MEASUREMENT OF SOIL MOISTURE WITH SYNTHETIC APERTURE RADAR[1]

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ABSTRACT

An experiment was performed in Northern Maine recently to evaluate the use of Synthetic Aperture Radar (SAR) data in the measurement of soil moisture content in small area plots with varying surface cover and at various subsurface depths. Ground preparation efforts involved defining six contiguous 30 m x 30 m plots with three surface cover conditions: bare tilled soil, short grass and forest. For each surface cover we irrigated one of the two plots to obtain areas of contrasting soil moisture content. The NASA/JPL DC-8 and its three frequency (P, L, and C) SAR made passes over the area on two days and at three different depression angles collecting a multifrequency and multiangle data set. Near the time of the SAR overflights, soil samples were taken at 2, 5, 10, and 25 cm depths and gravimetric moisture content (m_g) determined. While significant spatial variability was observed in the moisture samples, and variations in the SAR backscatter data induced by speckle due to surface roughness caused problems, a proportional relationship was observed between the backscatter coefficient and moisture content for the tilled and grass areas, especially near the surface. L band data seemed to be the most sensitive to m_g in the open areas, while P band data showed sensitivity to the surface moisture in the forest area. Inconclusive results were obtained in correlating the SAR data with moisture measurements at the 10 and 25 cm depths. Also, the variation in backscatter due to speckle seemed to be reduced through a Polarimetric Whitening Filter (PWF) transformation.

INTRODUCTION

In July 1990 an experiment was performed in Northern Maine to evaluate the use of multifrequency Synthetic Aperture Radar (SAR) data in the measurement of soil moisture content over small areas at various subsurface depths and under three surface cover conditions: bare tilled soil, short grass and forest. Since the NASA/JPL DC-8 three frequency SAR [1] was to acquire data over the area as part of another experiment [2] we were able to conduct this experiment on soil moisture for minimal additional cost by performing site preparation and ground truth collection.

The goal of the experiment was to determine if the use of polarimetric multifrequency SAR data could lead to information about the soil moisture content below the surface or through vegetation. While the actual penetration depth at a given frequency depends on many factors including surface roughness, soil particle size and chemical composition, presence of organic matter, as well as the amount of free and bound water, theory and measurements indicate that, in general, the penetration depth is proportional to radar wavelength. Following [3] who cited data from [4], the vertical penetration depth of radar waves in soil with 20% volumetric moisture can be approximated as 3 cm for C band, 14 cm for L band, and 56 cm for P band.

Thus, theory and measurements have indicated that the P band may be useful in sensing moisture below the surface of the soil. Also, the longer wavelength can be expected to provide some penetration of the vegetation, and while not sensing as deeply as in exposed soil, should still provide some indication of the soil moisture below the vegetation. Previous experiments have found P band backscatter poorly correlated with soil moisture [5]. It was our intention to investigate this further from an empirical point of view. This experiment afforded us the opportunity to make intensive preparation and measurement over various surface covers in a small area with accurate data calibration and registration.

A test site was chosen within the SAR coverage area near Portage Lake, Maine that was fairly level, had an open field next to a forest stand, and had access to a water supply. Located near the site were three trihedral corner reflectors whose locations were accurately surveyed, thus later allowing accurate registration of the radar image to our test site. The test site plots were defined and irrigated as described below, and the soil moisture measurements were obtained. The NASA/JPL DC-8 SAR flew over the area on two days making several passes at different depression angles to collect data. After obtaining the processed data from JPL, we performed calibration and registration to the ground map using the locations of the corner reflectors. The data were then analyzed using a variety of techniques to determine if there was a relationship between the SAR backscatter coefficients and the soil moisture content at the various depths and surface conditions. The following sections describe the experiment in more detail and provide a summary of initial results.

SITE PREPARATION

An area 100 meters by 60 meters that extended 30 meters into the woods was chosen and mapped as shown in Figure 1. The areas labeled TILLED were plowed so that the bare soil was exposed. The standard deviation of the surface height was 1.9 cm in TILLED area. The GRASS areas consisted of short (10 cm) grass that had been recently mowed. The FOREST area was populated with birch and pine trees that were approximately 10 meters tall. The 30 meter by 30 meter plots of each surface cover and moisture condition were chosen to obtain an adequate number of SAR image pixels (approximately 4 m by 4 m) over each area but small enough to allow the irrigation to be feasible.

