DEVELOPMENT OF SOIL MOISTURE RETRIEVAL ALGORITHM FOR L-BAND SAR MEASUREMENTS

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ABSTRACT — This paper reports a study of algorithm development and testing for soil moisture retrieval for bare fields using L-band SAR imagery. First-order surface scattering models predict that the co-polarization ratio is sensitive to soil moisture but not to surface roughness. In this study, we evaluated all possible ratios of the co-polarization signals and their linear combinations. The best sensitivity to soil moisture is achieved from the measurement of $\sigma^{hh}/(\sigma^{vv} - \sigma^{hh})$ as predicted by the first-order surface scattering model. The effects of system noise and volume scattering of soil are evaluated. To minimize the effect of the volume scattering, an algorithm which includes both the surface and volume scattering has been developed and tested using JPL AIRSAR data. The results show that the estimation of soil moisture can be improved after removing the system noise and including the volume scattering effect at large incidence angles.

INTRODUCTION

The purpose of this study is to develop an algorithm for soil moisture retrieval from L-band SAR imagery. Estimates of soil moisture are of great importance in numerous environmental studies, including hydrology, meteorology, and agriculture. Previous studies [1] using extensive scatterometer measurements have established the optimum parameters for moisture retrieval as C-band HH radar operating at incidence angle between 10° to 15°. However, these parameters have not been tested or verified with imaging radar systems. The results from different investigators have shown considerable variability in the relationship between soil moisture and radar backscattering. This variability suggests that those algorithms are site-specific. Furthermore, the small incidence angle requirement limits the spatial application, especially for airborne radar system. While it may be possible to operate at these angles for spaceborne radar systems, many other effects, such as layover etc., make it difficult to analyze spaceborne radar images acquired at such steep incidence angles. The algorithm should be applicable over as much of the swath as possible.

The imaging radar polarimeter permits measurement of the full polarization signature of every resolution element in an image. The radar polarization signature of an object permits a more accurate description of the object of interest than single-polarization measurements [2]. Thus, the solution for geometric shape and dielectric constant of an object is less ambiguous, making the development of a quantitative algorithm for soil moisture retrieval from Synthetic Aperture Radar (SAR) data possible. Our previous work [3] indicated that the ratio of the co-polarization signals, that is the ratio of σ^{hh} to σ^{vv}, could be used for soil moisture retrieval at longer wavelengths (L-band) and at larger incidence angles (> 40°). The algorithm to infer soil moisture from imaging radar data was based on a first-order surface scattering model. This model predicts that the co-polarization ratio is sensitive to soil moisture at large incidence angles but not to surface roughness. Since all ratios of the co-polarized signals and their linear combinations were predicted by the first-order surface scattering model not sensitive to surface roughness, we need to evaluate which ratio measurement provides the maximum sensitivity to soil moisture. Furthermore, the polarization signal ratio measurements are sensitive to the radar system noise and the other scattering contributions such as the multi-surface and volume scattering even if these effects only contribute a small portion of the total signal in the measurements. These factors result in an under-estimation of soil moisture when the first-order surface scattering algorithm was applied to imaging radar data. Therefore, it is necessary to evaluate the effects of these factors on the polarization ratio measurements for developing a quantitative algorithm for inferring soil moisture.

To address these problems, we evaluated the effects of the radar system noise, the multi-surface scattering [4], and the volume scattering on the co-polarization ratio measurements. In this study, the effect of the volume scattering of soil is addressed. Based on a first-order backscattering model which considers both the surface and volume scattering, the physically based algorithm for retrieval of soil moisture has been developed and tested using NASA/JPL aircraft SAR data. The radar data used in testing the algorithm consist of three sets in May 1988 and two sets in September 1989 acquired over an agricultural area near Fresno, California.

OPTIMAL MEASUREMENTS

First-order surface backscattering models predict that the ratio of the backscattering coefficients of the co-polarizations is sensitive to soil moisture and insensitive to surface roughness. Similarly, the ratios of the linear combinations from the co-polarized returns have the same properties. The task is to select the measurements which maximize the sensitivity to soil moisture.

Figure 1 shows the predictions of the first-order small perturbation model at L-band for four ratios of the co-polarized return measurements. The direct co-polarization ratio, i.e. σ^{vv}/σ^{hh} in (A), shows that this measurement has a positive correlation with the incidence angles and is sensitive to soil moisture change at higher incidence angles but not at smaller incidence angles. On the other hand, the ratios from the linear combinations of co-polarized returns have a negative correlation with incidence angles. The ratios of $\sigma^{vv}/(\sigma^{vv} - \sigma^{hh})$ in (B) and the $(\sigma^{vv} + \sigma^{hh})/(\sigma^{vv} - \sigma^{hh})$ in (D) show that these two measurements are sensitive to soil moisture change at smaller incidence angles but not at higher incidence angles. The best measurement with a maximum sensitivity to soil moisture at all incidence angles is found to be the ratio of $\sigma^{hh}/(\sigma^{vv} - \sigma^{hh})$ in (C). Sensitivities in all these four measurements decrease as soil moisture increase.

