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The Use of SAR Satellite Imagery to Measure Active Layer Moisture Contents in Arctic Alaska

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Synthetic aperture radar (SAR) has the potential for measuring near surface soil moisture contents for very large areas. The polar orbiting European Remote Sensing satellite (ERS-1) of the European Space Agency (ESA) has onboard an active C-band SAR sensor. We have analyzed SAR imagery over a small research watershed, Imnavait Creek, located in the northern foothills of the Brooks Range in Alaska, U.S.A. This watershed is treeless and completely underlain with permafrost. After geometrically and radiometrically correcting each pixel (25 m by 25 m) in the image, corrected pixel values were correlated with corresponding field moisture contents measured along transects in the watershed for two passes of the satellite. Coefficients of determination, r^2, between the corrected pixel value and measured moisture content were 0.49 on June 12, 1993 and 0.53 on August 2, 1993; with the data sets combined the value was 0.50.

Introduction

The ability to measure soil moisture levels spatially has long been recognized as a desirable goal and was recently accomplished with remote sensing for a watershed in Ontario, Canada by Pietroniro *et al.* (1993). It has also been understood that this could only be achieved by remotely sensed methods (Engman and Gurney 1991) and that synthetic aperture radar may be the tool that could achieve this task. Hydrologic models that incorporate both chemical and biologic processes are becoming more common. To include these processes, it is necessary for the hydrologic model to be physically based and spatially distributed. Soil moisture distribution, deter-

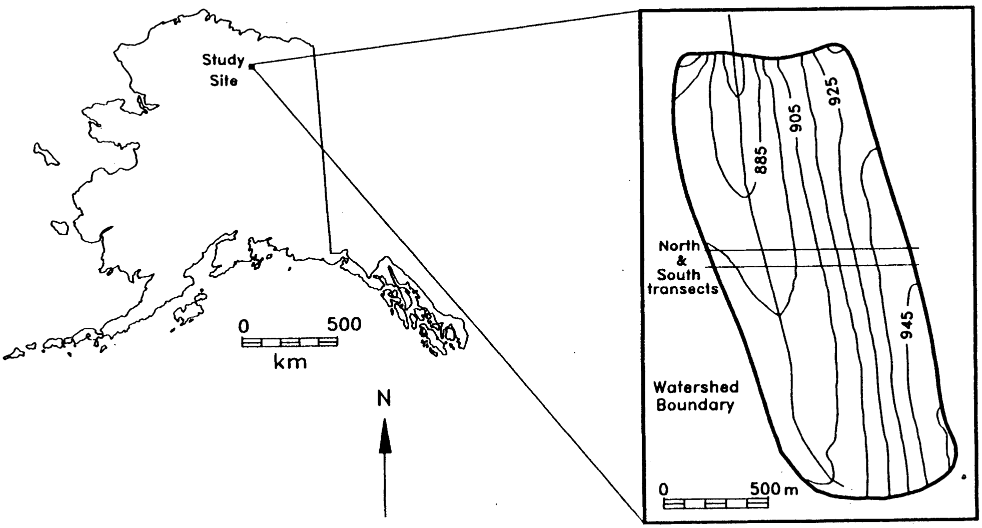


Fig. 1. The study site was located in Imnavait Creek Watershed (68°37'N, 14917'W), on the North Slope of Alaska, U.S.A.

mined from SAR imagery, could be used to initialize a model data set, but more importantly, it could be used to evaluate the performance of the model at selected times during the simulation. To date, we have not had the spatial data to adequately test spatially distributed models.

Presently there is considerable interest in the arctic terrestrial areas of the world because of the issue of climate change. Large carbon reserves have accumulated in these areas in the historic past and potentially have the capability of producing greenhouse gases such as carbon dioxide and methane at greater rates in warmer climate scenarios. Hydrologic processes, specifically soil moisture dynamics in the active layer, can play a key role in controlling the magnitude of the greenhouse gas fluxes. We have developed a physically based, spatially distributed hydrologic model of arctic processes that are driven by snowmelt and rainfall and include thawing and freezing of the active layer, snowmelt and evapotranspiration rates, and subsurface, surface and channel flow. If SAR imagery can be used to determine soil moisture levels, this data can be used not only to initialize the model, but also to determine the performance of the model spatially. The suitability of most models is judged by comparing the predicted runoff to measured runoff; the fallacy of this is that the researcher does not have a measure of how the model is performing spatially, and errors that accumulate in one area may be offset by errors in another area.

