Performance Evaluation of Single and Multichannel Microwave Radiometers for Soil Moisture Retrieval

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*T*he performance of single-channel, two-channel, and six-channel microwave radiometers is evaluated for the retrieval of soil moisture using parameterized numerical simulations. Commonly used frequencies of 1.4 GHz, 2.7 GHz, and 6.6 GHz at vertical and/or horizontal linear polarizations are considered. The best single-channel retrieval uses 1.4 GHz at vertical polarization (1.4 V). This channel is least sensitive to variable surface roughness and vegetation canopy, but all single-channel sensors, including 1.4 V, are degraded without some level of a priori information about these masking variables. The sensitivity to surface roughness is reduced significantly at 2.7 GHz and 6.6 GHz by increasing the angle of incidence beyond 25°. The best two-channel case uses 1.4 V and 2.7 H to simultaneously retrieve both soil moisture and surface roughness. This improves the soil moisture retrieval and eliminates the need for a priori information about surface roughness. The sensitivity to variations in vegetation canopy is also acceptably small. Simultaneous use of all six channels to retrieve soil moisture, surface roughness, and vegetation canopy provides only marginal improvement over the best two-channel performance. The small amount of additional information contained in the other four channels is largely masked by typical levels of measurement noise. ©Elsevier Science Inc., 2001

INTRODUCTION

Soil moisture is of major importance to the hydrological cycle. It is one of the few directly observable hydrological variables that play an important part in agricultural scheduling and water resource management (Jackson, 1993). Recent studies have shown the effects of soil moisture on the dynamics of the atmospheric boundary layer and hence on weather and climate. Such studies have also shown the influence of soil moisture on the feedback between land surface and atmospheric processes that lead to climate anomalies (Shukla and Mintz, 1982; Delworth and Manabe, 1989). The improved characterization of surface soil moisture, vegetation, and temperature in numerical weather prediction models can also lead to significant forecast improvements (Beljaars et al., 1996). For these reasons, the lack of a global hydrologic land surface-observing capability has been recognized as a limitation on improved climate forecasting and monitoring. Soil moisture has become a key measurement priority (Martin and Manu, 1999).

Passive microwave remote sensing has long been recognized as a viable alternative to ground truth measurements of soil moisture (Schmugge, 1978; Njoku, 1996). Ground- and aircraft-based microwave radiometers have been used in numerous field experiments to validate the approach and quantify its performance (e.g., Jackson, 1993; Wang and Choudhury, 1995; Jackson et al., 1999). Previous attempts to retrieve soil moisture from space-borne radiometer measurements have had limited success due to the use of frequencies at 6.6 GHz or above (Neale et al., 1990; van de Griend and Owe, 1994). Lower microwave frequencies are better suited to soil moisture retrieval, and there are now several space-borne mission designs being conducted that use them (Le Vine et al., 1989; Martin-Neira et al., 1994; Njoku et al., 1999). The two most commonly considered lower frequency options are 1.4 GHz and 2.7 GHz. Adequate spatial resolution from orbit at 1.4 GHz or 2.7 GHz would require much larger antenna apertures than have been flown in the past. One compromise that has re-

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sulted is a move at these frequencies away from traditional imagers that have a constant incidence angle across their field of view, the rationale being that the benefits of finer spatial resolution outweigh the additional interpretative complexity of a varying incidence angle. Current imaging geometries include that of ESTAR, a cross-track scanner with incidence angle varying from nadir to 45° (Le Vine et al., 1994), and that of MIRAS, an offset imager with most of the field of view lying between incidence angles of 20 and 35° (Camps et al., 1997). For this reason, the majority of simulations evaluated in this study, and especially those at the lower frequencies, assume an incidence angle of 25°, which is typical of MIRAS and is at roughly the midpoint in the ESTAR swath. Special attention at 6.6 GHz is paid to behavior at higher angles of incidence to be consistent with other previous and upcoming space-based radiometers at that frequency.

One central instrument design issue that is addressed in this study is the optimum choice of frequency or frequencies. The number of frequencies used is often dictated by size, weight, power, and, ultimately, cost constraints on a flight mission. We examine what is the best single-channel choice of frequency and polarization for soil moisture retrieval. We next address the effect on performance of adding a second channel and examine which is the best two-channel combination. Finally, we make the case that additional channels beyond the best two quickly reach a point of diminishing returns, where more channels do not result in significantly improved performance.

The emission of thermal microwave radiation from soils is strongly dependent on the soil moisture content. The difference between the dielectric constant of water and that of dry soil is very large. As a result, the emissivity of soils varies over a wide range from approximately 0.6 for wet soils to greater than 0.9 for dry soils. For a soil at a temperature of 285 K, this variation in emissivity corresponds to a soil brightness temperature variation of 90 K, covering a range of wetness from approximately 40% to 5% moisture by volume. This variation in the brightness signal is very much larger than the noise sensitivity threshold of a microwave radiometer, which is typically less than 1 K. The large available signal-to-noise ratio is a major advantage of the passive microwave technique for soil moisture remote sensing.

The above discussion suggests that by consideration of radiometer sensitivity alone, and for a bare soil, moisture estimation accuracy of better than 1% to 2% by volume should in principle be feasible. Such accuracy is difficult to achieve in practice. The soil brightness temperature is also affected by soil surface roughness (Choudhury et al., 1979), attenuation and emission by vegetation cover (Jackson et al., 1982; Ulaby et al., 1983), and, to a lesser degree, by soil texture and variability in the temperature of the soil and vegetation (Schmugge, 1980). These perturbing factors introduce varying amounts of uncertainty into the relationship between brightness tem-

perature and soil moisture, which in turn limits the accuracy with which soil moisture can be estimated. However, toward the longer-wavelength region of the microwave spectrum (wavelength>~10 cm) the effects of vegetation and roughness are greatly reduced. At these wavelengths and in areas of low to moderate vegetation, soil moisture has a dominant effect on the brightness temperature (Wang and Choudhury, 1995). For soil moisture sensing, 1.4 GHz (wavelength=21 cm) is considered most suitable, because it reduces atmospheric attenuation and allows greater vegetation penetration (Meeks, 1976).

In practice the dependence of brightness temperature on factors other than soil moisture (surface roughness, vegetation, etc.) limits the accuracy with which any single-channel radiometer can retrieve soil moisture. One solution, using a single channel, is to provide *a priori* information about the other variables. The accuracy required of this information to obtain satisfactory results becomes an important consideration. A second solution is to use multiple frequency and/or polarization channels to aid in the retrieval. This helps because vegetation and roughness have different spectral and polarization effects on the soil brightness compared with soil moisture. Using multifrequency and multipolarization channels, one can retrieve parameters other than soil moisture (surface roughness and/or vegetation water content), which gives better estimated soil moisture with less ancillary information.

This work addresses the question of which single-channel radiometer gives the most accurate soil moisture retrieval and how its performance is affected by the masking effects of variable surface roughness and vegetation canopy. It then considers how much the accuracy of the retrieval of soil moisture can be improved by using six channels and simultaneously retrieving other variables besides soil moisture. It next considers which is the best two-channel combination and which variable should be retrieved other than soil moisture.

FORWARD MODEL: T_B FROM SURFACE CONDITIONS

The forward model that relates Brightness Temperature (T_B) to the surface conditions is used in this study both to simulate measurements and as the kernel of a physically based retrieval algorithm. As such, the accuracy of the model is not included as a component of the error in the retrieval algorithm. The model is derived from previous work by numerous investigators. An overview description of the model is given here. The reader is referred to the citations for more complete descriptions.

Dielectric Properties and Smooth Surface Model

The dielectric constant of a soil-water mixture has been studied by numerous investigators (e.g., Njoku and Kong, 1977; Schmugge, 1978; Wang and Schmugge, 1980). The high dielectric constant of water significantly increases

both the real and imaginary parts of the soil as the volume fraction of water in the soil increases. The dependence on soil type (or "texture") is due to the different percentage of water bound to the particle surfaces in the different soils.

