MULTI-POLARIZATION C-BAND SAR FOR SOIL MOISTURE ESTIMATION

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ABSTRACT

Previous studies of synthetic aperture radar (SAR) imagery have shown qualitative relationships between radar backscatter and soil moisture. However, to be able to use these data in operational programs it will be necessary to establish quantitatively how the radar return is related to soil moisture and the effects of surface roughness, soil type, and vegetation cover and growth stage, as a function of frequency and polarization. To this end, a multi-year experiment began in 1990 as a cooperative venture amongst the Canada Centre for Remote Sensing, the Ontario Centre for Remote Sensing, the Land Resource Research Centre (Agriculture Canada), and the Universities of Guelph, Sherbrooke, Laval, and Waterloo.

During 1990, SAR imagery was acquired during two periods (May and July) to correspond to times of minimal and substantial vegetation cover. SAR data were acquired on three days in May and on four days in July to cover different soil moisture conditions. This unique comprehensive data set will be used to investigate the relationships between soil moisture and radar backscatter. This paper describes the experiment and data collected as well as providing a preliminary qualitative interpretation of the relationship between soil moisture and image tone.

INTRODUCTION

The determination of soil moisture is one of the important economic application areas (vegetation condition assessment) of synthetic aperture radar (SAR) which has good potential for success (Schmugge et al., 1980; Dobson and Ulaby, 1986). Starting with the launch of the European Space Agency (ESA) European Remote Sensing Satellite (ERS-1) in 1991, there will be a multitude of SAR sensors in space during the 1990s including the Japanese Earth Resources Satellite (JERS-1) (1992), Shuttle Imaging Radar (SIR-C) (1993,94,95), Radarsat (1994), ESA ERS-2 (1994) and an Earth Observation System (EOS) SAR (1999). In order to effectively use these data operationally it is necessary to establish a quantitative relationship between the radar backscatter and soil moisture which is valid over the wide range of SAR parameters. To address this problem a multi-year experiment was begun in 1990 called OXSOME (**OX**ford County **SO**il **M**oisture **E**xperiment) with the following objectives:

1) To evaluate the capabilities of multi-date, multi-parameter SAR to estimate near surface soil moisture in an agricultural environment for a variety of soils and crops early in the season (post emergence stage) and mid-season (peak growth stage).
2) To develop a robust model relating radar backscatter to soil moisture taking into account surface roughness, crop type, soil texture and other factors which affect this relationship.
3) To evaluate the effects of free canopy water on crop separability information as a function of frequency and polarization.

This latter objective was included to investigate the all-weather capabilities of SAR for crop discrimination.

This experiment was a cooperative venture amongst the Canada Centre for Remote Sensing (CCRS), the Land Resource Research Centre (LRRC) (Agriculture Canada), the Ontario Centre for Remote Sensing (OCRS), and the Universities of Guelph, Laval, Sherbrooke, and Waterloo. In any field experiment, it is difficult, but imperative, to collect a statistically valid data set which correctly characterizes the ground. In this experiment, this was accomplished with great success, by pooling the efforts and resources of 30 persons to generate about 20,000 soil moisture observations as well as an extensive ancillary data set.

Remotely sensed data were collected in May and July under a variety of soil moisture conditions and supported by an extensive ground data set. These ground data included soil moisture (Portable Dielectric Probe (PDP), Time Domain Reflectometry (TDR) and soil bulk density samples), soil surface roughness, crop type and condition information, plant moisture, anomaly investigation, and meteorological information. In addition, corner reflectors and active radar calibrators (ARC) were deployed so that relative and absolute calibration of the SAR data could be carried out.

SITE DESCRIPTION

The study site is located in southern Ontario just south of the town of Norwich. The detailed study site, which is approximately 3 by 6 km, is comprised of three major soil types (Proud et al., 1990) and the fields that were sampled represented an array of different crop types on this variety of soils. Oxford County has been previously used for remote sensing studies and thus a geographic information system database exists for the site.