For a small arctic watershed, Imnavait Creek (2.2 km^2, Fig. 1), we have compared pixel values of SAR imagery to measured field values of soil moisture. Reported in the following sections are the techniques we used to develop relationships for predicting near surface soil moisture of the active layer.

Satellite Capabilities

ESA launched ERS-1 on July 17, 1991 in a polar orbit at 780 km hight. The satellite circles the globe once about every 100 minutes. On board are three radar systems that can penetrate the cloud cover and collect data at any time of the day; they are the active microwave system (SAR) that we are using to measure soil moisture, a radar altimeter system capable of very accurately measuring the satellite's height above sea level, and a radiometer for measuring surface temperatures. At present, the SAR system can be operated for 12 minutes per orbit, doubling the expected coverage.

Data from the satellite is downloaded to many sites, including the Alaska SAR Facility at the University of Alaska Fairbanks. The active microwave frequency of the SAR transmitter is 5.3 GHz (C-band) and results in an uncorrected image of 100 km by 100 km. The resolution along and across the track after processing is 25 m. The frequency of coverage for our study area depends upon the orbit of the satellite. In 1991, the frequency was about once every three days with the satellite in repeating tracks, but the satellite orbit was changed for sea ice studies after calibration, and currently the coverage is less frequent.

The look angle of the SAR instrumentation is approximately 23° from vertical at the mid-point in the swath. This and the fact that the satellite is usually not in the same orbit means that when the sensor is aimed at the surface the local incidence angle can vary for each pixel depending upon the slope and aspect of the ground surface. In image processing, it is necessary to geolocate pixels on the image. When corner reflectors are installed on the ground they produce high returns that show up as bright spots on the image and therefore are very easy to identify and use for locating the image. Next, since the angle that the beam makes with the ground can vary depending upon local terrain, geometric terrain corrections must be made. Finally, radiometric corrections must be made because of terrain. For example, two physically identical pixels, one on an east-facing slope and one on a west-facing slope, should have the same pixel brightness if they are identical and viewed from the same angle. But if the local incidence angle is not the same, the return active radar signal from the slope facing away from the satellite will be lower because a smaller fraction of the signal is returned in the direction of the sensor (Goering *et al.* 1994).

Once all of the above corrections have been made to the image, then it can be analyzed for signal variations that may be due to surface roughness, vegetation, soil moisture, *etc.*

Study Site

Arctic regions of the world comprise 11% of the land surface area and although they are important in global dynamics, relatively little is known about them. Remote sensing offers an opportunity to collect large amounts of data that otherwise would not be possible. The ERS-1 satellite, with its microwave sensors, offers a good occasion to measure soil moisture over large spatial areas.

The area selected here is Imnavait Creek Watershed, located in the northern foothills of the Brooks Range (latitude 68° 37' N, longitude 149° 17' W). This arctic watershed has been the subject of considerable research since 1985. Imnavait Creek (2.2 km^2) is a north-draining headwater stream of the Kuparuk River at 900 m elevation. Pleistocene glaciation and subsequent erosion have produced rolling terrain with a frequency of 1 to 2 km and amplitude of 25 to 75 m locally. This area of the Alaskan Arctic is treeless and underlain by continuous permafrost with a thickness of 250 to 300 m in the Imnavait Creek area. Typical active layer thickness is about 50 cm (Hinzman *et al.* 1991) with depths being greater in better drained soils and less in poorly drained soils.

The watershed is dominated by a west facing slope that constitutes 78% of the basin area with slopes varying from 10% to 13%. The east-facing slope represents 17% of the basin area with slopes ranging from 1% at the headwater to 7% at the outlet. The remaining 5% of the watershed is the poorly drained valley bottom.

Soils of Imnavait Creek are listed as Histic Pergelic Cryaquepts and consist of about 10 cm of live and dead organic material over 5 to 10 cm of partially decomposed organic material mixed with silt, all over glacial till (Hinzman *et al.* 1991). Vegetation is mostly water tolerant plants such as tussock sedges and mosses associated with lichens and shrubs such as dwarf birch, alder and willows. Tussock sedges are common on ridge tops and slopes, but lacking in the valley bottom. Mosses are dominant in the valley bottom where the environment is usually the wettest.