The dry areas were left alone while the WET TILLED and WET GRASS areas were watered with an irrigation system. Since no water supply was available directly at the test site, two holding tanks were constructed nearby and kept full with water that was transported by truck from a nearby lake. The plots were irrigated by pumping the water from the tanks through sprinkler heads mounted on the plot edges and facing into the center of each plot. The forested area was too dense to permit this type of system and was watered down by running a hose into the area and periodically moving it. The plots were irrigated the day before and morning of the first flight day, as well as the day between flights. During the nights and the second day of the overflights the fields were allowed to dry. No precipitation occurred during the test period.

Soil moisture ground truth data were collected for both days of SAR overflights by obtaining samples of the soil at four locations within each of the six plots and at four depths: 2 cm, 5 cm, 10 cm, and 25 cm. Efforts were made at obtaining samples without rocks or organic material, but due to the soil conditions this was not always possible. The soil samples (about 15 cm^3 each) were collected in a small metal tube and sealed in a plastic bag. The gravimetric soil moisture content m_g was then determined.

The results of the moisture analysis showed substantial variability across each of the plots. Table 1 shows an example of the results for the TILLED areas as sampled on the first day. Obvious outliers were not used and replaced with field averages, but as can be seen in the measurements of the dry area at 5 cm depth, wide variability

[1]The collection of the radar data was funded jointly by DARPA and USAF Wright Laboratory

was observed. Indeed, considering the measurements at the other depths at these test points, this variability is most likely reflective of the actual conditions in the field, but it did complicate the analysis of the SAR data.

Table 1. Gravimetric soil moisture content (%) collected on the first day of overflights in the DRY TILLED and WET TILLED plots at four test points. Data points marked with an * were considered outliers and were not used in the analysis.

	Depth	TP1	TP2	TP3	TP4
DRY TILLED	2 cm	23.6	22.3	4.2	16.0
	5 cm	82.4	60.0	14.6	20.8
	10 cm	35.1	31.5	12.3	22.9
	25 cm	57.1*	7.0	13.4	20.2
WET TILLED	2 cm	33.2	38.9	45.6	32.7
	5 cm	45.5	27.5	155.1*	39.6
	10 cm	75.0	37.5	16.7	78.7
	25 cm	6.4	48.0	19.4	83.2

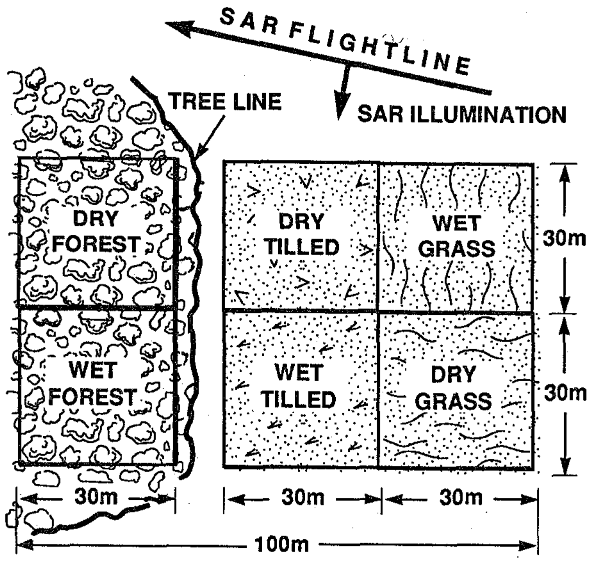

Figure 1. Plot layout within test site.

In general, the wet areas did have a higher moisture content near the surface than the dry areas, while there was less of a difference at greater depths. The range of m_g was quite large overall and varied from 4.1% at a test point in the DRY TILLED area to 95.9% at a test point in the WET FOREST area.