There are three principal soil types in nature: sand, silt, and clay. Individual polynomial expressions have been generated for the real (ε') and imaginary (ε'') parts of the dielectric constant as a function of volumetric water content (m_v) for each frequency and soil type (Hallikanen et al., 1985). At each frequency, the individual polynomials can then be combined into a single polynomial of the form [see Eq. (1)]:

$$\varepsilon = (a_0 + a_1 S + a_2 C) + (b_0 + b_1 S + b_2 C)m_v$$
$$+ (c_0 + c_1 S + c_2 C)m_v^2 \tag{1}$$

where ε is either the real or imaginary part of the dielectric constant, S and C are the percentages of sand and clay components of the soil by weight, and a_i, b_i, and c_i are regression coefficients, which vary with frequency and differ for ε' and ε''.

For a smooth soil surface of uniform dielectric constant, the expressions for reflectivity at vertical and horizontal polarization may be derived from electromagnetic theory using the laws of Fresnel and Snell. Kirchoff's reciprocity theorem is then used to relate the reflectivity to the emissivity (Ulaby et al., 1981). The T_B follows as the product of emissivity and surface physical temperature.

Rough Surface Correction

In general, the soil surface may not be smooth. The roughness of the surface is characterized by the height standard deviation (SD), σ. The expressions for reflectivity must be modified for rough surfaces. A simple, semiempirical expression for rough surface reflectivity has been proposed by Wang and Choudhury (1995) as [see Eqs. (2) and (3)]

$$R_H = [(1-Q)r_H + Qr_V]\exp(h') \tag{2}$$

$$R_V = [(1-Q)r_V + Qr_H]\exp(h') \tag{3}$$

where the subscripts H and V denote the horizontal and vertical polarization, respectively; lower case r represents the smooth surface reflectivities, and h' is a height parameter that is related to the height SD, σ, according to Eq. (4):

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

where λ is microwave wavelength, θ is incidence angle, and Q is a polarization mixing parameter given by Eq. (5):

$$Q = 0.35[1 - \exp(-0.6\sigma^2 f)] \tag{5}$$

where f is the operating frequency in units of MHz. The units of σ in Eq. (5) are cm. According to these expressions, surface roughness decreases the reflectivity and increases T_B. In general, the practical range of roughness is from 0.2 cm to 2 cm. At low roughness, H and V polarization is still well defined and their corresponding T_Bs differ. At high roughness, the polarization has little effect because of the randomized orientation of the local plane of incidence at the surface. It should be noted that (2)–(4) account for roughness effects on reflectivity in a somewhat simplified manner in which explicit account is not taken of the horizontal correlation length of the surface. This simplification was recognized by Choudhury *et al.* (1979) with the understanding that the height standard deviation, σ, be considered an *effective* value, consistent with the actual reflectivity, and not the actual height standard deviation of the surface. Using this interpretation, the results presented below with regard to σ should all be considered effective height standard deviations. The fact that large variations in the actual horizontal correlation length of the surface can alter the frequency dependence of the roughness effect on reflectivity from that assumed by (2)–(4) needs to be noted as a caveat to our results.

Vegetation Canopy Correction

Vegetation absorbs, emits, and scatters microwave radiation. At low microwave frequencies, the vegetation can be modeled as a single homogeneous layer above the soil, and the effects of scattering at the air-vegetation interface and within the volume of the vegetation are small and can be neglected. The T_B of a two-layer soil-vegetation medium can then be written as seen in Eq. (6) (Jackson and Schmugge, 1991):

$$T_B = e_p T_e \exp(-\tau) + T_c(1-\omega)[1-\exp(-\tau)][1 + r_p\exp(-\tau)] \tag{6}$$

where T_e is the soil effective temperature, T_c is the vegetation canopy temperature, τ is the opacity of the vegetation canopy, e_p and r_p are the emissivity and reflectivity of the soil surface at polarization p, and ω is the single scattering albedo of the vegetation, which is assumed to be 0.05 for the remainder of this study (Jackson and Schmugge, 1991). One key parameter in Eq. (6) is the vegetation opacity, τ. For sufficiently small values of τ (low vegetation density and/or water content), Eq. (6) reduces to $T_B \sim e_p T_e$ (i.e., the observed brightness above the canopy is negligibly affected by the canopy). For very large τ (dense vegetation) the observed T_B approaches T_c (i.e., the canopy appears as a blackbody and completely masks the underlying soil emission). It should be noted that there is also an additional component of opacity due to the intervening atmosphere between the sensor and the surface. At the low microwave frequencies under consideration here, this component is quite small under most atmospheric conditions. While an operational soil moisture retrieval algorithm would generally correct for

the atmosphere, we ignore the effect here because it will have a negligible influence on the issue of how many and which channels are needed to correct for the masking effects of surface roughness and vegetation canopy.

The magnitude of τ depends on the type of vegetation, its water content, and the wavelength. A simplified expression for τ suggested in Jackson and Schmugge (1991) describes this relationship as [see Eq. (7)]:

$$\tau = b \cdot W \qquad (7)$$

where W is the water content of the vegetation and b is an empirically determined value. The parameter b varies with wavelength and type of vegetation. According to Jackson and Schmugge (1991), b is found to be only weakly dependent on vegetation type at the frequencies under consideration here (especially at 6.6 GHz). In our work here, we use the values $b = 0.12$ at 1.4 GHz, 0.16 at 2.7 GHz, and 0.28 at 6.6 GHz, which are average values extracted from Table 1 of Jackson and Schmugge (1991). The simulations presented below consider vegetated cases with water content ranging from $W = 0$ (clear, vegetation free) to $W = 1.5$ kg/m². We limit the upper bound on W to 1.5 kg/m² for two reasons. First, the primary intent of this study is a comparison between soil moisture retrievals based on 1.4 GHz, 2.7 GHz, and/or 6.6 GHz radiometers. Since performance at 6.6 GHz is found to be severely degraded by vegetation near or in excess of 1.5 kg/m², this upper bound is sufficient to highlight one of the principle advantages of the lower frequencies. Second, while the vegetation water content can significantly exceed our upper bound, as demonstrated by numerous field campaigns (Jackson and Schmugge, 1991), our upper bound can be considered a typical level in many agricultural and natural settings and has been used in previous studies to assess performance with a typical vegetation canopy (Njoku et al., 1999). It should be noted that sensors using the lower frequencies still retain the ability to retrieve soil moisture at significantly higher values of W.

METHODOLOGY OF SOIL MOISTURE RETRIEVAL SIMULATION

The method of soil moisture retrieval uses an iterative least-squares minimization algorithm based on the forward model developed above to invert the measured T_B and estimate the unknown variable(s). The choice of which T_B channels to measure and which variable or variables to estimate is influenced by the sensitivities of each channel to each variable and by the variations in sensitivity between channels. We first characterize these relations by generating sensitivity curves based on the forward model to evaluate the type of information contained in each channel. This helps to guide the choice of possible channel combinations. A more rigorous retrieval performance analysis then follows for the most promising channel combinations.

Possible radiometer channels under consideration include 1.4-GHz H and V polarization, 2.7-GHz H and V, and 6.6-GHz H and V. The 1.4-GHz choice uses a protected frequency band allocated to radio astronomy (and other passive uses) and has been used most widely by the ground-based research community. A 2.7-GHz channel is considered for historical reasons (many ground and aircraft experiments have been conducted in this channel) and because of its dual-use capacity to retrieve sea surface salinity (Njoku et al., 1999). Past (SMMR), present (TMI), and upcoming (AMSR) instruments include a channel at or near 6.6 GHz, and thus this channel is considered a bridge between current capabilities and future dedicated soil moisture missions at the lowest frequencies. Retrievals will be considered that estimate either soil moisture (sm) alone, or sm plus one or both of RMS surface roughness (soilrms) and vegetation canopy water content (wcanopy).