Utilizing SAR Imagery to Measure Soil Moisture

The major factors that influence the microwave return signal from earth's surface to the ERS-1 satellite are topography, surface vegetation, surface roughness, soil moisture and whether the soil is frozen or unfrozen for the penetration depth of the radar. The effect of each of these factors on the returning radar signal strength has been studied by using towers, aircraft and passive satellite radar prior to ERS-1. Soils are made up of many constituents, all of which have different dielectric permittivities. Bulk water has a permittivity, ε, of 80, bound water is 3, mineral soil is 4 to 8, and air is 1 (Chanzy 1993). The value for a given soil depends upon how much of each constituent is found in the soil. Water as ice in frozen soils is similar to mineral soils (Stein and Kane 1984). The soil dielectric permittivity determines the amount of electromagnetic energy that is reflected by the soil, and the soil roughness governs the directional distribution of the reflected wave (Chanzy 1993).

Vegetation is a surface feature that can significantly alter the microwave signal. One of the reasons we felt that SAR imagery may be a good tool for measuring soil moisture in the Arctic was the complete lack of trees and the fact that surface vegetation was sparse and small. Prevot *et al.* (1993) examined the possible use of SAR for monitoring agricultural canopies. Ulaby *et al.* (1982) found that it was difficult to determine moisture contents on vegetated sites when the moisture content was low; the masking effect of the vegetation limited their ability to accurately determine soil moisture. Dobson and Ulaby (1981) found that signal attenuation by crop biomass could be minimized by using frequencies below 6 GHz and incidence angles less than 20°. This compares to the SAR criteria of 5.3 GHz and 23°.

Surface roughness has been raised as a physical feature that could alter the radar signal. It has already been mentioned that surface roughness influences the distribution of the scattering wave at the surface. Chanzy (1993) gives the following equation to quantify the surface roughness:

$h \gg \lambda / (8\cos(I))$ rough
$h \approx \lambda / (8\cos(I))$ medium roughness
$h \ll \lambda / (8\cos(I))$ smooth

where $h \equiv$ roughness height $\lambda \equiv$ wave length $I \equiv$ incidence angle

For the ERS-1 satellite, h equals about 1 cm, while field measurements in Imnavait watershed average about 8 cm with a standard deviation of 2.5 cm, so the surface is definitely rough.

The depth of penetration of the radar into the soil is strongly controlled by the moisture content and the fact that the dielectric properties of water are so much greater than the remaining components of the soil system. Bruckler *et al.* (1988) have shown that for soils with moisture contents of 10% by volume, that the depth of penetration of the radar is about 5 to 6 cm and much less for wetter soils. The return wave is derived from surface scattering in addition to that component produced by the soil.

Surface texture has also been identified as a variable that influences the return signal (Hallikainen *et al.* 1985; Dobson *et al.* 1984). However, one has to be careful because the moisture content is also related to texture. Characteristic curves that relate extraction pressure to moisture content have been developed for many typical soils. It is a well known fact that water retention is strongly correlated to surface areas and those soils that have the greatest surface area retain the greatest amounts of water at a given soil water pressure. The important fact here is that not all the water in soil has the same dielectric properties; for example, water closely bonded to the soil surface has similar properties to that of the soil (Chanzy 1993) while the bulk water has a much higher dielectric value. Whether water is frozen or thawed has a dramatic effect on SAR pixel values (Villasenor *et al.* 1993). Where ponded water exists, the backscatter attenuation coefficient, σ_0, is influenced by both the surface dielectric and the specular response (Merot *et al.* 1994). Merot *et al.* attempted to identify variable source areas for hydrologic modeling from SAR imagery.

SAR Imagery Terrain Correction Model

In order to obtain an accurate representation of the soil moisture distribution, one must first remove radiometric terrain distortion from the SAR imagery. This type of distortion tends to increase image pixel values on slopes that face toward the satellite and decrease those on slopes facing away from the satellite. For terrain with moderate relief, such as that in the Imnavait watershed, this terrain-induced distortion can alter pixel values substantially.