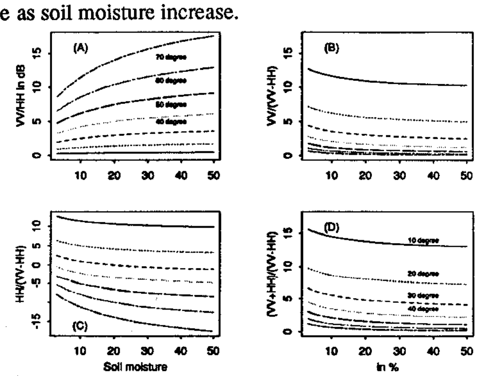

Fig. 1. Predictions of the ratios of the co-polarized signals by the first-order small perturbation model.

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To evaluate the applicability of the first-order surface scattering model for soil moisture retrieval, we show the sampled measurements of $\sigma^{hh}/(\sigma^{vv}-\sigma^{hh})$ in 1989 data from dry bare fields in Figure 2. These measurements present samples from 10 x 10 pixel boxs. The back-scattering coefficients for VV and HH polarizations were determined from an averaged Stokes matrix. The solid line in Figure 2 is the predictions by the first-order small perturbation model for soil moisture at 3 percent by volume, while the dashed line is the prediction for 9 % soil moisture by volume. The soil moisture range measured during the over flights ranged from 3 to 9 percent for dry bare fields. Figure 2. indicates that a direct application of the first-order surface scattering inversion algorithm will result in an under-estimation of soil moisture.

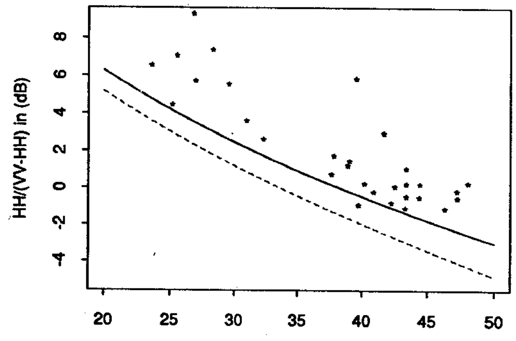

Fig. 2. The sampled measurements of $\sigma^{hh}/(\sigma^{vv}-\sigma^{hh})$ from dry bare fields. The solid and dashed lines are the predictions by the first-order small perturbation model for soil moisture at 3 and 9 percent, respectively.

Through examining the image radar measurement properties and the simulations by both second-order surface scattering models and the models which considers that soil is an inhomogeneous medium, we found that there are three main factors needed to be considered in development of an algorithm to infer soil moisture. They are (1) the effect of radar system noise, (2) the effect of the multi-surface scattering, and (3) the effect of volume scattering of soil. Assuming the noise power to be the same in all channels, the effect of system noise on the ratio measurement of $\sigma^{hh}/(\sigma^{vv}-\sigma^{hh})$ can be expressed as

$$\frac{\sigma^{hh}+\text{noise}}{\sigma^{vv}-\sigma^{hh}} \geq \frac{\sigma^{hh}}{\sigma^{vv}-\sigma^{hh}} \tag{1}$$

for all values under the condition of $\sigma_{hh}<\sigma_{vv}$. This results in an under-estimation of the soil moisture especially at larger incidence angle range because the signal to noise ratio typically decreases as incidence angle increases. We should note that the effect of system noise on the different co-polarization ratios is not the same. For instance, the effect of system noise on σ^{vv}/σ^{hh} results in a smaller value than the actual measurement. In other words,

$$\frac{\sigma^{vv}+\text{noise}}{\sigma^{hh}+\text{noise}} \leq \frac{\sigma^{vv}}{\sigma^{hh}} \tag{2}$$

But the effect of system noise causes an under-estimation of soil moisture regardless of which co-polarization ratio is used. Based on the assumption that the noise power in the two co-polarized channels are typically of the same magnitude, the amount of noise in co-polarization channels can be estimated [5]. This estimated noise can be then used to adjust the observed measurement before inferring soil moisture.

