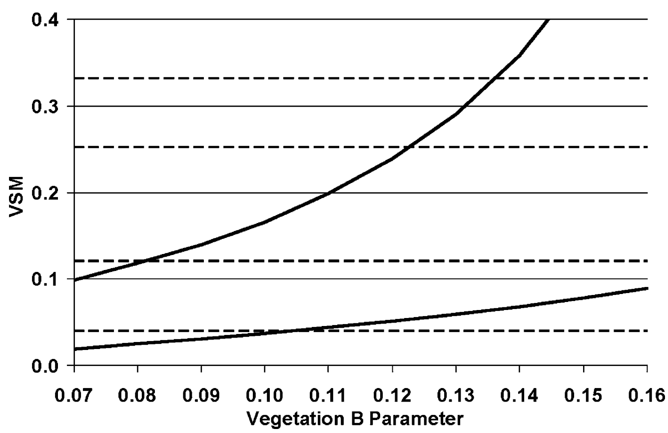

Fig. 9. Sensitivity to vegetation B parameter of VSM retrieved using T_{BH} for corn with single-scattering albedo $= 0.03$ and surface roughness $= 1.0$ cm. The upper and lower curves correspond to July 7 and July 2, respectively. The dashed lines indicate the observed mean ±0.04 VSM for each day.

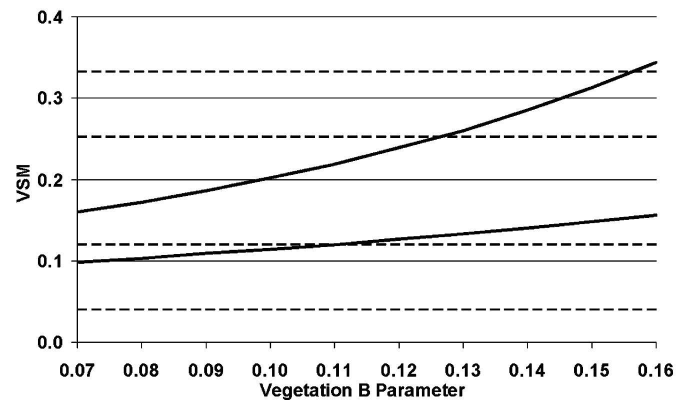

Fig. 10. Sensitivity to vegetation B parameter of VSM retrieved using T_{BV} for corn with single-scattering albedo $= 0.03$ and surface roughness $= 0.6$ cm. The upper and lower curves correspond to July 7 and July 2, respectively. The dashed lines indicate the observed mean ±0.04 VSM for each day.

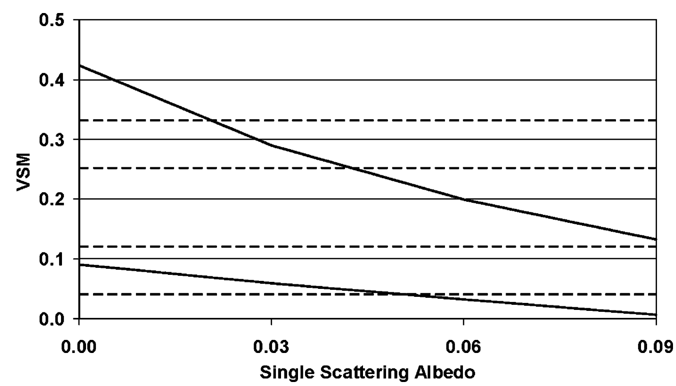

Fig. 11. Sensitivity to single-scattering albedo of VSM retrieved using T_{BH} for corn with surface roughness $= 1.0$ cm and B $= 0.13$. The upper and lower curves correspond to July 7 and July 2, respectively. The dashed lines indicate the observed mean ±0.04 VSM for each day.

although for July 7 reasonable estimates are obtained only up to $\sigma = 1.2$ cm. The dashed lines represent the daily observed VSM ±0.04, i.e., the tolerance limit for remote sensing used to constrain valid ranges as shown in the parameter space matrices. Intersection of the retrieved VSM with the two dashed lines indicates the acceptable range of that parameter for the day. For July 2 (dry), the slope of retrieved VSM with respect to σ is small over a broad range of σ values (<2 cm), i.e. the retrieval is insensitive. For the wetter conditions of July 7, the slope is much steeper (sensitivity is greater), and consequently a very narrow acceptable range of roughness values is indicated. Sensitivity of retrieved VSM to roughness is slightly less at V-pol than at H-pol, as shown in Fig. 8. For dry conditions, sensitivity is very low. For the wet case, sensitivity is considerable only for high roughness values.