Nonlinear Iterative Retrieval Algorithm

Because the relationship between T_B and soil moisture, and surface roughness and vegetation water content, is nonlinear, an iterative least-squares method is used to invert the measurements. Assume that a vector of brightness temperatures, $\vec{T}_B$ (with elements at different frequencies and/or polarizations) is described by a nonlinear forward model, $Q(\vec{x})$, where $\vec{x}$ are the parameters soil moisture, roughness, and vegetation canopy. Given measurements $\vec{T}_B$ and a model $Q(\vec{x})$, solve for $\vec{x}$, which minimizes $\|\vec{T}_B - \hat{\vec{T}}_B\|^2$, where $\hat{\vec{T}}_B = Q(\vec{x})$ is the estimate of $\vec{T}_B$.

The solution, $\vec{x}$, is found iteratively. A first guess is made for $\vec{x}$, called $\vec{x}_0$. The first guess can be either an average value for the surface parameters, if no *a priori* information is available, or an estimate based on other information (e.g., historical records of surface roughness or vegetation estimates from other sensors). A second guess for $\vec{x}$ is then computed as seen in Eq. (8):

$$\vec{x}_{k+1} = \vec{x}_k + (J_k^T J_k)^{-1} J_k^T [\vec{T}_B - Q(\vec{x}_k)] \qquad (8)$$

where $k = 1$, J_k is the Jacobian matrix for Q evaluated at $\vec{x}_k$, and the superscript T denotes matrix transposition. The ijth element of J_k is given by Eq. (9):

$$[J_k]_{ij} = \frac{\partial Q_i}{\partial x_j} \Big|_{\vec{x}_k} \qquad (9)$$

In practice the partial derivatives in (9) are estimated numerically by perturbing x_j a very small amount and noting the corresponding change in Q_i. Estimates of $\vec{x}$ are iteratively refined by incrementing k in Eq. (8) until either the RMS difference between the measured and estimated values of T_B is sufficiently small or the change in $\vec{x}$ between iterations is suitably small. In practice, both of these convergence criteria tend to happen within 3 to

10 iterations, depending on the surface parameters and the closeness of the first guess to the truth.

Noise Multiplication Factor

One useful measure of a channel's ability to estimate soil moisture is the sensitivity of the retrieval algorithm to noise in the measurements. For single-channel algorithms, the noise sensitivity is simply the inverse of the partial derivatives, $\partial T_B/\partial sm$. For retrieval algorithms using multiple channels, the noise sensitivity is a more complicated function of both these partials, the partials with respect to the masking surface parameters, and the variations in the partials between channels. Formally, assume that the measurements, $\vec{T}_B$, are contaminated by independent, identically distributed, additive Gaussian noise with SD, ΔT. The presence of such additive noise is an unavoidable consequence of the fact that brightness temperature is proportional to the variance of microwave thermal emission and the variance statistic is estimated from a finite number of samples. Typical levels of ΔT are 0.5–1.0 K. The covariance of the measurement vector then is diagonal, with main diagonal elements ΔT^2, and the covariance of the estimated surface parameter vector will be [see Eq. (10)]:

$$\Gamma_x = [(J^TJ)^{-1}J^T][(J^TJ)^{-1}J^T]^T\Delta T^2 \qquad (10)$$

where J is the Jacobian described by Eq. (9). The covariance of the estimate thus scales linearly with the variance of the measurements. The square root of the main diagonal of Γx represents the SD of the error in each of the retrieved surface parameters due to measurement noise. Assuming that the first element of the surface parameter vector, $\vec{x}$, is the soil moisture, and setting $A=[(J^TJ)^{-1}J^T][(J^TJ)^{-1}J^T]^T$, we define the Noise Multiplication Factor as $NMF=A_{11}^{1/2}$. NMF represents the sensitivity of the soil moisture retrieved by a given combination of channels to measurement noise.

Figures 1a to 1c show NMF plots for all single-channel retrievals of soil moisture vs. soil moisture, surface roughness, and vegetation water content, respectively. In all cases, the incidence angle is 25° and the surface temperature is 285 K. In Fig. 1a, for smooth bare soil, the NMF is very stable over the full range of soil moistures. In Fig. 1b, for bare soil at a moderate level of soil moisture, the NMF at low surface roughness is very low. But high surface roughness has a significant detrimental effect on NMF, especially at the highest frequency. High surface roughness severely limits the inversion method at 6.6 GHz. Figure 1c suggests that the presence of a vegetation canopy won't drastically affect the noise in the inversion for the lower (1.4 GHz and 2.7 GHz) channels. However, the detrimental effects of increasing vegetation are significantly larger at 6.6 GHz.
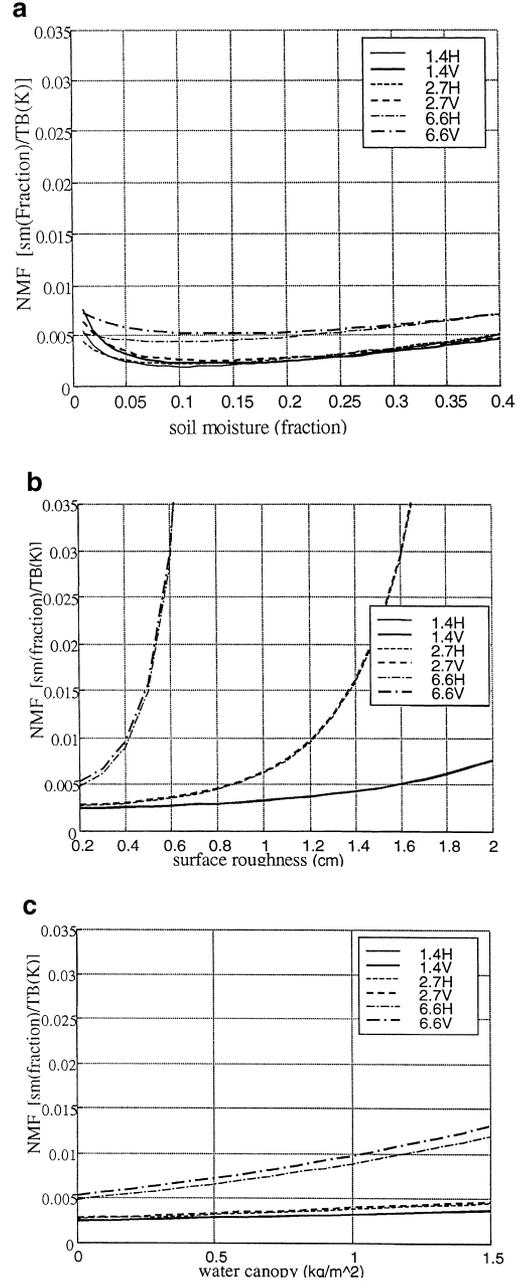
Figure 1. Noise Multiplication Factor (NMF) for all single-channel retrievals of soil moisture vs. (a) soil moisture, (b) surface roughness, and (c) vegetation water canopy. Incidence angle is 25° and surface temperature is 285 K. Soil moisture is 20% in (b) and (c), surface roughness is 0.2 cm in (a) and (c), and vegetation water canopy is 0 kg/m² (bare soil) in (a) and (b).