Table 1
CCRS C/X SAR System Parameters

	Nadir	<u>Mode</u> Narrow Swath	Wide Swath
Resolution (m)	6x6	6x6	Range-20 azimuth-10
Swath Width (km)	22	18	63
Incidence Angle (°)	0-74	45-76	45-85

AIRBORNE DATA

The CCRS airborne SAR (Livingstone et al., 1987, 1988) was used to acquire C- and X-band data at four polarizations (VV, VH, HH and HV) in three modes; nadir, narrow and wide with various resolutions and incidence angles. Table 1 provides a summary of the system parameters of the CCRS SAR for these operating modes. These data were acquired three times in May and four times in July, 1990 just after significant rains. The flights were scheduled to follow the drying of the soil with the additional flight on July 14 used to acquire data while it was raining to address crop discrimination under wet plant and soil conditions. In summary the dates of acquisition and site conditions were as follows:

(a) May 22 and July 10- Soil conditions were very wet, standing surface water was evident on the majority of the fields. However, the soil dried somewhat throughout the day (day 1);
(b) May 23 and July 12 -Soil conditions were less saturated with water. Almost all the surface water had dried. The soil had dried out mainly in the 1 -2 cm surface range (day 2) ;
(c) May 25 and July 13- Soil conditions were considerably drier, with the surface dry from the surface to 5 -7 cm (day 3); and
(d) July 14- The flight took place during a light rain event (about 1 cm of precipitation).

Infrared air photographs were acquired by the Ontario Centre for Remote Sensing on May 22 and on July 19 to coincide with the radar overflights. Ground information was acquired on and between the flight days with priorities established according to the dynamics of the target. Quick Look imagery on silver halide paper from the Real Time Processor in the CCRS aircraft was used for in-situ anomaly assessment. During the experiment these Quick Look images were taken back into the field within a day of data acquisition to determine the cause of anomalous tones on the images (anomaly assessment).

Three ARCs and three corner reflectors were deployed on separate bare soil plots on each of the flights in May and July (in July one was deployed near a sewage pond so that the recirculation signal would propagate over the water) to insure a low backscatter background for each of the calibration devices. During the flight while it was raining (July 14), the ARCs were covered with plastic to protect them from the precipitation. A detailed description of the ARC architecture and operating characteristics can be found in Brunfeldt and Ulaby, (1984) and the use of these devices for calibration of the CCRS SAR is described in Hawkins et al., (1989), Ulander et al., (1990), and Daleman et al., (1990).

The SAR soil moisture experiment plan required both relative and absolute calibration to meet the study objectives. Relative calibration establishes a relationship between the sensor output and a reference source. Hence, relative calibration establishes measurement consistency. Absolute calibration establishes a relationship between the sensor output and a physical quantity (such as a radar cross section of a point target). Hence, absolute calibration provides measurements which are independent of the specific system and directly represent a quantitative and predictable measure of a ground target property.

GROUND DATA SOIL MOISTURE MEASUREMENTS

Twenty-one fields were extensively sampled to determine soil moisture on the May and July flight days using the following instruments/techniques:

- (a) portable dielectric probes (PDP);
- (b) time domain reflectometry instruments (TDR);
- (c) soil sampling (bulk density samples) and sample weighting to extract volumetric soil moisture, bulk density, organic matter, and soil grain size distribution.

The main characteristics of these three instruments/techniques are fully described in: Brunfeldt (1987); Topp et al. (1980), and Cihlar et al. (1987), respectively. The fields were sampled along three transects (Figure 1). There were three "tie points" along the central transect where all three techniques/instruments were used to collect data to establish correlations between the different measuring techniques.