Fig. 9 shows the VSM retrieval sensitivity at H-pol to the B parameter for corn for July 2 and July 7, with a parameter vector of $\sigma = 1.0$ cm and $\omega = 0.03$. Because vegetation optical depth is given by the product of B and the vegetation water content, an error in estimating B has the same effect on retrieved soil moisture as a proportional error in estimating W_c. In practice, B is a fixed parameter, whereas W_c may have significant temporal and spatial variability, especially in agricultural regions. Thus, the sensitivity and error analysis discussed here are applicable for understanding the effects of uncertainties in estimating vegetation water content. Results are very similar to those for roughness in that sensitivity is much higher for July 7, leading to a much narrower acceptable range of B values. As shown in Fig. 10, the sensitivity to B is lower at V-pol than at H-pol. On the dry day, there is very little sensitivity at V-pol; for the wet day, the sensitivity is slightly greater.

The effect of single-scattering albedo on retrieved VSM for H-pol is shown in Fig. 11 for corn for July 2 and July 7; here $\sigma = 1.0$ cm and B $= 0.13$. Again, retrieval sensitivity is much higher for wet conditions. For dry conditions, in this example the valid range for ω is approximately 0.00–0.05, whereas for wet conditions the range is approximately 0.02–0.04. At V-pol, sensitivity to ω is only slightly higher for wet conditions compared to the dry case (Fig. 12).

In a separate analysis (not shown) in which we varied model input T_{B} below and above the observed value for a given day, we estimated the sensitivity of retrieved VSM to T_{BH} to be approximately 0.01 VSM per Kelvin for both wet and dry days for corn. Based on a specified error bound of ±0.04 VSM, this implies an error tolerance in T_{BH} of ±4 K. For T_{BV}, sensitivity is estimated to be approximately 50% higher than for T_{BH}, or about 0.015 VSM per Kelvin.

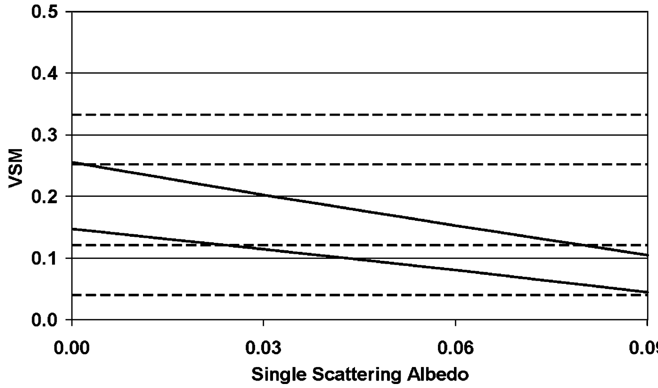

Fig. 12. Sensitivity to single-scattering albedo of VSM retrieved using T_{BV} for corn with surface roughness $= 0.6$ cm and B $= 0.10$. The upper and lower curves correspond to July 7 and July 2, respectively. The dashed lines indicate the observed mean ± 0.04 VSM for each day.

3) Valid Parameter Ranges: To address issues of input parameter error tolerances and how they vary as functions of moisture conditions, for each day we determined ranges for each parameter that produce retrieved VSM values within ± 0.04 VSM of the observations. For corn, this was done using a reference vector defined by $\omega = 0.03$, B $= 0.13$, and $\sigma = 1.0$ cm $(h = 0.34)$; this point falls within the intersection of valid parameter regions at H-pol for all days. Around this point, each parameter was allowed to vary within its respective range while the other parameters were fixed. Fig. 13(a)–(c) shows, for H-pol, valid ranges for each parameter plotted as functions of the mean observed VSM for each day. This is simply another way to represent the valid parameter regions for all days, as shown in Figs. 4–6 for selected days. The ranges are shown here solely to illustrate the general relationships between soil moisture and the parameter tolerances; because of the interrelated nature of the parameters, the exact ranges of valid parameter values could be quite different for another reference point in the parameter space. For each parameter, there is a clear tendency for the range to narrow as soil moisture increases. This is an obvious consequence of the higher sensitivity of retrieved VSM to all parameters for wet conditions, as demonstrated in Figs. 7, 9, and 11. From the dry days to the wettest day, the width of the valid range of surface roughness decreases by a factor of 5, the range of B decreases by a factor of 4, and the range of single-scattering albedo decreases by a factor of 2. At V-pol (not shown), there is a tendency for the valid ranges to narrow on the wet days, especially for roughness and single-scattering albedo, but due to the generally lower parameter sensitivity this pattern is not as clear as at H-pol.