RESULTS

Single-Channel Retrieval

To assess the accuracy of soil moisture retrievals, we use a Monte Carlo simulation. Artificial measurements of T_B

Table 1. Simulation Type 1 at 1.4&2.7 GHz/V&H-pol

σ_{TB} (K)	σ_{Tsurf} (K)	$F\sigma_{rms}$ (fraction)	$F\sigma_{wcan}$ (fraction)	$F\sigma_{sand}$ (fraction)	$F\sigma_{clay}$ (fraction)	RMS error in Soil Moisture (fraction)			
						1.4H	1.4V	2.7H	2.7V
0	0	0	0	0	0	1.00E-06	2.50E-06	3.00E-06	2.50E-06
1	3	0.1	0.1	0.2	0.2	0.037	0.035	0.1	0.1
1	3	0.2	0.2	0.2	0.2	0.052	0.053	0.125	0.12

are generated from a "true" value of the surface parameters: sm, soilrms, and wcanopy. The parameters are then estimated by nonlinear iterative inversion. Simulations are performed under the following conditions: the incidence angle is 25° and the surface temperature is 285 K. Zero mean Gaussian noise is added to the T_B values to simulate radiometer measurement errors. The assumed surface temperature also has a zero mean, additive Gaussian error with SD of 3 K. The error in assumed fractions of sand and clay has a Gaussian error with SD equal to 20%. There are also additive Gaussian errors associated with the soil moisture, surface roughness, and vegetation water content. The soil moisture "noise" is a perturbation of its true value and is used as the first guess for the iterative retrieval. When surface roughness and water content are retrieved as well, the surface roughness noise and water content noise are also first guess errors. When not retrieved, these perturbations of the true value are their assumed values throughout the iterative process. For example, if only soil moisture and water content are retrieved, the noises for soil moisture and water content are first guess errors and the surface roughness noise is the assumed value, which never changes during the iterative retrieval.

There are two kinds of simulations conducted. For simulations of Type 1, the three true values (soil moisture, surface roughness, and vegetation water content) are all varied simultaneously selected from a uniform distribution over typical ranges of 0.01–0.40 (i.e., 1–40% by volume) for soil moisture, 0.2–2.0 cm for roughness, and

0–1.5 kg/m² for water content, and the true soil type is 25% sand and 25% clay. Simulations of Type 2 are similar except that one of the true values (soil moisture, surface roughness, or water content) is not uniformly distributed for every realization, but rather is a fixed value. What that fixed value is can then be varied to assess the dependence of the retrieval performance on that variable. Type 1 simulations produce overall performance estimates for soil moisture retrieval, whereas Type 2 simulations highlight the behavior of the retrieval as a function of the three surface parameters.

Using Either 1.4-GHz H- or V-pol
Table 1 shows the results of Type 1 simulations at 1.4-GHz H and 1.4-GHz V. In the table, σ_{TB} is the SD of additive Gaussian noise on the measured T_B and σ_{Tsurf} is the SD of Gaussian noise on the assumed soil surface temperature. The error in surface roughness is Gaussian with SD equal to $F\sigma_{rms}$ multiplied by the true value of the surface roughness. The error in vegetation water content is Gaussian with SD equal to $F\sigma_{wcan}$ multiplied by the true value of water content. These multiplicative scale factors for roughness and water content produce additive uncertainties that are percentages of the true values. The error in sand percentage is Gaussian with SD equal to $F\sigma_{sand}$. The error in clay percentage is Gaussian with SD equal to $F\sigma_{clay}$. In all cases, the first guess at soil moisture is 0.20 (i.e., the middle of the range of values).

From the first rows of Tables 1 we find that with no noise or first guess errors in knowledge of the other

Table 2. Simulation Type 1 at 6.6 GHz H-pol

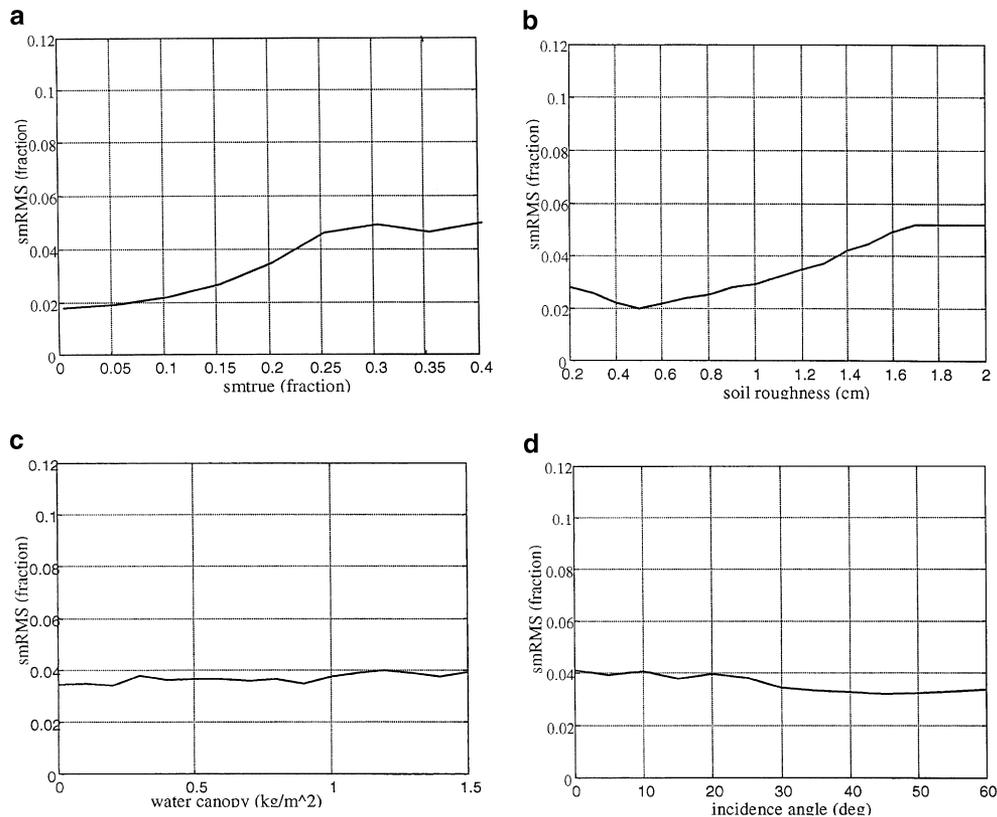| σ_{TB} (K)	σ_{Tsurf} (K)	$F\sigma_{rms}$ fraction	$F\sigma_{wcan}$ fraction	$F\sigma_{sand}$ fraction	$F\sigma_{clay}$ fraction	smRMS fraction
0	0	0	0	0	0	0.013
1	3	0.1	0.1	0.2	0.2	0.195
0	3	0.1	0.1	0.2	0.2	0.195
1	0	0.1	0.1	0.2	0.2	0.19
1	3	0	0.1	0.2	0.2	0.192
1	3	0.1	0	0.2	0.2	0.192
1	3	0.1	0.1	0	0	0.195
1	0	0.1	0.1	0.2	0.2	0.195
1	0	0	0	0	0	0.185
0	0	0.1	0	0	0	0.135
0	0	0	0.1	0	0	0.175

Figure 2. Single-channel 1.4-GHz H-pol RMS error in soil moisture retrieval vs. (a) soil moisture, (b) surface roughness, (c) water canopy, and (d) incidence angle, assuming 285 K surface temperature, 25° incidence angle [for (a) to (c)], uniformly distributed values for soil moisture over 0.01–0.40 [for (b) to (d)], for surface roughness over 0.20–2.0 cm [for (a), (c), and (d)], and for water canopy over 0–1.5 kg/m² [for (a), (b), and (d)], 10% uncertainty in knowledge of surface roughness and water canopy, 1 K measurement noise, 3 K uncertainty in surface temperature, and 20% uncertainty in soil composition.

parameters, the soil moisture estimates are essentially perfect. This confirms the functionality of the retrieval method. For simulations with any level of noise or first guess error, the RMS error in the soil moisture retrieval, smRMS, should be less than the SD of the true soil moisture, which is uniformly distributed over 0.01–0.40 and so has an SD of 0.113.

The second and third rows of Table 1 suggest that the overall performance of the 1.4-GHz channel is good, even with some amount of noise and error in knowledge of the other parameters. The smRMS with 10% errors for surface roughness and water content is 0.035 and the smRMS with 20% errors for surface roughness and water content is 0.052. The relative performance of the two polarizations is roughly equivalent.