Figure 2 shows that the measured cp-polarized ratios are higher than the predictions by the first-order surface scattering model. We believe that this could be caused by inhomogeneities in the soil. The surface scattering models assume that the scattering medium is a homogeneous dielectric half-space. In practice, natural soil is not a perfectly homogeneous dielectric medium. Instead, it is a mixture of soil particles, air pockets, and liquid water. This results in dielectric discontinuities inside the soil. Therefore, natural soil should be described as a inhomogeneous dielectric medium. Because soil is a densely packed medium, the effects of these discontinuities will be reduced for longer wavelengths, especially when the distance between scatterers is much smaller than the wavelength. The result is that the volume scattering of soil contributes only a small portion of the observed signals at longer wavelength and that the dominant scattering source is the surface backscattering at the air-soil interface. In evaluating the magnitude of each co-polarization signal, the surface scattering can be used to explain the general relations between the backscattering measurements and soil physical properties. However, in attempting to relate the polarization ratio or difference to the physical properties of soils, the volume scattering contribution becomes significant even if it only contributes a small portion in the observed backscattering returns. This effect is also expected when using long-wavelength sensors because of deeper penetration. To overcome the volume scattering effect on estimation of soil moisture, we propose an algorithm which is based on the first-order scattering model considering both the surface and volume scattering contributions.

ALGORITHM DEVELOPMENT

As we have discussed in the last section, the volume scattering affects the co-polarization ratio measurements, especially at longer wavelengths and high incidence angles when soil moisture is low. To minimize this effect, we construct a more general inversion model by considering both surface and volume backscattering

$$\sigma_t^{pp} = \sigma_s^{pp} + \sigma_v^{pp} \tag{3}$$

where pp indicates polarization. σ_t is the total backscattering coefficient. σ_s is the surface backscattering from air-soil interface and σ_v is the volume backscattering from soil.

The surface backscattering is a function of the permittivity of soil and the roughness of the air-soil interface which is described by the auto-correlation function of random surface height, the standard deviation of the surface height, and the correlation length. When the multi-scattering is not significant, the single surface backscattering can be represented as a product of dielectric and surface roughness functions. The relationship of the surface backscatterings between VV and HH polarization signals can be derived

$$D_R(\theta_i,\varepsilon_r) = \frac{\sigma_s^{vv}}{\sigma_s^{hh}} = \frac{D(vv,\theta_i,\varepsilon_r)}{D(hh,\theta_i,\varepsilon_r)} \tag{4}$$

where $D(pp,\theta_i,\varepsilon_r)$ is the dielectric function. Here, we simply denote D_R as the surface backscattering ratio of VV and HH polarizations, which is only a function of incidence angle and the permittivity of soil.

Similarly, the volume backscattering coefficient is a function of the permittivity, incidence angle, volume scattering albedo, and surface roughness. Under the spherical particle assumption, the relationship for the first-order volume backscattering signals of VV and HH polarizations can be also obtained

$$D_T(\theta_i,\varepsilon_r) = \frac{\sigma_v^{vv}}{\sigma_v^{hh}} = \frac{T_{vv}^2(\theta_i,\varepsilon_r)}{T_{hh}^2(\theta_i,\varepsilon_r)} \tag{5}$$

where T_{vv}^2 and T_{hh}^2 are double pass of the power transmission coefficients. We simply denote D_T as the volume backscattering ratio of VV and HH polarizations, which is also a function of incidence angle and permittivity of soil.

To further reduce the number of unknowns in order to measure soil moisture, we introduce the ratio of the surface backscattering contribution, denoted by C_{pp},

$$\frac{\sigma_s^{hh}}{\sigma_t^{hh}} = C_{hh} \tag{6a}$$

and

$$\frac{\sigma_v^{hh}}{\sigma_t^{hh}} = 1 - C_{hh} \tag{6b}$$

for the surface backscattering contribution in HH polarization signal.

Using Equations (2), (4), (5), and (6), two ratios of the combined VV and HH polarization signals can be represented as

$$\frac{\sigma_t^{vv}}{\sigma_t^{hh}} = D_T(\theta_i,\varepsilon_r) + C_{hh}\,(D_R(\theta_i,\varepsilon_r) - D_T(\theta_i,\varepsilon_r)) \tag{7}$$

and

$$\frac{\sigma_t^{hh}}{\sigma_t^{vv} - \sigma_t^{hh}} = \frac{1}{D_T(\theta_i,\varepsilon_r) - 1 + C_{hh}\,(D_R(\theta_i,\varepsilon_r) - D_T(\theta_i,\varepsilon_r))} \tag{8}$$

From these two measurements, the two unknowns, ε_r and C_{hh}, can be solved. The reason why these two measurements are selected is that they provide the best sensitive to soil moisture change at large incidence angles.

From equation (8), we can derive the physical condition of the co-polarization ratio measurement

$$D_T(\theta_i,\varepsilon_r) \le \frac{\sigma_t^{vv}}{\sigma_t^{hh}} \le D_R(\theta_i,\varepsilon_r) \tag{9}$$

Similarly, the physical condition for equation (9) is

$$\frac{1}{D_R(\theta_i,\varepsilon_r) - 1} \le \frac{\sigma_t^{hh}}{\sigma_t^{vv} - \sigma_t^{hh}} \le \frac{1}{D_T(\theta_i,\varepsilon_r) - 1} \tag{10}$$

The algorithm derived above does not require any information about the surface roughness and the volume scattering albedo. It only involves the calculation of soil permittivity.