Removal of radiometric terrain distortion in regions of arctic tundra has been the focus of a recent investigation by Goering *et al.* (1994). In this study a radiometric terrain correction algorithm was derived and then calibrated for arctic tundra. The algorithm treats the backscattered radiation as a combination of diffuse and specular components. During the correction process, each pixel in the original image is multiplied by a correction factor that is a function of local topography and the SAR imaging geometry. This factor is given by the following expression

$$\frac{d_{nc}}{d_n} = C\left(\frac{\cos\theta}{\sin\alpha\,\cos\beta}\,(k_{ds}\cos\theta + \cos^n 2\theta)\right)^{-\frac{1}{2}}$$

where

d_{nc}	=	corrected pixel value
d_n	=	original pixel value
θ, α, and β	=	angles obtained from the relation between the local normal vector at the ground surface and the satellite view direction
k_{ds}	=	a parameter which represents the relative importance of diffuse and specular backscatter
n	=	a parameter which controls the width of the specular beam
C	=	a constant which is a function of the reference angles used for the correction.

Once calibrated, this algorithm can be used to effectively remove radiometric terrain distortion from SAR images. Plotted in Figs. 2a and 2b are terrain corrected images for June 12 and August 2, 1993. Notice that the topographic sensitivity to moisture levels now appears quite evident, yielding high pixel values in valley bottoms and low values on ridges.

Field Program

For two passes of the ERS-1 satellite (Table 1), on June 12, 1993 and August 2, 1993, extensive field soil moisture data was collected along established transects from ridge to ridge across Imnavait Creek (Fig. 1). Every 25 m, soil moisture samples were collected from the upper 10 cm of soil, one sample from a high point and one sample from a low point. These samples of a known volume were returned to

Fig. 2a.

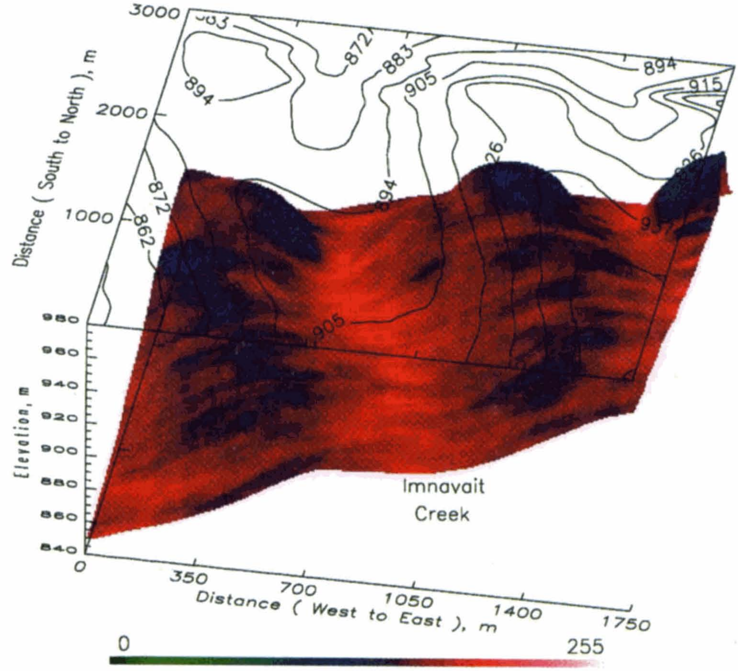


Fig. 2b.