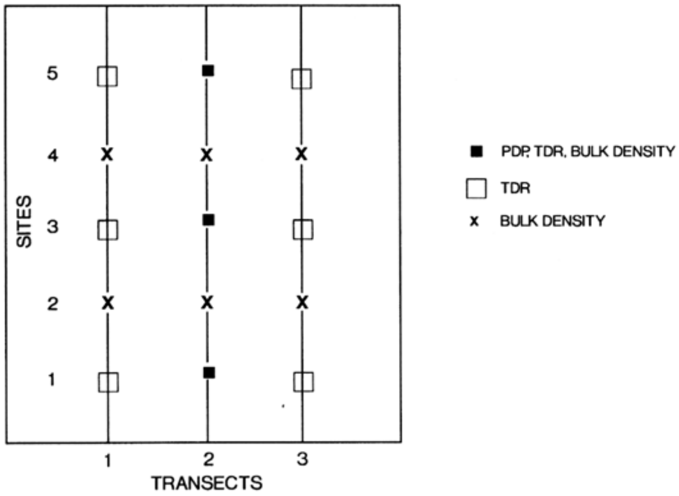

Figure 1. Soil moisture sampling scheme (32 metres spacing between sites).

The PDPs measure the complex dielectric over a small depth (approximately 1 cm), consequently a depth profile of dielectric constant of the soil can be obtained. This profile can then be converted into a volumetric soil moisture profile using algorithms developed at CCRS (Brisco et al., 1991). The OXSOME experiment used four PDP's (two C-bands, one L-band, and one P band). Disks of known dielectric value were used to calibrate the PDP instruments after each flight period. Seven soil dielectric measurements were made at each 2 cm depth intervals from 0-10 cm at sites 1, 3, and 5 of transect 2 (Figure 1).

The TDR instrument (furnished by LRRC) provides a quick, reliable, and non-destructive average measurement of the soil dielectric values over a depth determined by the length of the probe. This average soil dielectric value can be converted into average volumetric soil moisture content using the relationship established by Topp et al. (1980). Accuracies achieved with TDR compare favourably to those obtained using gravimetric techniques. The TDRs were used to make measurements of 0-5, 0-10, and occasionally 0-15 cm layers at sites 1, 3, and 5 on all three transects (Figure 1). Three measurements were made at each depth range.

The bulk density sample technique is the most widely used method to determine soil moisture mainly because of its simplicity. The sample is obtained by vertically pressing a tube of known volume into the soil. The excessive soil at both ends of the tube is then removed to produce smooth/level planes, and the soil is then placed into an airtight bag. Samples were double bagged to prevent water loss and sent to a portable computerized weighing station within hours of extraction. The samples are then oven-dried and were weighed again at LRRC. Six bulk density samples were obtained per site, three at the 0-5 cm layer and three at the 5-10 cm layer. The bulk density samples were taken from all sites on transect 2 and from sites 2 and 4 on transects 1 and 3 (Figure 1). Samples were also saved for further soil analysis which included organic matter content and particle size distribution. The methodology used to acquire samples on the rain flight (July 14) was different due to limited resources and poor field conditions (it rained heavily for the first hour and lightly the second hour). TDR, PDP, and one bulk density sample were obtained at site 1 on each of the transects.

SURFACE ROUGHNESS

The surface roughness measurements were taken on May 24 and 25 and on July 11 using the Surface Roughness Meter model SRM-100 (Brisco et al., 1989; Paterson et al., 1990). This instrument is a two-component system designed to measure the roughness along 50 cm lengths on the ground using a photogrammetric technique. The field component of the system is based upon a 35 mm camera which photographs the target from a height of about a meter. Illumination is provided by a xenon flash which projects a rectangular bar of light onto the target. The camera is mounted at an acute angle to the axis of the projector, and thus the image contains information about the profile of the surface along the two edges of the bar.

The laboratory component of the system is an micro-computer interfaced to a solid-state video camera. The images of the light bars on the 35 mm negatives film are digitized and the subsequent analysis of the images provides full (x:y:z) profiles of each edge of the projected bar of light, RMS heights, and correlation lengths. The SRM-100 system was calibrated by using a photograph of a flat surface as an image positioning point. In addition to this fiat-surface calibration process, three additional artificial surfaces, (rough, medium and fine), were measured to further compare the SRM-100 method of measuring with other surface roughness instruments. The results of the roughness calibration indicate accuracies of ~ 1 mm in RMS and 5 mm for correlation length (Winebrenner et al., 1991).

