Radar mapping of surface soil moisture

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Abstract

Intended as an overview aimed at potential users of remotely sensed spatial distributions and temporal variations of soil moisture, this paper begins with an introductory section on the fundamentals of radar imaging and associated attributes. To place the soil moisture sensing task in proper perspective, the prerequisite step of classifying terrain into four basic types—bare surfaces, short vegetation, tall vegetation, and urban—is addressed by demonstrating how dual-frequency polarimetric radar can correctly classify terrain with an accuracy greater than 90%. Over 5000 image pixels with known terrain identity were involved in the evaluation of the radar image classifier. For bare soil (with vegetation cover shorter than 15 cm), radar can estimate the volumetric moisture content (expressed in percent) of the top 5 cm soil layer with an m.s.e. of 3.5%. Based on theoretical model predictions as well as experimental observations, strong evidence exists in support of radar’s potential for sensing soil moisture under vegetation cover, but no operational algorithm exists at present.

1. Imaging radar overview

High-resolution imaging radar systems operate in a side-looking mode as illustrated in Fig. 1. The imaging radar configuration most commonly used today is the synthetic aperture radar (SAR) which transmits a series of pulses as the radar antenna flies across the imaged scene, and then these pulses are processed together to simulate a very long aperture capable of very high angular resolution along the direction of flight (Ulaby et al., 1982; Elachi, 1988; Curlander and McDonough, 1991). The along-flight direction is usually called the azimuth direction and the direction across the imaged swath is called the ground-range direction. The
The purpose of this section is to present an overview of the operational characteristics of an SAR system and to relate the quantities measured by the radar to the scattering parameters of the imaged scene. To focus the discussion on spaceborne SARs in particular, we shall often use the Shuttle Imaging Radar-C (SIR-C) for...
illustration purposes (Fig. 2). SIR-C, which flew on the Space Shuttle in April and October 1994, is a joint US-European design consisting of two polarimetric SARs operating at L-band (23.5 cm wavelength) and C-band (5.8 cm wavelength), both designed and built by the Jet Propulsion Laboratory (JPL), and a single polarization SAR operating at X-band (3.1 cm wavelength), built by a joint German-Italian consortium. Table 1 provides a summary of the SIR-C-X-SAR system characteristics (Jordan et al., 1991).

1.1. Single-look vs. multi-look resolution

The single-look resolution of an SAR system refers to the resolving capability that

<table>
<thead>
<tr>
<th>Parameter</th>
<th>L-Band</th>
<th>C-Band</th>
<th>X-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital altitude (km)</td>
<td>225</td>
<td>225</td>
<td>225</td>
</tr>
<tr>
<td>Wavelength (m)</td>
<td>0.235</td>
<td>0.058</td>
<td>0.031</td>
</tr>
<tr>
<td>Resolution (m)</td>
<td>-30 x 30</td>
<td>-30 x 30</td>
<td>-30 x 30</td>
</tr>
<tr>
<td>Swathwidth (km)</td>
<td>15-90</td>
<td>15-90</td>
<td>1540</td>
</tr>
<tr>
<td>Look angle range (from nadir)</td>
<td>17-63°</td>
<td>17-63°</td>
<td>17-63°</td>
</tr>
</tbody>
</table>
A dual-polarized radar antenna has two sets of elements, one for transmitting (or receiving) waves with horizontally polarized electric fields and the other for vertically polarized electric fields.

Wave polarization refers to the direction of the electric field of the electromagnetic wave transmitted or received by a radar antenna. For a horizontally polarized antenna, its elements are configured to transmit or receive waves whose electric field points only along the length of the antenna (Fig. 3), which is also parallel to the Earth’s surface. The electric field direction for a vertically polarized antenna is along its height dimension, as illustrated in Fig. 3.
waves are scattered by terrain surfaces and volumes (such as vegetation) is a function of the polarization of the incident wave, radars use multiple polarizations to image terrain, to increase the amount of information extractable from radar images. If the incident wave is horizontally polarized, the energy backscattered towards the radar will, in general, consist of a wave that is also horizontally polarized, as well as a wave that is vertically polarized. The latter is referred to as cross-polarized.