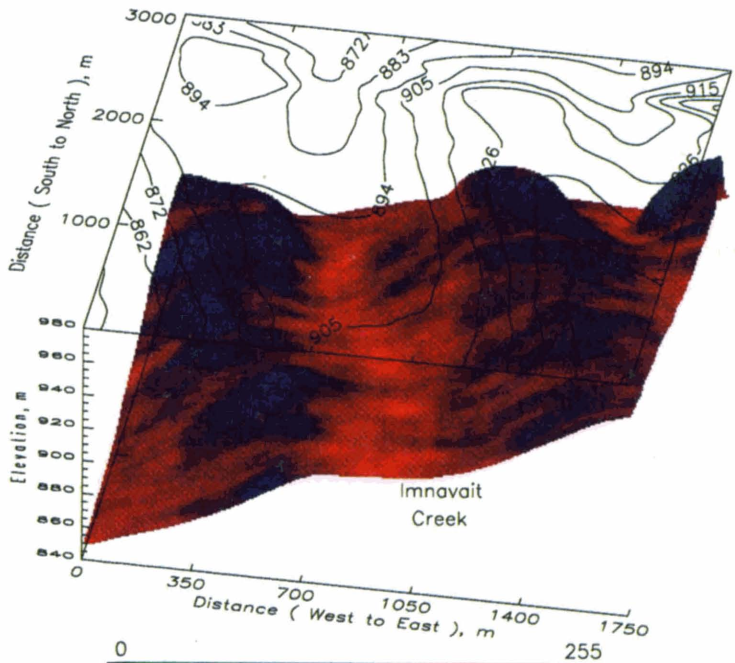


Fig. 2. Terrain corrected ascending SAR image of test area, North Slope of Alaska, U.S.A., a) June 12, 1993 (© EASA 1993) b) August 2, 1993 (© ESA 1993).

Table 1 – SAR data configuration

Scene center time	June 12, 1993	August 2, 1993
Platform ID	E-ERS1	E-ERS1
Sensor ID	SAR	SAR
Mode	C-Band	C-Band
Frequency	5.3 GHz	5.3 GHz
Polarization	VV	VV
Wave length	5.66 cm	5.66 cm
Sensor clock angle	90 degree	90 degree
Image pass	Descending	Descending
Resolution	25 m × 25 m	25 m × 25 m
Center Lat./Long.	68.517/-150.0519	68.423/-149.4264
Heading	203.28 degree	203.19 degree
Image size	8192 × 8192	8192 × 8192
Center incidence angle	23-079 degree	23.082 degree
Mean sample value	99.1477	93.349
Processing facility	ASF	ASF

the laboratory where the soil moisture content and the bulk density were determined. Organic soils were dried in a microwave oven until the dried weight remained unchanged. At the time of field measurements, surface roughness was measured at the same points by measuring a number of surface heights and then averaging them.

Continuous meteorological data are collected within 1 km of the transect. This data has been used to assist in analyzing the sensitivity of SAR imagery to change in meteorologic conditions (Villasenor *et al.* 1993). Data collected include precipitation, air temperature, relative humidity, wind speed, wind direction, incoming and reflected short wave radiation, incoming and emitted long wave radiation, net all-wave radiation and evaporation pan. Numerous field sites exist where soil moisture profiles in the active layer are measured about twice per week, using time domain reflectometry (TDR). Measurements, including soil temperature, are made about every 5 cm.

Correlation of SAR Imagery and Field Moisture Contents

During the first summer of operation of the ERS-1 satellite (1991), we had access to a number of images where the satellite looked at the watershed from essentially the same position. This allowed us to evaluate changes that occurred with time in the imagery for hillslopes with similar slopes and aspect without having to make terrain corrections. With very little change in the vegetation, we did observe changes occurring in the pixel values. We attributed these to changes in soil moisture, in one case due to significant rainfall. The other characteristic of these images that encouraged us to continue pursuing the use of SAR imagery for soil moisture was the ability to detect drainage patterns. Areas that should be wet were indicated as such, for example along drainages and valley bottoms, and those areas that should be dry were so indicated. Small drainage features on the hillslope known as water tracks were also apparent in the images.

Before we could proceed any further, we had to make terrain corrections as described above. The next step in the study was to take the terrain-corrected SAR images and determine what pixels corresponded to the points on the ground where the field measurements were made. This task is relatively easy since a readily identified corner reflector is located very close to the transect. There are also other features that are easily recognizable in the SAR images as a check.

Both field measurements of soil moisture and geometrically and terrain-corrected SAR images were obtained for June 12 (Fig. 2a) and August 2, 1993 (Fig. 2b). Along the same transect where field soil moistures were determined, pixel values are plotted (Figs. 3a, 3b and 3c). Terrain corrected pixel values are then plotted against measured soil moistures (Figs. 4a, 4b and 4c). Realistically there is considerable variation in each pixel area because of the make-up of the terrain. At least 75% of the watershed area is covered by tussocks with considerable vertical variation in the moisture gradient (Walker and Walker 1996). Therefore sampling in the field to obtain the average moisture content over a pixel area is quite difficult.