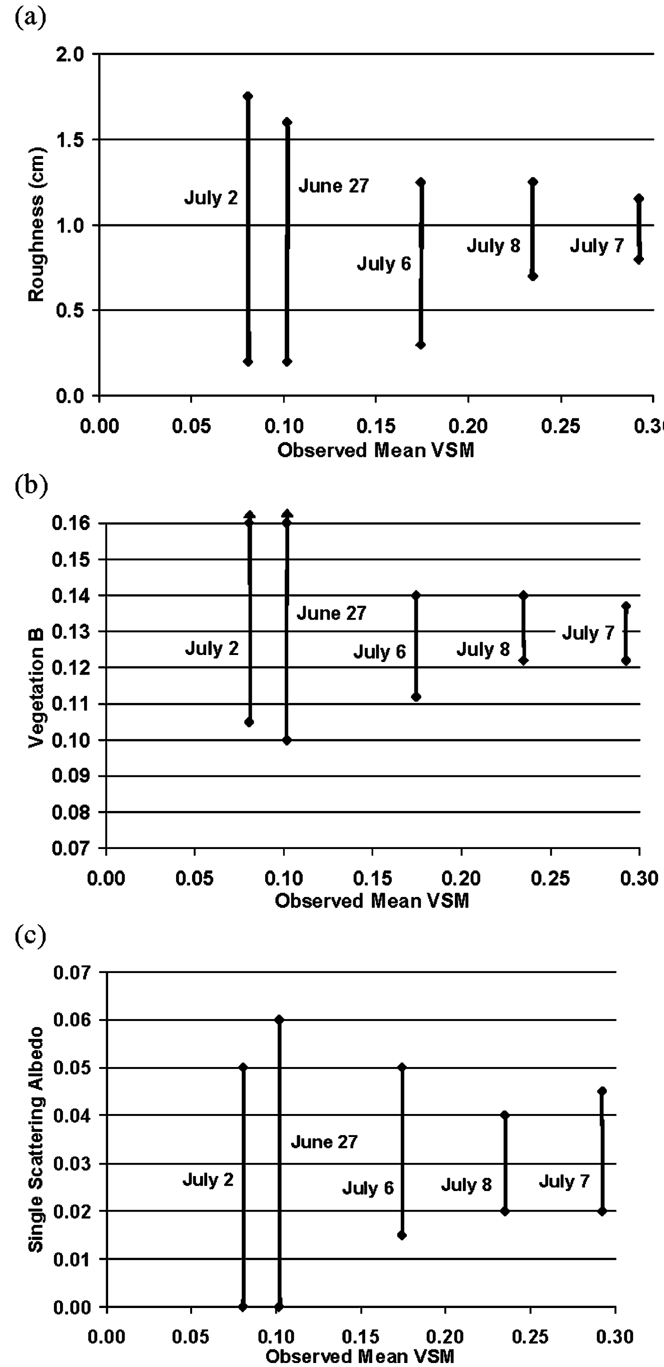

Fig. 13. Valid ranges of (a) roughness, (b) B parameter, and (c) single-scattering albedo as functions of VSM for corn at H-pol.

B. Soybeans

1) Parameter Space Analysis: Retrieved VSM at H-pol for soybean conditions are shown as functions of surface roughness and vegetation B parameter in Fig. 14. These retrievals were performed using a single-scattering albedo of 0.03. The valid parameter region is much larger on the two dry days (July 2 and June 27), and the region is shifted toward higher roughness values compared with the wet case of July 7. There is a small intersection of the valid parameter regions for the three days for roughness values of 1.2–1.4 cm. At V-pol, the valid parameter regions are quite large for all days, resulting in considerable overlap for all days (Fig. 15).