Figures 2a to 2d plot smRMS vs. soil moisture at 1.4-GHz H-pol using a Type 2 simulation. Knowledge of the roughness and water content are assumed to be accurate to 10%. Knowledge of the soil type is accurate to 20%. From Fig. 2a, the error in retrieved soil moisture

increases with increasing soil moisture. From Fig. 2b, smRMS reaches its smallest value when surface roughness is approximate 0.5 cm. At lower surface roughness, the smRMS is slightly higher; when surface roughness is above 0.5 cm, the smRMS increases with increasing surface roughness. The increases in smRMS at high roughness suggests that the absolute value of sensitivity of brightness temperature to soil moisture is smaller at high than at low surface roughness. Figure 2c plots smRMS vs. vegetation water content. The smRMS over the range of water content is very stable. This tells us that the effect of water content on smRMS is negligible. This result suggests that the sensitivity of T_B to soil moisture varies in a small range over the range of water content. Figure 2d plots smRMS vs. incidence angle over the range 0–60°. In this case, soil moisture, surface roughness, and water content are all uniformly distributed over their ranges of values. Here, the smRMS decreases with increasing incidence angle. This indicates that the sensitivity of brightness temperature to soil moisture increases

Table 3. Using 2 Channels to Solve for Soil Moisture and Surface Roughness

Channel	σ_{TB} (K)	σ_{Tsurf} (K)	$F\sigma_{rms}$ fraction	$F\sigma_{sand}$ fraction	$F\sigma_{clay}$ fraction	smRMS fraction	rmsRMS (cm)
1.4 H+1.4 V	1	3	0.1	0.2	0.2	0.048	0.27
1.4 H+2.7 H	1	3	0.1	0.2	0.2	0.045	0.22
1.4 H+2.7 V	1	3	0.1	0.2	0.2	0.045	0.25
1.4 V +2.7 H	1	3	0.1	0.2	0.2	0.043	0.19
1.4 V +2.7 V	1	3	0.1	0.2	0.2	0.043	0.22
1.4 H+6.6 H	1	3	0.1	0.2	0.2	0.073	0.54
1.4 H+6.6 V	1	3	0.1	0.2	0.2	0.077	0.56
1.4 V +6.6 H	1	3	0.1	0.2	0.2	0.066	0.57
1.4 V +6.6 V	1	3	0.1	0.2	0.2	0.066	0.57
2.7 H+6.6 V	1	3	0.1	0.2	0.2	0.13	0.65
2.7 H+6.6 H	1	3	0.1	0.2	0.2	0.14	0.66

with increasing incidence angle. However, the effect of the incidence angle on the soil moisture retrieval at 1.4 GHz is not that significant.

Using Either 2.7-GHz H- or V-pol

Table 1 also shows the results of Type 1 simulations at 2.7 H and 2.7 V. Conditions are similar to those in Tables 1 and 2 for the 1.4-GHz case. The first row of the table confirms the functionality of the retrieval method. The second and third rows of the table demonstrate a very significant degradation in performance at 2.7 GHz, relative to that at 1.4 GHz. If the surface roughness and vegetation water content values are known to 10% *a priori*, then the RMS error in soil moisture retrieval, at 0.10, is only slightly better than the variation in soil moisture itself (0.113). By contrast, the 1.4-GHz retrievals had RMS errors of 0.037 and 0.035 at H- and V-pol. With *a priori* knowledge of the surface parameters reduced to 20%, the performance at 2.7 GHz becomes worse yet. The 2.7-GHz channels are too sensitive to the secondary surface parameters, and adequate retrieval performance is only possible provided they are known *a priori* to significantly better than 10% of their true values. Examination of Type 2 simulations at 2.7 GHz vs. surface roughness and water content [not shown here but available in Zhang (1999)] indicates that the primary source of the additional error incurred at 2.7 GHz is inadequate knowledge of the surface roughness, not the water content.

Figure 3 shows the results of Type 2 simulations at 2.7 GHz vs. incidence angle. The dependence on incidence angle is very significant. At 25° (the value assumed in Table 1) the smRMS is similar to the SD of the true soil moisture, and thus little additional information is contained in the 2.7-GHz channel. At higher angles of incidence, the smRMS drops considerably, and 2.7 GHz becomes a much more valuable source of information. The variations in T_B at 2.7 GHz caused by changes in surface roughness are greatly reduced at higher angles of incidence. This reduces the need for accurate *a priori*

Figure 3. Single-channel 2.7-GHz (a) H-pol and (b) V-pol RMS error in soil moisture retrieval vs. incidence angle, assuming 285 K surface temperature, uniformly distributed values for soil moisture (0.01–0.40 cm), surface roughness (0.2–2.0 cm), and water canopy (0–1.5 kg/m²), 10% uncertainty in knowledge of surface roughness and water canopy, 1 K measurement noise, 3 K uncertainty in surface temperature, and 20% uncertainty in soil composition.
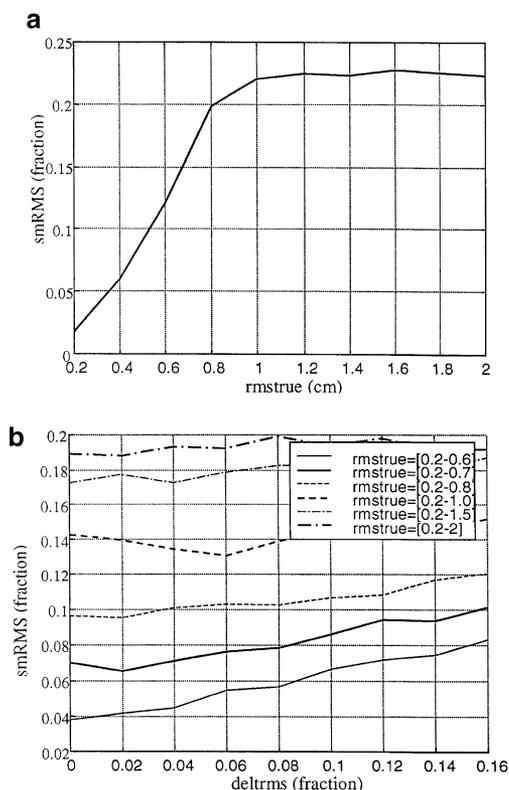
a

b

a

b
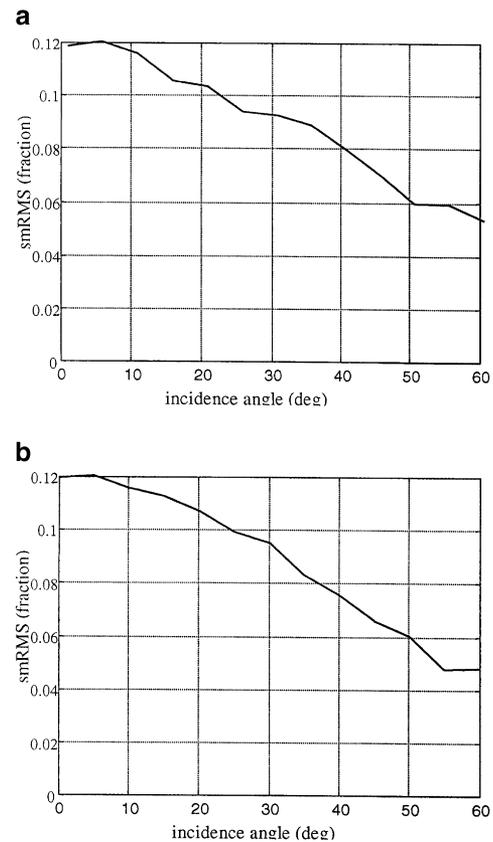
Figure 4. Single-channel 6.6-GHz, H-pol RMS error in soil moisture retrieval vs. (a) surface roughness and (b) *a priori* knowledge of surface roughness, assuming 285 K surface temperature, 25° incidence angle, perfect knowledge of no water canopy, uniformly distributed value for soil moisture over 0.01–0.40 cm, 1 K measurement noise, 3 K uncertainty in surface temperature, and 20% uncertainty in soil composition, 10% uncertainty in knowledge of surface roughness [(a) only], uniformly distributed value for surface roughness over 0.2 variable cm [(b) only].

a

b

Figure 5. Single-channel 6.6-GHz (a) H-pol and (b) V-pol RMS error in soil moisture retrieval vs. incidence angle, assuming 285 K surface temperature, perfect knowledge of no water canopy, uniformly distributed soil moisture (0.01–0.40 cm), uniformly distributed surface roughness (0.2–0.6 cm), 10% uncertainty in knowledge of surface roughness, 1 K measurement noise, 3 K uncertainty in surface temperature, and 20% uncertainty in soil composition.

information about the roughness. Note, also, that the difference in smRMS performance between polarizations (Fig. 3a vs. 3b) also becomes more significant at the higher incidence angles. V-pol is less sensitive to variations in roughness and thus is better able to retrieve soil moisture. A similar dependence on incidence angle and polarization was seen at 1.4 GHz, but to a much lesser degree because the 1.4-GHz channels are generally less sensitive to surface roughness in the first place.