SAR DATA COLLECTION

The NASA/JPL DC-8 flew passes with the SAR at 30°, 45° and 60° depression angles from horizontal on each of the two days of data collection. In October of 1991 six image sets each including the C, L, and P bands were made available in the 10 byte compressed format along with calibration coefficients. The images were registered to the ground using the three nearby corner reflectors. Elevation differences and slant range effects were taken into account with the final registration accuracy of the image pixels believed to be better than ± 1 pixel.

For each of the six image sets, pixels to be used in calculating the field averages were identified as those that were inside each of the six plots by at least one pixel, thereby reducing the chance of using pixels that spanned two different plot types. This resulted in making available a range of samples from approximately 40 pixels per plot in the 30° passes to 15 per plot in the 60° passes. Fewer pixels were available in the 60° passes due to the greater ground range size of the pixels in the steeper observations.

Table 2 shows typical results for the mean of σ^0 for the 45° passes as calculated from the pixels within each plot. The backscatter powers were averaged before converting to the dB scale. The most significant differences in σ^0 between wet and dry areas were found to be in the L band data over the TILLED fields. Here, differences of up to 8 dB were observed between the wet and dry areas.

Table 2. Mean σ^0 for the 45° depression angle passes.

	GRASS		TILLED		FOREST	
	Dry	Wet	Dry	Wet	Dry	Wet
C Band						
HH	-10.5	-9.3	-9.6	-8.7	-6.5	-5.8
HV	-15.2	-14.7	-18.3	-14.6	-13.4	-12.2
VV	-9.1	-8.8	-9.6	-8.6	-7.2	-6.5
L Band						
HH	-19.6	-16.5	-16.4	-11.6	-7.3	-5.7
HV	-27.1	-24.0	-26.9	-20.6	-11.9	-11.1
VV	-17.5	-14.0	-17.0	-9.0	-8.2	-8.4
P Band						
HH	-19.5	-20.2	-19.9	-18.9	-6.9	-3.2
HV	-27.3	-26.4	-27.5	-24.2	-16.7	-12.0
VV	-23.5	-21.8	-19.9	-17.2	-8.3	-7.7

RELATIONSHIP BETWEEN SOIL MOISTURE AND σ^0

Attempts to correlate the backscatter coefficient σ^0 with the soil moisture content led to mixed results. Because of the great variability in the SAR values due to speckle effects, field averages were computed. However, the plots exhibited a wide variation in moisture content within each area, thus making the use of averages questionable. Also, by reducing the data to field averages, only four data points resulted (two days of data over wet and dry areas) for each cover type, frequency, polarization, and depression angle. A regression analysis was attempted nonetheless and correlation coefficients greater than 0.95 were observed for the L band data over the TILLED and GRASS areas and the 2 cm moisture content. However, these were considered not very meaningful since only four data points were used.

A more significant number of data points were obtained by locating the pixels in each image nearest the moisture test points within each plot. This became possible since the registration was believed to be within ±1 pixel. To account for small misregistration errors and to reduce the effects of speckle noise in the imagery, nine pixels centered on the test point were averaged together. Also, since some test points contained outliers in the their m_g, not all 16 were utilized, which resulted in making available 12 samples in the GRASS area, 13 in the TILLED area, and 9 in the FOREST area.

Figure 2 shows a scatter plot of these samples for the L band VV polarization data from the 30° depression angle passes and m_g in the upper 2 cm of the soil in the TILLED plots. Also plotted are L band data combined from all three polarizations (HH, HV, and VV) through a transformation by a Polarimetric Whitening Filter (PWF) [6] which combines the multipolarization elements within a band (or across all bands) in a way that minimizes the ratio of the standard deviation to the mean for the pixel intensities. Here, the filtered data showed a higher correlation with the moisture content. While that was generally the case across frequencies, surface covers and angles, there were combinations where the filtered data exhibited a weaker correlation with m_g.

Table 3 shows the resulting correlation coefficients when comparing these PWF filtered data from the 30° passes to the average moisture measurements for the surface to varying depths. The average moisture content from the surface to the depth was calculated by using the measurements at the specific depths and weighting them according to their depth. The band labeled ALL refers to data that had been transformed with the PWF using all nine (three frequencies times three polarizations) dimensions.

Table 3. Correlation coefficient vs. surface-to-depth m_g for PWF filtered data from 30° depression angle pass over the TILLED area.