2) Sensitivities of Retrieved VSM to Model Parameters: The relationship between retrieved VSM and input surface roughness at H-pol for soybeans is shown in Fig. 16. In this example, B $= 0.10$ and $\omega = 0.03$. As was the case for corn conditions discussed above, retrieval sensitivity to σ is relatively low on July 2 for low to intermediate σ values, but for July 7 the sensitivity is much greater. The range of σ that produces accurate VSM retrievals is only about 1.2–1.5 cm for July 7, but about

SS albedo = 0.03						<-- Roughness (cm) -->					
July 2	Veg-B	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
	0.07	0.000	0.001	0.003	0.007	0.012	0.018	0.026	0.035	0.048	0.064
	0.08	0.000	0.002	0.004	0.008	0.013	0.019	0.027	0.036	0.049	0.065
	0.09	0.001	0.003	0.005	0.009	0.014	0.020	0.028	0.038	0.050	0.067
	0.10	0.002	0.004	0.006	0.010	0.015	0.021	0.029	0.039	0.052	0.069
	0.11	0.003	0.005	0.007	0.011	0.016	0.022	0.030	0.040	0.053	0.070
	0.12	0.004	0.006	0.008	0.012	0.017	0.023	0.031	0.042	0.055	0.072
	0.13	0.005	0.007	0.009	0.013	0.018	0.024	0.033	0.043	0.056	0.074
	0.14	0.006	0.008	0.010	0.014	0.019	0.025	0.034	0.044	0.058	0.076
	0.15	0.007	0.008	0.011	0.015	0.020	0.027	0.035	0.046	0.060	0.078
	0.16	0.008	0.009	0.012	0.016	0.021	0.028	0.036	0.047	0.061	0.080
June 27	0.07	0.020	0.021	0.024	0.029	0.035	0.042	0.052	0.065	0.083	0.106
	0.08	0.021	0.022	0.025	0.030	0.036	0.043	0.054	0.067	0.084	0.108
	0.09	0.021	0.023	0.026	0.031	0.037	0.044	0.055	0.068	0.086	0.110
	0.10	0.022	0.024	0.027	0.032	0.038	0.046	0.056	0.070	0.088	0.112
	0.11	0.023	0.025	0.028	0.032	0.039	0.047	0.057	0.071	0.089	0.114
	0.12	0.024	0.026	0.029	0.033	0.040	0.048	0.058	0.072	0.091	0.116
	0.13	0.025	0.027	0.030	0.034	0.041	0.049	0.060	0.074	0.093	0.118
	0.14	0.026	0.028	0.031	0.035	0.042	0.050	0.061	0.075	0.094	0.121
	0.15	0.027	0.028	0.032	0.036	0.043	0.051	0.062	0.077	0.096	0.123
	0.16	0.027	0.029	0.033	0.037	0.044	0.052	0.064	0.078	0.098	0.125
July 7	0.07	0.126	0.131	0.140	0.153	0.172	0.198	0.236	0.293	0.382	0.537
	0.08	0.130	0.136	0.144	0.158	0.177	0.205	0.245	0.305	0.399	
	0.09	0.135	0.140	0.149	0.163	0.184	0.212	0.254	0.317	0.417	
	0.10	0.139	0.145	0.154	0.169	0.190	0.220	0.264	0.330	0.436	
	0.11	0.144	0.150	0.160	0.175	0.197	0.228	0.274	0.343	0.457	
	0.12	0.149	0.155	0.165	0.181	0.203	0.236	0.284	0.358	0.479	
	0.13	0.154	0.160	0.171	0.187	0.211	0.245	0.295	0.373	0.503	
	0.14	0.159	0.165	0.176	0.193	0.218	0.254	0.307	0.389	0.528	
	0.15	0.165	0.171	0.183	0.200	0.226	0.264	0.319	0.407		
	0.16	0.170	0.177	0.189	0.207	0.234	0.274	0.333	0.425		
		0.01	0.06	0.12	0.22	0.34	0.50	0.68	0.88	1.12	1.38
						<-- Roughness h -->					

Fig. 14. Same as Fig. 4 except for soybeans.