For this experiment a roughness measurement consisted of six separate photographs, three perpendicular and three parallel to the row direction. In May, the roughness of five of the 21 detailed fields was measured at sites l, 3, and 5 on all three transects. Also roughness measurements were obtained for many bare and semi-bare fields that appeared to have different roughnesses in the general study site. For the July sortie, roughness measurements were taken on four of the original May fields and on one extra field (bean field). These were taken on transects 1 and 3 at sites l, 2 and 3.

VEGETATION SAMPLING

Vegetation biomass samples were obtained from all fields where soil moisture measurements were acquired, if sufficient plant cover existed. This was done once during the May and once during the July flight period. One sample was cut with a knife at the soil surface from sites l, 3 and 5 on all three transect lines. The grain, pasture, alfalfa, and bean samples were cut from a twenty-five cm square. The corn plants were sampled as whole plants, and the number of plants per meter row was recorded. Biomass samples were placed in two plastic bags to prevent moisture loss, weighed within two hours of extraction, then dried at 70 degrees C, and weighed again to obtain the dry weight.

Biomass sampling was also conducted during the rainfall on July 14. Wet canopy biomass samples were acquired from site 1 on all three transect lines (Figure 1). The general methodology was the same as the dry canopy biomass methodology, but the samples were bagged in a way that attempted to capture all the canopy water. This was done by placing the plant material in the bag before cutting it away from the ground.

The following general ground information was also collected on each field within the study site using procedures described in King and Mack, (1984): vegetation/crop type, plant maturity, percentage of cover, plant condition, weed infestation, canopy height, row direction and spacing, photographs of each field, and general comments.

METEROLOGICAL DATA

Three farmers within the study site recorded temperature and precipitation measurements from May 1 to July 31. In addition, a Campbell Scientific portable weather station was set up on the site. The weather station recorded hourly information on the temperature, humidity, wind speed, and precipitation. Further weather data and storm radar information were also obtained from Environment Canada. Another 15 rain gauges were set up prior to the July 14 wet SAR flight. These rain gauges were placed at three different locations within the fields (i.e. between plants along a row, between rows, and in an adjacent bare field). The data obtained from the rain gauges will qualitatively aid in determining how much water actually reached the soil surface and how it is distributed within the canopy. During the rain-day acquisition about 10 mm of rain fell, within the first hour of the two hour event followed by light rain in the second hour.

Table 2

Summary of Roughness Statistics for Bare Fields in May

Number of Fields	RMS Height (mm)		Correlation Length (mm)	
	Min	Max	Min	Max
65	2.53	33.70	7.0	52.0

Table 3

Summary of 0.5 cm Gravimetric Soil Moisture (gm/cm^3) Content for May

Date	Sand	Clay
May 22	21.7 ± 4.8	31.1 ± 1.1
May 23	20.7 ± 4.9	28.7 ± 2.1
May 25	18.8 ± 4.5	22.5 ± 1.7

QUALITATIVE INTERPRETATION

At the time of this writing the ground data have been checked for quality control and put into digital format for subsequent analysis. The qualitative evaluation of these data indicate the excellent nature of this data set and the wide range of soil moisture and surface roughness conditions prevalent during the experimental period. For example the data in Table 2 summarizes the roughness statistics from 65 fields measured in May. The data represent a large range of conditions from quite smooth (RMS=2.53 mm) to quite rough (RMS=33.7 mm). The May gravimetric soil moisture data for a "sandy" versus a "clay" field are given in Table 3. The sandy field is considerably drier on day 1 (May 22) with about a 10% decrease in soil water content when compared to the clay field. This difference is only about 4 % by day 3 (May 25). These results are also supported by the PDP data shown in Figures 2 and 3. Here the progressive drying of the soil profile and increasing depth of the wetting front is apparent. The convergence of soil moisture content for the sandy and clay fields over the experiment period is also supported in these figures. The qualitative interpretation of the ground data was very promising, as these results show, and excellent quantitative results are expected.