Band	Depth (cm) 0-2	0-5	0-10	0-25
C	0.7	0.6	0.5	0.3
L	0.9	0.6	0.7	0.5
P	0.3	0.4	0.5	0.3
ALL	0.7	0.6	0.7	0.4

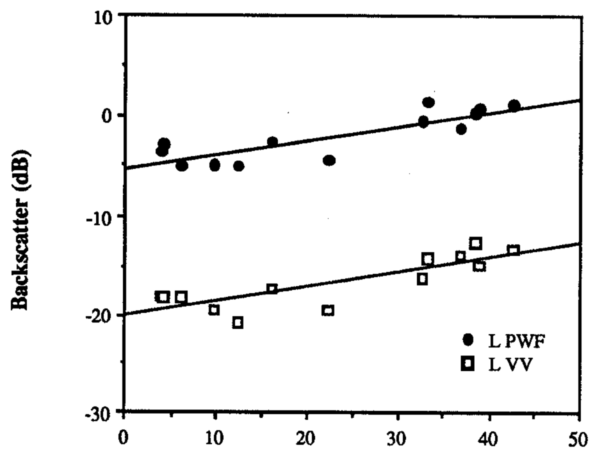

Figure 2. Gravimetric soil moisture content m_g vs. backscatter for the 30° depression angle pass over tilled fields. The correlation for the L band VV polarization was 0.8, while for the PWF filtered L band result it was 0.9. Note that the PWF filtered data does not have the same units as the original data, but are shown in dB on the same scale for comparison.

The C and L bands seemed to be sensitive to the moisture at the upper levels, with the L band being the most sensitive. The P band seemed to exhibit a slightly greater sensitivity to m_g at the deeper levels, but with such low correlations this characteristic is questionable at best.

Figure 3 shows the effect of depression angle for the various surface types. The correlation coefficient is plotted for the band of filtered data that showed the most sensitivity to m_g for that surface cover.

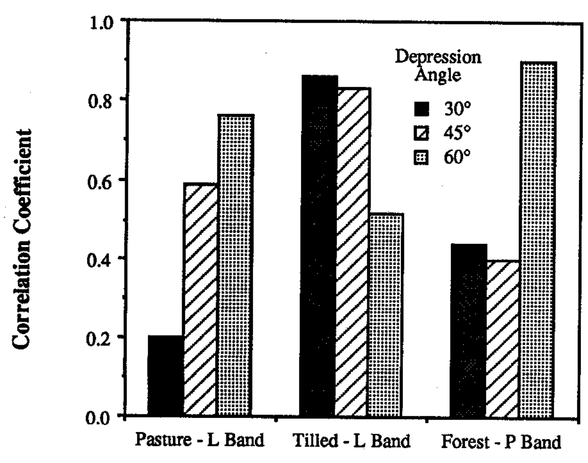

Figure 3. Effect of depression angle on correlation coefficient between the m_g in the upper 2 cm of soil and the SAR data filtered with the PWF. For each surface cover the band is shown that had the highest correlation with m_g.

This figure shows a trend indicating that the tilled area was best observed with the oblique angle, while the grass and forest areas showed more sensitivity to moisture at steeper observation angles. Also, it is interesting to note that while the L band results were superior in the grass and tilled areas, the P band did show the best sensitivity to the surface moisture in the forest area.

SUMMARY

An experiment was conducted to explore the measurement of soil moisture content in small areas through vegetation and below the soil surface with Synthetic Aperture Radar. We found that the L band radar at 30° depression angle in the bare area and 60° in the grass area was most sensitive to soil moisture conditions that were in the upper 2 cm of the soil surface. P band was found to be sensitive at 60° depression angles to surface moisture in a forested area, thus showing some evidence of penetration of the vegetation canopy. Little convincing evidence was found so far to allow the retrieval of subsurface moisture content. However, we did find that surface roughness effects in the SAR backscatter could be reduced through the use of a polarimetric transformation that minimized the variation in the data. This technique should be considered by other experiments using SAR imagery.

The results presented in this paper are initial and further work is planned in the analysis of the data. At the completion of such work, a report will be published documenting the findings in complete detail.

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