A polarimetric radar, such as the L-band and C-band SAKS of SIR-C, is capable of measuring the radar response for VV, HH, HV, and VH, where the first letter denotes the polarization of the receive antenna and the second letter denotes the polarization of the transmit antenna. Because of a reciprocity property of radar scattering, the responses for HV and VH are identical. The quantity measured by the radar is called a scattering matrix, which later is converted to the scattering coefficient $\sigma^o$ (Ulaby and Elachi, 1990). The scattering coefficient, which is a unitless quantity representing the radar cross-section (in m$^2$) of a given pixel on the ground per unit (physical) area of that pixel (in m$^2$), is akin to the optical reflectivity responsible for the intensity recorded by an optical imaging system. To denote the receive–transmit polarization combination associated with the scattering coefficient, the latter is denoted by $\sigma_{ij}^o$, where $i,j = HH$ or V. Often, because $\sigma_{ij}^o$ may exhibit a wide dynamic range, it is expressed in decibels:

$$\sigma_{ij}^o (\text{dB}) = 10 \log_{10} \sigma_{ij}^o (\text{m}^2 \text{m}^{-2})$$

(3)

In addition to measuring $\sigma_{hh}^o$, $\sigma_{vv}^o$, and $\sigma_{hv}^o$, which collectively are referred to as the multi-polarized magnitudes of the scattering response, a polarimetric radar can measure the polarization phase differences between the multi-polarized backscattered waves: co-polarized phase difference:

$$\phi_{c} = \phi_{hh} - \phi_{vv}$$

(4)

cross-polarized phase difference:

$$\phi_{x} = \phi_{hv} - \phi_{vh}$$

(5)

In practice, $\phi_x$ has not been found to contain much useful information about the imaged scene. In contrast, the co-polarized phase difference $\phi_{c}$ has proved to be a very useful parameter in image classification.

In summary, a polarimetric radar is capable of producing five basic products of the imaged scene, namely three images representing the magnitudes $\sigma_{hh}^o$, $\sigma_{vv}^o$, and $\sigma_{hv}^o$, and two images representing $\phi_{c}$ and $\phi_{x}$. All five co-registered images are manifestations of the scattering character of the scene, and are independent of all system parameters except for the wavelength $\lambda$ and the incidence angle $\theta$ at which the scene is imaged.

1.3. Swathwidth

SIR-C was designed to generate images with swathwidths varying between 15 km and 90 km, depending on the specific mode selected for imaging. The different modes
correspond to different combinations of bands, polarizations, and spatial resolution. The constraint is imposed by the data rate allowable by the TDRS communication channel. Conceptually, it is possible to image the terrain with a 30 m spatial resolution over a swath several hundred kilometers in width. This can be achieved by increasing the TDRS data rate, or by partial preprocessing of the SAK data on board before transmission. At this stage, SIR-C is regarded as an experimental system providing the opportunity to evaluate the use of space SAR data for a variety of oceanographic, geologic, hydrologic, and ecological applications.

### 1.4. Microwave band

SAR systems are designed to operate at specific frequencies (wavelengths) designated by the Federal Communication Commission as allowable bands for radar transmission. Table 2 provides a summary of these bands for the commonly used part of the microwave frequency range, together with the commonly used letter designations.

The choice of bands for remote sensing is dictated by two sets of factors: (1) technology considerations, such as the availability of space-qualified power sources to provide the necessary transmitter power; (2) the dependence of the scattering by and propagation through terrestrial media on wavelength. Further discussion of the role of wavelength relative to the soil-moisture sensing problem is given in Section 3.

### 2. Image classification

Section 3 and Section 4 of this paper discuss the status of algorithms used to estimate soil moisture content from the measured radar response for bare-soil surfaces and vegetation-covered surfaces, respectively. Before the application of such algorithms, however, it is necessary to classify the imaged scene with as much detail as possible. Numerous techniques have been proposed for classifying terrain on the basis of SAR images (Wu and Sader, 1987; Kong et al., 1987; Yuch et al., 1988; Lim et al., 1989; Lin and Allebach, 1990; Rignot and Chellappa, 1992; Van Zyl and Burnette, 1992; Lozano-Garcia and Ioffer, 1993; Wong and Posner, 1993). In this section, we describe the capability of an SAR image classifier that was developed at the University of Michigan in support of the SIR-C April 1994 mission, as well as the JPL AIRSAR, which is an airborne version of SIR-C. Actually, the classifier is part of an image interpretation processor designed to
extract various types of terrain data from the L-band and C-band polarimetric radar data (Dobson et al., 1995; Pierce et al., 1994). A diagram of the image interpretation processor is shown in Fig. 4. After calibrating the SAR images (using techniques that were developed over the past 5 years at JPL and the University of Michigan), a Level-1 classifier is applied to classify each pixel in the imaged scene as urban, tall vegetation (trees), short vegetation (grasses and crops), or bare surface. Bare surfaces include water surfaces, roads, and bare soil surfaces with vegetation cover less than 15 cm in height. A summary of the operation of the Level-1 classifier and its identification accuracy is given in Section 2.1.
For the non-water-covered bare surfaces, the algorithm described in Section 3 is used to estimate the soil moisture content and the roughness of the soil surface, as shown in Fig. 4. For the tall vegetation and short vegetation pixels, a level-2 classifier is applied to each, to further refine the identity of the vegetation cover. Tree canopies, for example, are classified as excurrent (e.g., pine and spruce), decurrent (e.g., oak and maple), or columnar (e.g., palm). This classification scheme is based on the canopy structural character as viewed by a radar wave. Finally, for each canopy class, a biophysical estimator is used to estimate such parameters as total above-ground biomass and tree density (number of trees per unit area), as described by Dobson et al. (1998).