SS albedo = 0.03						<-- Roughness (cm) -->					
July 2	Veg-B	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
	0.07	0.080	0.082	0.084	0.088	0.094	0.101	0.110	0.120	0.134	0.151
	0.08	0.081	0.083	0.085	0.089	0.095	0.102	0.111	0.122	0.136	0.153
	0.09	0.082	0.083	0.086	0.090	0.096	0.103	0.112	0.123	0.137	0.154
	0.10	0.083	0.084	0.087	0.091	0.097	0.104	0.113	0.124	0.138	0.156
	0.11	0.083	0.085	0.088	0.092	0.098	0.105	0.114	0.125	0.139	0.157
	0.12	0.084	0.086	0.089	0.093	0.099	0.106	0.115	0.126	0.141	0.159
	0.13	0.085	0.087	0.090	0.094	0.100	0.107	0.116	0.128	0.142	0.161
	0.14	0.086	0.088	0.091	0.095	0.101	0.108	0.117	0.129	0.144	0.162
	0.15	0.087	0.089	0.092	0.096	0.102	0.109	0.118	0.130	0.145	0.164
	0.16	0.088	0.089	0.092	0.097	0.103	0.110	0.119	0.131	0.146	0.165
June 27	0.07	0.112	0.115	0.118	0.124	0.131	0.140	0.153	0.168	0.187	0.213
	0.08	0.113	0.116	0.119	0.125	0.132	0.142	0.154	0.169	0.189	0.214
	0.09	0.114	0.117	0.120	0.126	0.133	0.143	0.155	0.171	0.191	0.216
	0.10	0.115	0.117	0.121	0.127	0.134	0.144	0.156	0.172	0.192	0.218
	0.11	0.116	0.118	0.122	0.128	0.135	0.145	0.158	0.174	0.194	0.220
	0.12	0.117	0.119	0.123	0.129	0.136	0.146	0.159	0.175	0.196	0.222
	0.13	0.118	0.120	0.124	0.130	0.138	0.148	0.160	0.177	0.197	0.224
	0.14	0.119	0.121	0.125	0.131	0.139	0.149	0.162	0.178	0.199	0.226
	0.15	0.120	0.122	0.126	0.132	0.140	0.150	0.163	0.180	0.201	0.228
	0.16	0.121	0.123	0.127	0.133	0.141	0.151	0.164	0.181	0.203	0.230
July 7	0.07	0.197	0.201	0.208	0.218	0.231	0.250	0.274	0.306	0.349	0.408
	0.08	0.200	0.204	0.211	0.221	0.235	0.254	0.279	0.312	0.356	0.417
	0.09	0.203	0.207	0.214	0.225	0.239	0.258	0.284	0.318	0.363	0.425
	0.10	0.207	0.211	0.218	0.229	0.243	0.263	0.289	0.324	0.370	0.435
	0.11	0.210	0.214	0.222	0.233	0.248	0.268	0.294	0.330	0.378	0.444
	0.12	0.213	0.218	0.225	0.237	0.252	0.272	0.300	0.336	0.385	0.454
	0.13	0.217	0.221	0.229	0.241	0.256	0.277	0.305	0.343	0.393	0.464
	0.14	0.221	0.225	0.233	0.245	0.261	0.282	0.311	0.349	0.402	0.475
	0.15	0.224	0.229	0.237	0.249	0.265	0.287	0.317	0.356	0.410	0.485
	0.16	0.228	0.233	0.241	0.253	0.270	0.293	0.323	0.363	0.419	0.497
		0.01	0.06	0.12	0.22	0.34	0.50	0.68	0.88	1.12	1.38
						<-- Roughness h -->					

Fig. 15. Same as Fig. 14 except for V-pol.

1.0–2.0 cm for July 2. The sensitivity to roughness for soybeans at V-pol is similar to, but slightly lower than, that at H-pol.

For soybean conditions, the retrieval sensitivity to the vegetation B parameter is quite small at H-pol, especially for dry conditions. Results in Fig. 17, based on $\sigma = 1.4$ cm and $\omega = 0.03$ indicate that retrieved VSM has almost no sensitivity to B on July 2 and moderate sensitivity on July 7. For V-pol, sensitivity to B is very small for both days such that valid VSM estimates could be obtained with any value of B within the range of 0.07–0.16.