RESULTS AND DISCUSSIONS

To test the algorithms for measuring soil moisture over a large areas, a field map was first obtained by performing the supervised bayes classification and the vegetation covered fields were masked. The data sets used in classification are σ^{hv} and the correlation coefficient of HH and VV polarization channels. The selection of these two data sets were based on the evaluation of the separability from the sampled bare and vegetation covered fields over a large incidence angle range. Secondly, the backscattering coefficients of VV and HH polarizations for a given pixel were determined from an average Stokes matrix within a 5 by 5 window to reduce the effect of image speckle. Then, the algorithm for removing noise power in co-polarization returns is applied. After the measurements of σ^{vv}/σ^{hh} and $\sigma^{hh}/(\sigma^{vv} - \sigma^{hh})$ were tested using the physical conditions from Equation (9) and (10), the algorithm was applied.

Figure 3(A) shows an image of the inferred soil moisture map of the study sites from SAR data. This map was produced using an first-order surface scattering model only. The soil moisture map shown in (B) was derived by the algorithm which includes both surface and volume scattering of soil. The image brightness is proportion to the soil moisture in both images and ranges from 2 to 30 percent by volume. The black regions are vegetation covered fields. When applying the first-order surface scattering algorithm, only about 20 to 30 percent pixels were within the possible physical conditions predicted by the first-order surface scattering model. As shown in Figure 3(A), there are many pixels with missing values even after post-processing. It is especially evident at large incidence angles. However, applying the algorithm with both surface and volume scattering considerations, about 80 percent of the pixels were within the physical limits. During the SAR flights, the volumetric soil moisture for the sampled dry fields varied between 3 and 10 percent. Most bare fields were dry because none of them had been irrigated for at least several weeks. The inferred soil moisture from SAR data agrees well with the field measurements and values ranges from 2 to 14 percent were inferred.

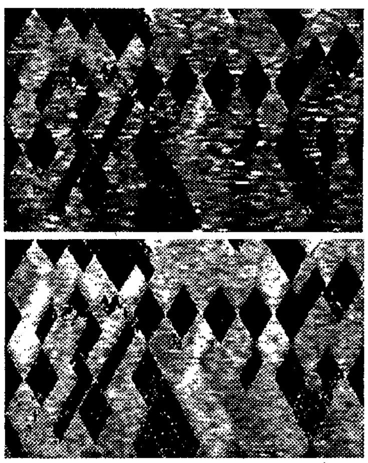

Fig. 3. Comparison of inferred soil moisture map by using the first-order surface scattering model in (A) at top with the map derived by the algorithm which includes both surface and volume scattering at bottom in (B). The image brightness is proportional to soil moisture ranging from 2 to 14 percent by volume.

Figure 4. shows the comparisons between the field measurements and the SAR derived soil moisture for the locations where the field measurements were available. The line indicates where the soil moistures are exactly same from the field and SAR derived measurements. The measurements above and below this line indicate an over-estimation and under-estimation, respectively. The maximum relative error can reach about 100 percent but most of the measurements have relative errors smaller than 25 percent. The average error was about 30 percent from all measurements. Both regional and point measurement comparisons between the field and SAR derived measurements indicates that the algorithm performs very well.

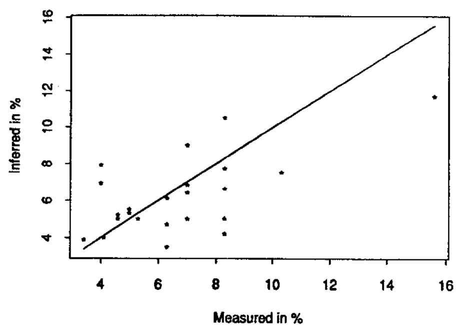

Fig. 4. Comparison the field soil moisture measurements with the inferred by SAR data.

CONCLUSIONS

This paper reports a study of algorithms development and testing for soil moisture retrieval for bare fields using L-band SAR imagery. In this study, we evaluated all possible ratios of direct and their linear combinations of the co-polarization signals. The best sensitivity to soil moisture is achieved from the measurement of $\sigma^{hh}/(\sigma^{vv} - \sigma^{hh})$ as predicted by the first-order small perturbation scattering model. The effects of system noise and volume scattering have been evaluated. An algorithm which includes both the surface and volume scattering has been developed and tested on JPL AIRSAR system. The results show that the algorithm performed well and should be useful for repetitive, large-area soil moisture monitoring, without requiring surface roughness measurements.

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