Using Either 6.6-GHz H- or V-pol
Table 2 shows Type 1 simulation results at 6.6 H. The results at V-pol are similar. Clearly, the 6.6-GHz channel does not work well under conditions similar to those at 1.4 GHz and 2.7 GHz considered above, even if the noise and assumed errors are reduced considerably. Examination of Type 2 simulations vs. surface roughness
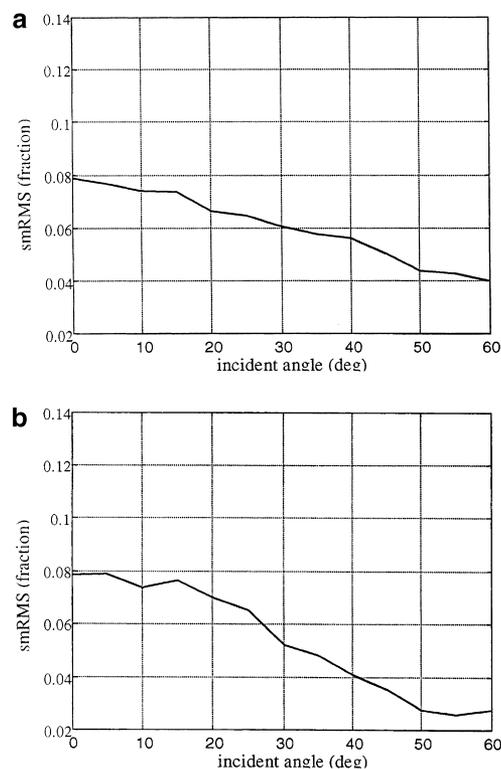
and water content indicate that the problem at 6.6 GHz arises principally from the surface roughness effect, as in the 2.7-GHz case but worse here, and from the presence of a vegetation canopy, which significantly obscures the underlying soil emission (Zhang, 1999). For this reason, all remaining simulation results considered here for the 6.6 GHz channel are without vegetation.

Figure 4a shows the results of Type 2 simulations at 6.6 H vs. surface roughness and assuming a 10% error in *a priori* knowledge of the roughness. There is a strong dependence on the magnitude of the roughness; surfaces much rougher than ~0.6cm cannot be accurately inverted for soil moisture. The dependence of the retrieval on the accuracy of the *a priori* knowledge of surface roughness is shown in Fig. 4b for a variety of ranges of possible surface roughness values. If the roughness is constrained to lie between 0.1 cm and 0.6 cm, then the smRMS is reduced considerably, as suggested by Fig. 4a. The accuracy of the *a priori* knowledge also has a strong influence on the quality of the retrieval. For example, a

reduction in *a priori* error from 10% to 2% reduces the smRMS from ~0.07 to ~0.04. High-quality information about the surface roughness is much more critical at 6.6 GHz. Note, however, that even with very high *a priori* knowledge of the roughness, the retrieval is still quite poor if surfaces much rougher than ~0.6 cm are included. Useful retrievals at 6.6 GHz, then, require both relatively smooth surfaces and little or no vegetation canopy. In addition, the retrieval algorithm must know with high accuracy that both of these conditions are satisfied.

Figure 5 shows the results of Type 2 simulations at 6.6 GHz vs. incidence angle. These results are for bare (no canopy) and smooth (roughness 0.2–0.6 cm) soils. The dependence on incidence angle is even more significant here than at the lower frequencies. The smRMS at 25° incidence angle is ~0.07 for both H- and V-pol. It drops at 55° to ~0.04 for H-pol and ~0.03 for V-pol. The improvement with incidence angle is due to the reduced sensitivity to variations in surface roughness, similar to the 2.7-GHz case. The improvement at V-pol, relative to H-pol, is also due to a reduced sensitivity to uncertainty in roughness.

Multiple-Channel Retrieval

If more than a single channel is used, there is the option of retrieving one or both of surface roughness and vegetation water content simultaneously with soil moisture. If additional parameters are retrieved in the following simulations, then the first guess at that parameter is set at its average value, just as the first guess at soil moisture is in all cases 0.20. For surface roughness values ranging over 0.2–2.0 cm, the first guess is 1.1 cm. The water content ranges over 0–1.5 kg/m^2 and its first guess is 0.75 kg/m^2. For other surface parameters that are not iteratively retrieved, they are set *a priori* to a fixed value.

Using All Six Channels and Retrieving All Three Surface Parameters

A Type 1 simulation was run using all six channels (1.4 V&H, 2.7 V&H, and 6.6 V&H) to simultaneously retrieve soil moisture, surface roughness, and water content. Other assumptions in the simulation were: 1 K independent measurement noise in each channel, 3 K uncertainty in surface temperature, 25° angle of incidence, 25% true sand and clay composition with 20% error in knowledge of the composition, and uniformly distributed variations in the three surface parameters. The resulting smRMS is 0.05. Type 2 simulations were run for this six-channel algorithm to evaluate the dependence of the estimates of each of the three surface parameters on soil moisture. The results are shown in Fig. 6. In Fig. 6a, the RMS error in retrieved soil moisture is seen to rise with soil moisture up to ~0.25 and then remain relatively constant. This behavior is similar to the earlier single frequency cases. In Fig. 6b, the RMS error in retrieved surface roughness is seen to decrease markedly with soil
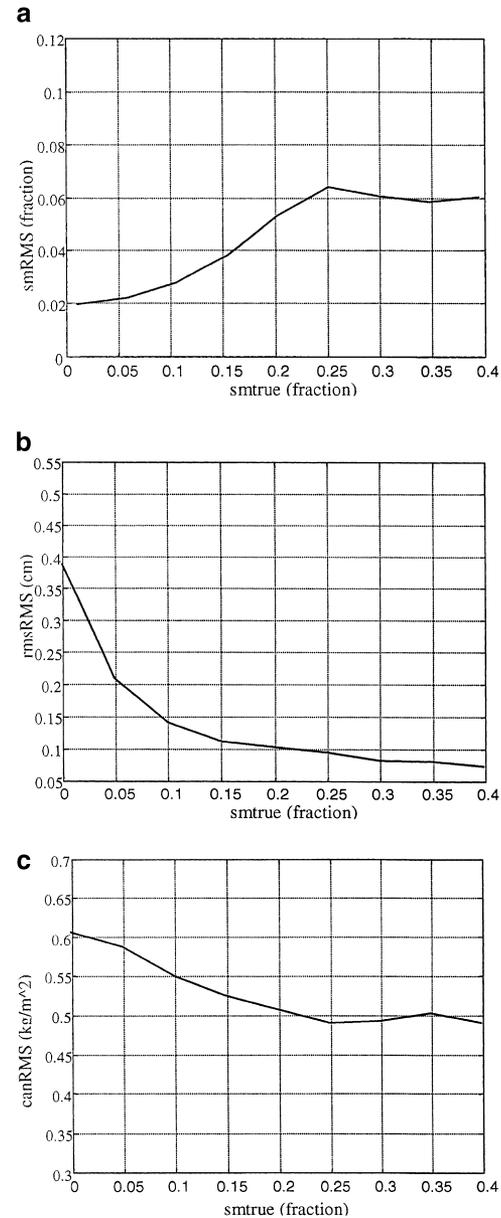