Sensitivity to single-scattering albedo for soybeans for both polarizations was found to be very low. This is consistent with

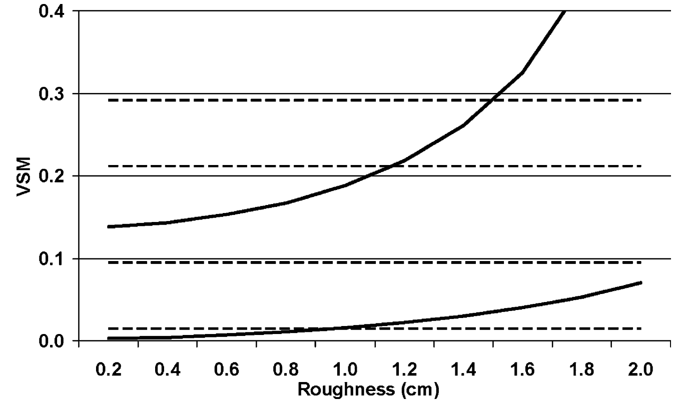

Fig. 16. Sensitivity to surface roughness of VSM retrieved using T_{BH} for soybeans with single scattering albedo $= 0.03$ and B $= 0.10$. The upper and lower curves correspond to July 7 and July 2, respectively. The dashed lines indicate the observed mean ± 0.04 VSM for each day.

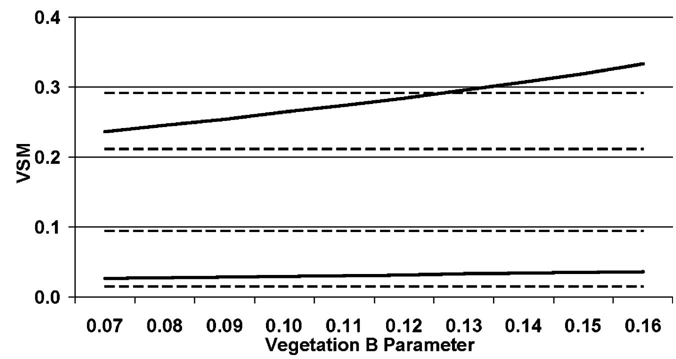

Fig. 17. Sensitivity to vegetation B parameter of VSM retrieved using T_{BH} for soybeans with single scattering albedo $= 0.03$ and surface roughness $=$ 1.4 cm. The upper and lower curves correspond to July 7 and July 2, respectively. The dashed lines indicate the observed mean ± 0.04 VSM for each day.

results of [7]. Over the examined range of 0.00–0.06, retrieved VSM typically varied by less than 0.02 for wet conditions and less than 0.01 for dry soils.

The sensitivities of retrieved VSM to T_{BH} and T_{BV} for soybeans were estimated to be approximately 0.005 and 0.007 VSM per Kelvin, respectively, or about half of the values found for corn. For our imposed error bound of ± 0.04 VSM, this implies T_{BH} and T_{BV} tolerances for soybeans of ± 8 K and ± 6 K.

3) Valid Parameter Ranges: Fig. 18(a) and (b) shows the valid surface roughness and B parameter ranges at H-pol for soybeans plotted against observed VSM for each day. The parameter reference vector here is $\omega = 0.03$, B $= 0.10$, and $\sigma = 1.4$ cm; this parameter combination produces accurate VSM retrievals for four of the five days but underestimates VSM on June 27. Similar to the results shown for corn in Fig. 13, the valid range of surface roughness narrows with increasing soil moisture, in this case by a factor of at least 3 from dry to wet conditions. Due to the fairly small sensitivity to the B parameter, the ranges are quite wide and the lower and upper bounds exceed the limits used in the retrievals on many days, so the true ranges are difficult to define. For V-pol (not shown), valid parameter ranges are in general quite large due to the lower sensitivities compared to H-pol.