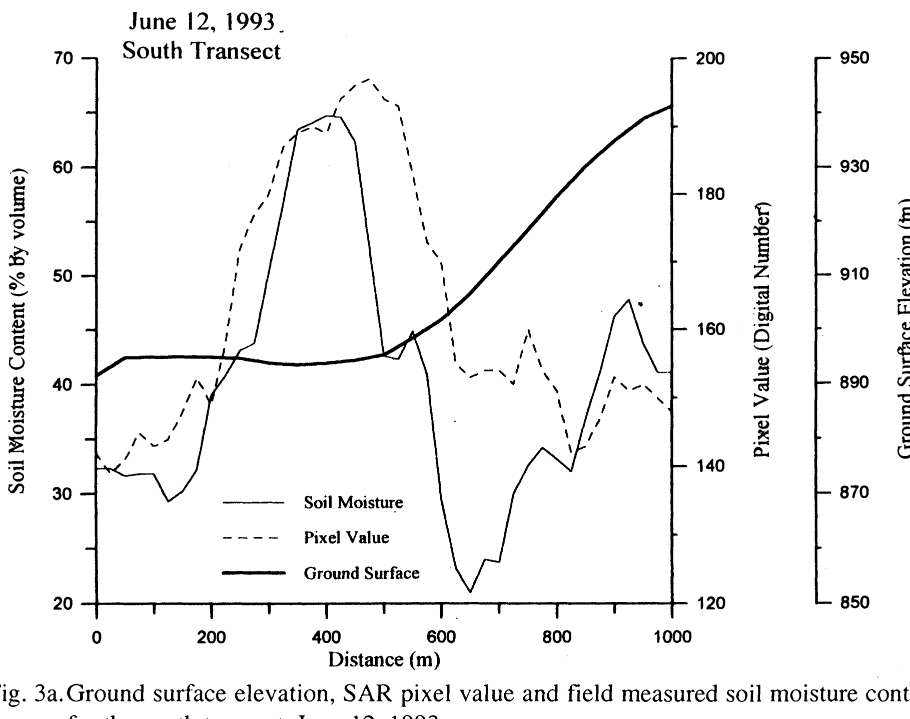


Fig. 3a. Ground surface elevation, SAR pixel value and field measured soil moisture content for the south transect, June 12, 1993.

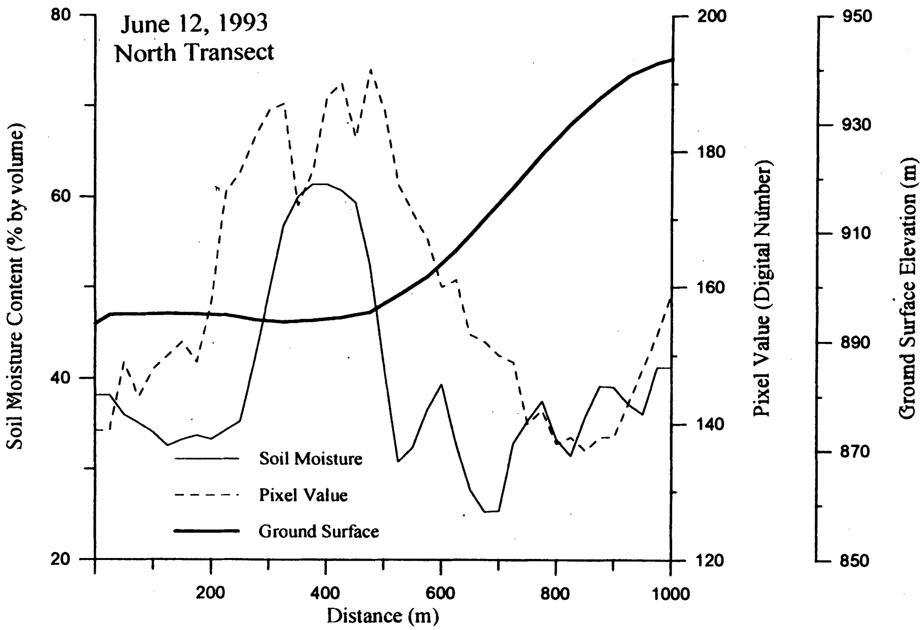


Fig. 3b.Ground surface elevation, SAR pixel value and field measured soil moisture content for the north transect, June 12, 1993.