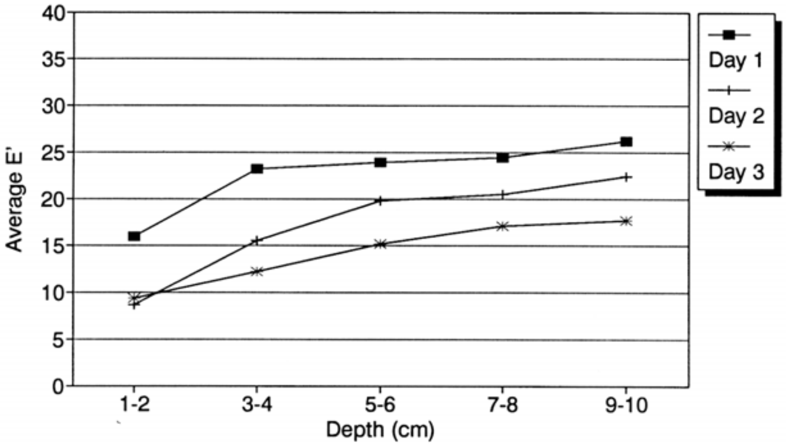

Figure 2. The dielectric constant verses depth of a sandy field for the three flights in May.

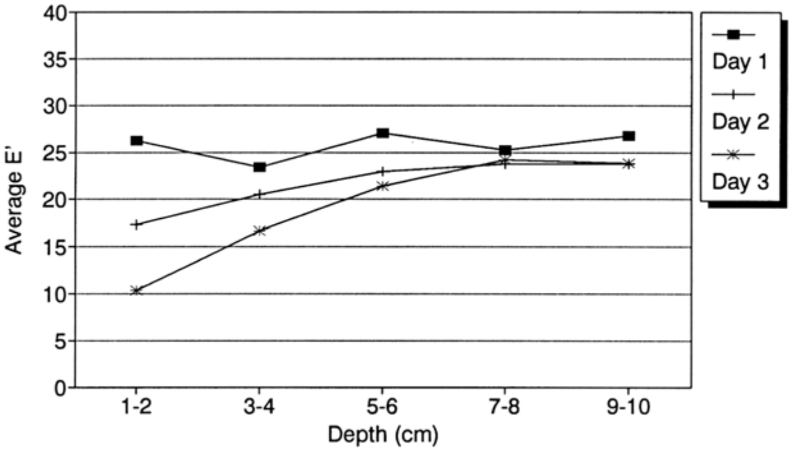

Figure 3. The dielectric constant verses depth of a clay field for the three flights in May.

This is supported by an image interpretation of a three-band colour composite shown in Figure 4. This image is a combination of C-W (red), C-HV (green), and C-HH (blue) narrow swath data from May 22 and clearly demonstrates several aspects of the data set. First of all, notice that the field marked A on Figure 4, which is alfalfa, has a lower backscatter than the bare fields in all polarizations and thus are very dark on the colour composite. Thus the vegetation appears to be attenuating the radar backscatter and thus severely limiting the information content on soil moisture content. Secondly, notice the range of backscatter in the bare fields indicating different polarization response from the bare soil. Roughness, row direction and soil water content could all play a role in determining these differences, which will be investigated in later analyses. Also note the area marked B in Figures 4 and 5 where there is a marked change in backscatter due to the soil change from a sandy soil to a heavier textured clay soil. This soil type change is very evident on the SAR false colour image and shows up clearly in the aerial photography (Figure 5) as well. These relationships will be studied in detail once the data is calibrated, which is the next step in the overall analysis plan.

Figure 4. False colour SAR composite of C-W, C-CH, and C-HH narrow swath data from May 22.

Figure 5. A colour infra-red photograph of the study area showing the change from clay to sandy soil.

This paper is intended to give an overview of the airborne and ground data set which was acquired during OX SOME 1990. There will be a considerable number of scientific publications on the results of the analysis which will appear in the open literature in the next couple of years.

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