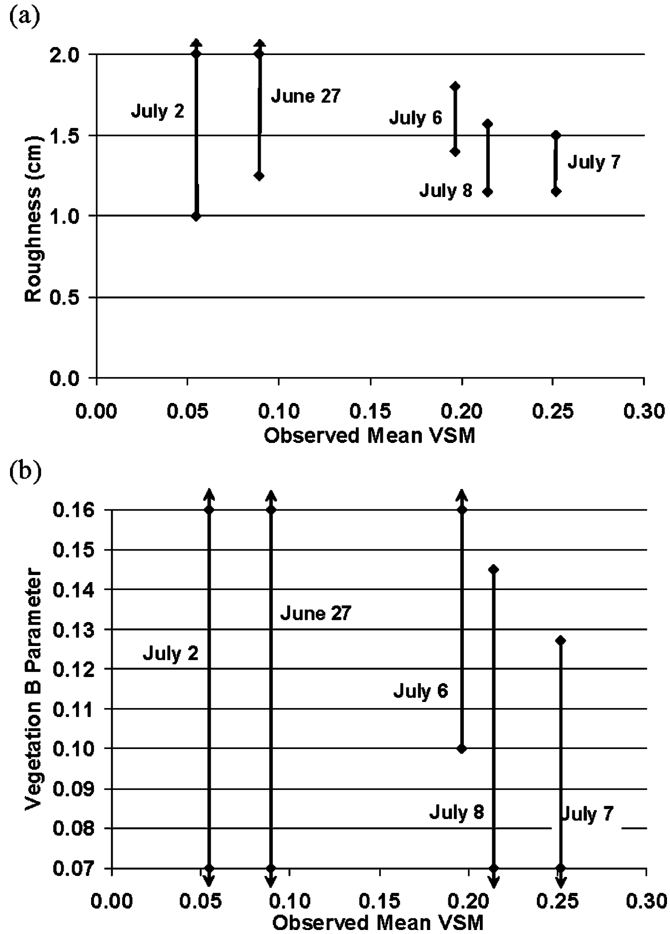

Fig. 18. Valid ranges of (a) roughness and (b) B parameter as functions of VSM for soybeans at H-pol.

C. Mixed Crop

In order to help understand the performance and sensitivities of a soil moisture retrieval algorithm using microwave remote sensing data in an agricultural setting such as central Iowa in which sensor footprints typically contain mixtures of various land cover elements, we have applied the algorithm based on linear combinations of corn and soybean inputs. This represents an idealized corn–soybean landscape that is not too unlike the SMEX02 study area. Here, we have assumed the surface to be covered with 56% corn and 44% soybeans, based on the landcover classification within the PALS region, neglecting the areas of other classes. This weighting was applied to brightness and soil temperatures and vegetation water contents and the resulting "mixed crop" values were used as input to the retrieval model. Observed soil moistures for corn and soybean sites were also weighted to produce the VSM against which the retrievals were compared. Retrieved VSM values for the mixed crop case, for a given input parameter vector, are quite similar to retrievals for corn, even more so than expected given the 56% weighting applied to corn. Thus, the valid parameter regions for mixed crop conditions are very similar to those for corn. Also, sensitivities of retrieved VSM to model parameters were very consistent with the corn results. This appears to be the result of the generally higher parameter sensitivities for corn dominating the retrieval process.

IV. Summary and Conclusion

Using aircraft-based microwave brightness temperature measurements as well as observations of vegetation water content and surface and deep soil temperatures for a mixed agricultural region in Iowa, we applied a standard single-frequency, single-polarization soil moisture retrieval algorithm in order to test the model's sensitivities to variations in model parameters. By doing so, inferences are made about the model's accuracies when applied for the two dominant crop types (corn and soybean) within the study area. Possible limitations of model application, based on moisture and land cover conditions, are also inferred.

For corn conditions using horizontally polarized brightness temperatures, examination of the valid three-dimensional parameter space (combinations of surface roughness, vegetation B parameter and single-scattering albedo) showed reasonable day-to-day consistency. That is, there are certain parameter vectors that produce soil moisture retrievals within a prescribed tolerance (± 0.04 VSM) of the observed values on all five days analyzed. For soybeans, the valid parameter region corresponds to lower roughness or B parameter values on the wet days, but there is a small overlap of the regions for all days. At V-pol, there was no intersection of the valid parameter spaces among the five days for corn, but for soybeans the valid parameter regions were large with considerable intersection between days. The better day-to-day consistency for soybeans is related to the significantly lower retrieval sensitivity to the vegetation B parameter.