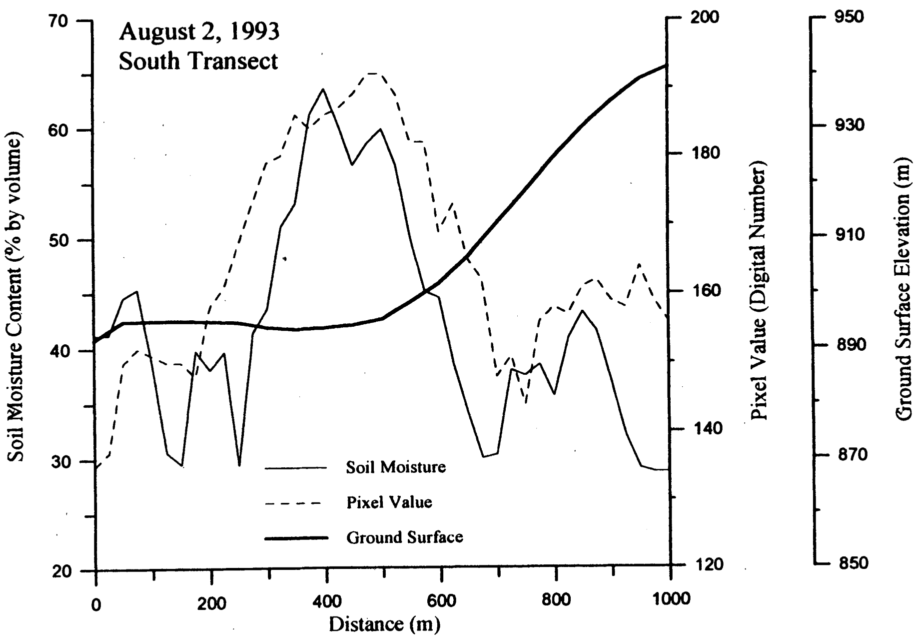
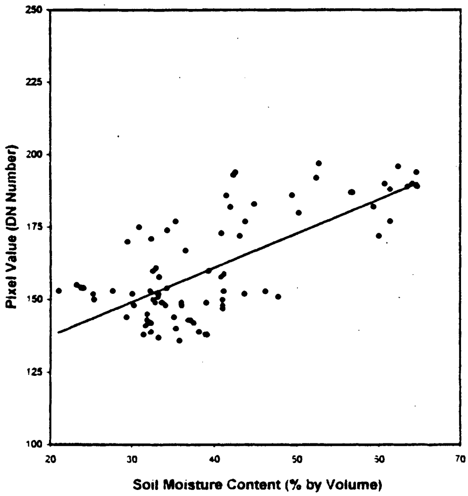
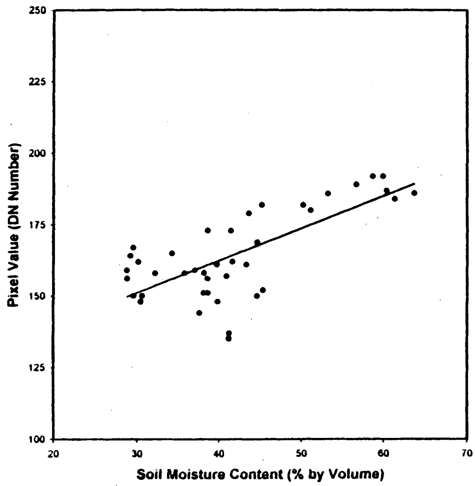


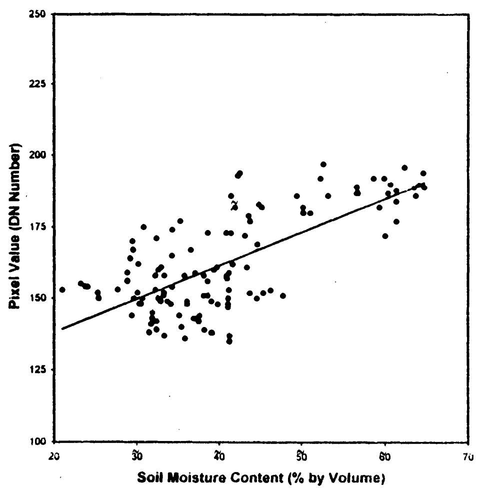
Fig. 3c.Ground surface elevation, SAR pixel value and field measured soil moisture content for the south transect, August 2, 1993.