Figure 6. Six-channel (1.4 H&V, 2.7 H&V, and 6.6 H&V) RMS error in (a) soil moisture, (b) surface roughness, and (c) water canopy retrieval vs. soil moisture, assuming 25° incidence angle, 285 K surface temperature, 1 K measurement noise, 3 K uncertainty in surface temperature, 20% uncertainty in soil composition, uniformly distributed values for surface roughness (0.2–2.0 cm) and water canopy (0–1.5 kg/m^2), and no *a priori* information about either surface roughness or water canopy.

moisture, from a high of ~0.4 cm for very dry soils to ~0.1 cm for essentially saturated soils. The spectral signature of surface roughness under conditions of high soil moisture is very different from that of soil moisture or vegetation water content, and the inversion algorithm
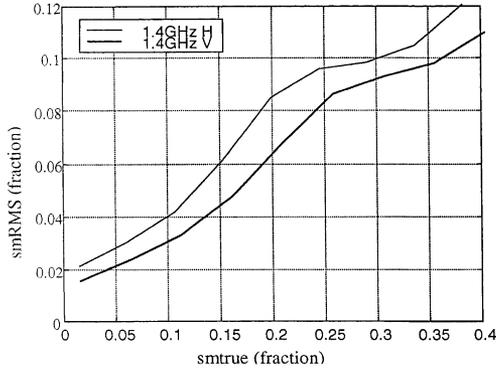
Figure 7. Single-channel (1.4 H- or V-pol) RMS error in soil moisture retrieval vs. soil moisture, assuming 25° incidence angle, 285 K surface temperature, 1 K measurement noise, 3 K uncertainty in surface temperature, 20% uncertainty in soil composition, uniformly distributed values for surface roughness (0.2–2.0 cm), and water canopy (0–1.5 kg/m²) and no *a priori* information about either surface roughness or water canopy. Surface roughness and water canopy cannot be retrieved simultaneously given a single measurement channel.

can very easily distinguish it. Note that compared to the SD of the uniformly distributed surface roughness of 0.52 cm, the retrieval errors are quite low. In contrast, Fig. 6c shows that the RMS error in retrieved vegetation water content is higher than its inherent SD of 0.43 kg/m² for all levels of soil moisture. This indicates that given the levels of uncertainty and measurement noise assumed here, there is no useful information about the water content contained in the measurements. (In other words, the algorithm would be better served by assuming a constant average value for water content and not attempting to iteratively retrieve it.) The fact that the six-channel algorithm cannot extract useful information about the vegetation water content results from the combination of measurement noise and the variability of other masking parameters. Variations in the other parameters (e.g., soil composition and surface temperature) cause changes in T_B vs. channel that are similar enough to the changes due to vegetation water content that given the measurement noise, the retrieval algorithm cannot distinguish them. The result is an inversion with an RMS retrieval error comparable to the original variations in the parameter.

The RMS error in retrieved soil moisture shown in Fig. 6a cannot be compared directly to the performance estimates given earlier (e.g., Fig. 3a) because those earlier results assumed some level of *a priori* knowledge about the other surface parameters than soil moisture. To directly compare the performance of the six-channel retrieval to the best single-channel version (using 1.4 GHz), a Type 2 simulation was run using 1.4 GHz alone

and assuming no knowledge of the other surface parameters. This is equivalent to assuming an average value of 1.1 cm for surface roughness and 0.75 kg/m² for vegetation water content. The results are shown in Fig. 7. Note in Fig. 7 that vertical polarization is significantly less sensitive to the masking variations in surface roughness and so would be the preferred single-channel sensor. This is in contrast to the earlier results in which, given sufficient *a priori* information about the other surface parameters (especially surface roughness, which depolarizes the brightness), there was no significant difference between the two polarizations. V-pol is evidently more forgiving of uncertainty in surface roughness. The single-channel retrieval performs comparably to the full six-channel version for dry soil moisture, below ~0.1, but deteriorates rapidly at higher levels. It should be kept in mind that these results assume a wide and unknown variation in vegetation and surface roughness. They are intended to model a retrieval algorithm applied with no prior information and to a global variety of conditions. The performance will necessarily be worse than those of the many local field campaigns that have been conducted to date, in which masking parameters generally do not vary so widely and freely. The intent here is to illustrate the need for some form of control of masking parameters [be it with *a priori* information or by retrieving the other parameter(s) directly] in an algorithm that is to be applied globally.

Using All Six Channels and Retrieving Two Surface Parameters

We first consider which six-channel retrieval of two variables is better: (soil moisture+surface roughness) or (soil moisture+vegetation water content), by checking which combination gives the better smRMS. In either case, soil moisture is uniformly distributed over the range 0.01–0.4, soil roughness is uniformly distributed over the range 0.2–2 cm, and water content is uniformly distributed over the range 0–1.5 kg/m². The first guess at soil moisture is 0.2, the first guess at soil roughness is 1.1 cm if it is retrieved, and the first guess at water content is 0.75 kg/m² if it is retrieved. If a parameter isn't retrieved, then it is fixed at its true value±a 10% Gaussian error. The results are smRMS=0.04 for (soil moisture+surface roughness) and smRMS=0.06 for (soil moisture+water content). In addition, the RMS error in the retrieval of surface roughness is 31% of its natural variability, whereas the water content is retrieved with an RMS error that is slightly greater than its natural variability. Surface roughness is clearly the better secondary parameter to retrieve.

Using Two Channels and Retrieving Soil Moisture and Surface Roughness

We next examine the performance of all possible two-channel combinations of measurements, where soil mois-
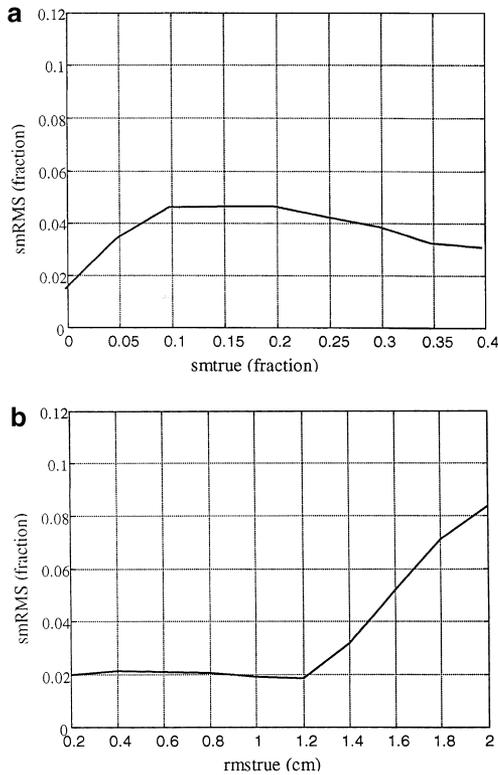
a

b

Figure 8. Two-channel (1.4 V and 2.7 H) RMS error in soil moisture retrieval assuming 25° incidence angle, 285 K surface temperature, 1 K measurement noise, 3 K uncertainty in surface temperature, 20% uncertainty in soil composition, uniformly distributed values for water canopy (0–1.5 kg/m²), 10% uncertainty in knowledge of water canopy, and no *a priori* information about surface roughness; (a) vs. soil moisture, assuming uniformly distributed values for surface roughness (0.2–2.0 cm), and (b) vs. surface roughness, assuming uniformly distributed values for soil moisture (0.01–0.40).