Model sensitivity to the three input parameters was found to be much greater when soil moisture is high. The soil surface emissivity is quite high for dry soil and the effects of surface roughness and vegetation on brightness temperature are much smaller than for wet soil. For even moderately wet soils, extremely high sensitivity of retrieved VSM was observed to both B and σ for corn and to σ for soybeans. On first inspection it may appear that excellent soil moisture estimation can be achieved across a wide range of moisture conditions using the best fit parameter vector. However, parameter sensitivity causes the retrievals to be unstable. This can be quantified by examination of the parameter space representations for each crop. As an example, consider corn retrievals at H-pol with $\omega = 0.03$, $\mathrm{B} = 0.13$, and $\sigma = 1.0$ cm ($\mathrm{h} = 0.34$) as the best fit parameters. Because any of these estimates is subject to uncertainty, assume that the estimate of B is in error by 20%. This is equivalent to a 20% error in vegetation water content since the two are multiplied as part of the vegetation correction; note that vegetation water content for corn and soybeans increased by 20% every 3–4 days during SMEX02. For the driest day, July 2, the VSM estimate with the best fit parameters is 0.059, with a range associated with a 20% error in B of 0.040–0.084. These limits are within the tolerance of ± 0.04 VSM with respect to the best fit estimate. However, for the wettest day, July 7, the best estimate of VSM is 0.290 with an error range of 0.178–0.520. Clearly, the uncertainty in this case well exceeds the ± 0.04 VSM tolerance. Similar errors in VSM result from uncertainties in surface roughness for corn and in the B parameter for soybeans.

Although the analyses presented here are not meant to provide exact estimates of model parameters, they can be used to approximate the accuracies required in estimating these parameters in order to reliably estimate soil moisture using similar single-frequency models in mixed agricultural areas like the one used in this study. The required accuracies certainly depend on moisture conditions; in order to ensure that retrieval algorithm specifications (± 0.04 VSM tolerance) are consistently met, we use high moisture conditions to define parameter accuracy requirements. Based on L-band H-pol moisture retrievals, we can approximate these requirements for corn crops as a percentage of the true values: $\pm 15\%$ to 20% for surface roughness, $\pm 10\%$ to 15% for the vegetation B parameter (or vegetation water content) and ± 0.01 for single-scattering albedo. The tolerance on $T_{\rm BH}$ is approximately ± 4 K. For soybeans at H-pol, the accuracy requirements for surface roughness and vegetation B parameter are about $\pm 10\%$ to 15% and 25% to 30%, respectively, while retrievals are quite insensitive to single-scattering albedo. The tolerance for $T_{\rm BH}$ for soybeans is approximately ± 8 K. For a remote sensing footprint consisting of a mixed crop, accuracy requirements would be between the corn and soybean values given.

At V-pol, the parameter tolerances are somewhat less well defined by this analysis, but our best estimates for corn are $\pm 10\%$ to 20% for surface roughness and B and ± 0.005 for single-scattering albedo. For soybeans at V-pol the tolerance for roughness and B are approximately 50%; sensitivity to single-scattering albedo is very low and thus the tolerance is large. Tolerances on $T_{\rm BV}$ for corn and soybeans are approximately ± 3 K and ± 6 K, respectively.

This analysis may shed light on the potential accuracies of dual-polarization algorithms because they involve independent application of radiative transfer model calculations at each polarization. Based on the results shown in the parameter space figures, one can infer how well a dual-polarization algorithm, based on the same physics and parameterizations, might have worked in our study. For example, in a dual-polarization approach, one parameter, say roughness, would be assumed known and the algorithm would determine the combination of VSM and B-parameter (or vegetation water content) that minimized the difference between RTM-estimated and observed brightness temperatures. A comparison of Fig. 5 (H-pol) and Fig. 6 (V-pol) for July 2 or June 27 shows that the VSM obtained through such an algorithm would be a compromise between the lower values estimated at H-pol and the higher values at V-pol. Accuracy in this case may be low; this is graphically depicted by the fundamentally different parameter space regions at H-pol and V-pol for a given day.

Given the spatial variability of vegetation and soil conditions and the temporal changes in vegetation density, it seems unlikely that, for agricultural conditions like the ones used here, the accuracy requirements for model parameters in the single-frequency, single-polarization retrieval algorithm used in this analysis can be met with any current satellite-based land surface products, such as vegetation indices from the Moderate Resolution Imaging Spectroradiometer, available at eight-day intervals. This supports the conclusions of [7] that a single-channel algorithm failed to provide robust soil moisture estimates for wheat and soybean crops due to sensitivity to model parameters. In that study, better results were obtained using multiple frequencies or look angles. Based on our study, we conclude that for regions with substantial vegetation, particularly where the vegetation is changing rapidly, any soil moisture retrieval algorithm that is based on the physics and parameterizations used in this study will require multiple frequencies, polarizations, or look angles to produce stable, reliable soil moisture estimates.

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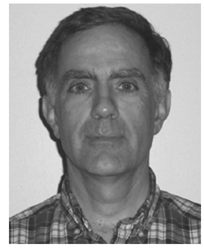

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