4a) for all data collected June 12, 1993.



4b) for data collected August 2, 1993.



4c) for combined data sets.

Fig. 4. Relationship between surficial soil moisture (top 10 cm) and terrain corrected SAR pixel values.

Three regression equations are derived for measured soil moisture and pixel values for the imagery of June 12 and August 2 and also a combined set of data

$$V_{pixel} = 1.18(\mathrm{Soil}_{mc}) + 114 \qquad r^2 = 0.49 \quad \text{June 12}$$
$$V_{pixel} = 1.13(\mathrm{Soil}_{mc}) + 117 \qquad r^2 = 0.53 \quad \text{August 2}$$
$$V_{pixel} = 1.17(\mathrm{Soil}_{mc}) + 115 \qquad r^2 = 0.50 \quad \text{Combined}$$

where

$Soil_{bd}$ – dry bulk density of soil in g/cm^3
h_{rough} – terrain roughness height in cm

This correlation neglects the effects of vegetation, surface roughness and soil texture. Including vegetation type as an independent variable in a regression analysis improves these relationships somewhat. This is probably due to the fact that vegetation type is closely correlated with surface roughness and surface soil density. We have regressed bulk density of the soil (surrogate for soil texture), soil moisture and surface roughness against the pixel value for the two images and a combined data set :

$$V_{pixel} = -14.6\{Log(Soil_{bd})\} - 0.438\{Log(Soil_{bd}) \times Soil_{mc}\} - 9.02\{Log(h_{rough})\} + 96.5 \qquad r^2 = 0.72$$

$$V_{pixel} = -6.82\{Log(Soil_{bd})\} - 0.414\{Log(Soil_{bd}) \times Soil_{mc}\} - 1.07\{Log(h_{rough})\} + 140 \qquad r^2 = 0.57$$

$$V_{pixel} = -6.49\{Log(Soil_{bd})\} - 0.421\{Log(Soil_{bd}) \times Soil_{mc}\} - 6.67\{Log(h_{rough})\} + 115 \qquad r^2 = 0.64$$

where

V_{pixel} – terrain corrected pixel value on the SAR image
$Soil_{mc}$ – volumetric moisture content of the upper 10 cm in%

These relationships show some improvement in our understanding as to what influences the SAR return signal. The problem is that on a watershed scale we generally do not have measurements of surface roughness and soil bulk density. The potential exists for utilizing a vegetation map to ascertain both surface roughness and dry bulk density, but they are only available in detail for very small areas.

If ponding of water occurs on the surface, then decorrelation between moisture content and SAR pixel values may occur due to specular reflectance of radar signal (Merot *et al.* 1994). Although much of the valley bottom in this watershed does become saturated, the total area of ponds or standing surface water is quite small.

It may be possible to improve periodic predictions of soil moisture in a given area if one were to use a differencing technique (Villasenor *et al.* 1993). If one collects a time series of co-registered images of the exact same area and a series of soil moisture measurements, then it may be possible to filter the effects of surface roughness and soil density, which may be considered constants. It may be necessary to begin with a measured value of soil moisture, and the calculate changes in soil moisture over short time periods where vegetative changes are minor.

Conclusions

ERS-1 SAR imagery displays a very strong correlation with terrain, and before one may extract other useful information from this imagery, it is first necessary to correct the pixels values to minimize the effect of terrain. After the influence of terrain, SAR is primarily impacted by soil moisture, surface roughness and surface soil density. A method has been presented to obtain useful information on distributed levels of soil moisture. Before SAR imagery can be reliably used to operationally determine soil moisture, additional work must be undertaken to separate the effects of surface roughness and soil density. Although additional research is warranted, SAR imagery displays considerable promise for monitoring soil moisture levels in areas of low vegetative cover.

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