Figure 9. Single-channel (1.4 V or 1.4 H) RMS error in soil moisture retrieval vs. soil moisture, assuming 25° incidence angle, 285 K surface temperature, 1 K measurement noise, 3 K uncertainty in surface temperature, 20% uncertainty in soil composition, uniformly distributed values for surface roughness (0.2–2.0 cm) and water canopy (0–1.5 kg/m²), 10% uncertainty in knowledge of water canopy, and no *a priori* information about surface roughness.

ture and surface roughness are retrieved. The conditions are similar to the six-channel/two-parameter simulation discussed above. The results are presented in Table 3. The combination of 1.4 V and 2.7 H performs best. The error in its soil moisture retrieval is as good as or better than any of the others. Its retrieval of surface roughness is superior to all others. This indicates that the 1.4 V/2.7 H combination will perform most robustly with respect to variations in surface roughness.

Figures 8a and 8b plot the smRMS for Type 2 simulations using the 1.4 V/2.7 H combination. The vegetation water content is uniformly distributed over a range 0–1.5 kg/m² and is assumed to be known by the retrieval algorithm within ±10% of its true value. In Fig. 8a, the surface roughness is uniformly distributed over a range 0.2–2.0 cm and no *a priori* information about it is assumed. The results demonstrate that the effect of soil moisture level on the retrieval is not significant. In Fig.
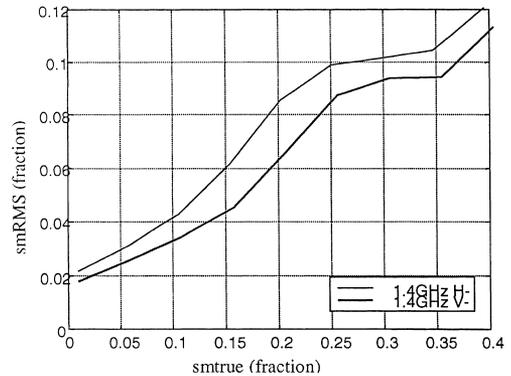
8b, the surface roughness is varied parametrically, and the soil moisture is uniformly distributed over the range of 0.01–0.40. In this case, we see that soil roughness of greater than 1.2 cm causes a significant error in the soil moisture retrieval.

The value of a two-channel retrieval over the best single-channel version is demonstrated by a Type 2 simulation similar to that shown in Fig. 8a, but using only a single 1.4-GHz channel. The results are shown in Fig. 9. These results differ from those shown earlier, in Fig. 2a, in that there is now assumed to be no *a priori* information about the surface roughness. Comparing the performance at vertical and horizontal polarizations in Fig. 9, we see that V-pol is slightly less sensitive to variations in roughness. However, comparing Fig. 2a and Fig. 9, the additional masking effect of the variable surface roughness is seen to significantly degrade both V- and H-pol single-channel retrievals of soil moisture at all but the driest levels. In contrast, Fig. 8a demonstrates that the two-channel retrieval is able to satisfactorily account for the variations in surface roughness and successfully retrieve soil moisture.

A comparison among the best single- and two-channel retrievals and the full six-channel version can be made, assuming no *a priori* information about either the surface roughness or the vegetation water content. Results for the single- and six-channel cases were presented above (see Figs. 6a and 7). The comparable results for 1.4 V/2.7 H case are shown in Fig. 10. At very low soil moisture levels, all three retrievals perform similarly. At higher levels, the single-channel performance rapidly deteriorates. But the two-channel algorithm continues to
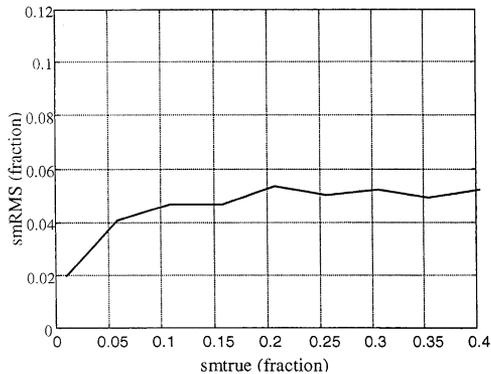
Figure 10. Two-channel (1.4 V and 2.7 H) RMS error in soil moisture retrieval vs. soil moisture, assuming 25° incidence angle, 285 K surface temperature, 1 K measurement noise, 3 K uncertainty in surface temperature, 20% uncertainty in soil composition, uniformly distributed values for surface roughness (0.2–2.0 cm) and water canopy (0–1.5 kg/m²), and no *a priori* information about either surface roughness or water canopy. Surface roughness, but not water canopy, is retrieved simultaneously with soil moisture.

perform very similarly to that with six channels at all levels of soil moisture. There is no significant benefit to the soil moisture retrieval in including the four additional channels.

SUMMARY AND CONCLUSIONS

Current channel options for a future space-borne microwave radiometer mission to retrieve soil moisture include 1.4 GHz, 2.7 GHz, and 6.6 GHz with horizontal and/or vertical linear polarization. The performance of single and combined two- and six-channel soil moisture retrieval algorithms was considered given different combinations of assumptions about the ancillary surface parameters of surface RMS roughness and water content of the vegetation canopy. Cases with and without a vegetation canopy were considered at 6.6 GHz. Cases with varying levels of *a priori* information about one or both of the ancillary surface parameters were considered for all channel combinations.

If 6.6 GHz alone is used, then the soil moisture retrieval performance is severely degraded unless there is no vegetation canopy present and the retrieval algorithm knows *a priori* that this is the case. In addition, there is considerable sensitivity to variations in the surface roughness. Performance is best with a relatively smooth surface (RMS roughness<0.6 cm) and provided the retrieval algorithm knows *a priori* that it is smooth. Given a canopy-free surface, performance at 6.6 GHz is also considerably improved by increasing the angle of incidence. This significantly reduces the sensitivity to variations in surface roughness, most markedly so at vertical polarization.

Single-channel retrievals at 1.4 GHz and 2.7 GHz are much less affected by variations in either the roughness or canopy. However, satisfactory performance at all soil moisture levels requires that the roughness and canopy be known *a priori* with sufficient accuracy (±10% of their true values). Without this *a priori* knowledge, performance is particularly degraded at the higher levels of soil moisture. Of the four individual possibilities, the 1.4-GHz channel at vertical polarization is least sensitive to variations in the ancillary parameters and so performs best. The improvement in performance with increasing incidence angle that was seen at 6.6 GHz is also noted here but is less pronounced at 2.7 GHz and is negligible at 1.4 GHz.

If no *a priori* information is assumed about the roughness or canopy, then additional channels are needed to simultaneously estimate and correct for the ancillary parameters. In the two-channel cases, a simultaneous solution for soil moisture and soil roughness is found to perform better than solving for soil moisture and vegetation water content. The combination of 1.4 V and 2.7 H has the best overall performance. In the six-channel case, simultaneous solutions for all three surface parameters, or for just soil moisture and surface roughness, perform similarly. Most notably, the performance of the six-channel algorithm is not significantly better than the two-channel retrieval. This important conclusion results because the small amount of additional information contained in the six-channel data set has been largely masked by the level of measurement noise that have been assumed.

To make any recommendations about the right choice for a sensor design, it is very important to establish what level of *a priori* information will be available to the soil moisture retrieval algorithm. If both the roughness and vegetation canopy can be well characterized by external data sources, then a single 1.4-GHz sensor can provide significant information about the soil moisture. If roughness is well known and performance is only required over clear terrain, then a single 6.6-GHz sensor can suffice. However, even in this case it should be noted that the penetration depth into the soil at 6.6 GHz is significantly shallower than that at the lower frequencies. This makes hydrologically useful inferences about integrated water content below the surface more susceptible to variations in the moisture profile. If neither the surface roughness nor the canopy can be adequately constrained, and if the most "stand alone" retrieval algorithm possible is desired, then a two-channel sensor operating at 1.4 V and 2.7 H is necessary and sufficient.

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