Fig. 5 is an SAR image of an area located in northern Michigan. The image, which was acquired by the JPL AIRSAR system on 10 July 1991, covers an area 7.5 km x 12.4 km, represented by 750 x 1024 pixels, each 6.6 m x 12 m in area. A comprehensive geographic information database is available for the imaged area, including digital terrain elevation, soil type, and ground cover. Specific areas (identified by square boxes on the image in Fig. 5) were selected for evaluating the classification accuracy of the classifier. Fig. 6 shows the sequential steps used by the classifier. Each step identifies the specific radar parameters used in that step. For example, the tall vegetation step uses \( a_{GH} (U) \) and \( a_{GH} (H) \), which are the measured HH- and HV-polarized backscattering coefficients at L-band. These two parameters are capable of identifying tall vegetation correctly (Fig. 7) with
an accuracy of 98%. Comparable results are obtained for the short-vegetation and bare-surface classes (Table 3), but not for urban pixels. The classification accuracy for urban pixels is only 30% because although the geographic information data base would identify an area as urban, in reality that area may contain vegetation and other types of cover; therefore, it is not possible for the radar to classify it as urban. Table 3 contains classification results obtained by the same classifier when applied to two different test sites, imaged 3 months apart. In each study, over 5000 image pixels with known terrain identity (established by direct ground observations) were involved in evaluating the accuracies given in Table 3.

3. Radar estimation of bare-soil attributes

The magnitude of the backscattering coefficient $\sigma^o$ of a ground surface observed by a radar system is governed by two quantities: (a) the dielectric constant of the ground surface; (b) the roughness of the surface. The dielectric constant is, in turn, very strongly dependent on the moisture content of the soil surface layer, and to a much lesser extent, on the soil textural composition and physical temperature (for non-frozen soil). Accordingly, this section deals with three topics: (1) the relationship...
between the dielectric constant of a soil medium and its physical properties; (2) the depth of penetration associated with a microwave propagating in a soil medium; (3) the algorithm used for estimating the soil’s moisture content from the observed radar response.

Table 3  
Classification results for two areas imaged 3 months apart, no urban areas were present in the Race area

<table>
<thead>
<tr>
<th>Classified as</th>
<th>True class</th>
<th>Tall vegetation</th>
<th>Short vegetation</th>
<th>Bare surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellston, MI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>30.7</td>
<td>0.22</td>
<td>0</td>
<td>0.06</td>
</tr>
<tr>
<td>Tall vegetation</td>
<td>37.9</td>
<td>98.32</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Short vegetation</td>
<td><strong>28.5</strong></td>
<td>1.46</td>
<td>94.74</td>
<td>0.87</td>
</tr>
<tr>
<td>Bare surface</td>
<td>2.9</td>
<td>0</td>
<td>5.26</td>
<td>99.07</td>
</tr>
<tr>
<td>Race, MI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tall vegetation</td>
<td>100</td>
<td>0</td>
<td>99.12</td>
<td>2.06</td>
</tr>
<tr>
<td>Short vegetation</td>
<td>-</td>
<td>0</td>
<td>0.88</td>
<td>97.94</td>
</tr>
<tr>
<td>Bare surface</td>
<td>0</td>
<td></td>
<td>0.88</td>
<td>97.94</td>
</tr>
</tbody>
</table>
3.1. Soil dielectric properties

The dielectric constant $\varepsilon$ of a material, which is a fundamental property that characterizes both the reflection and attenuation properties of a wave interacting with that material, consists of a real part $\varepsilon'$ and an imaginary part $\varepsilon''$:

$$\varepsilon = \varepsilon' - j\varepsilon''$$

The dielectric constant $\varepsilon$ is related to the index of refraction $n$ of the material, by

$$n = \sqrt{\varepsilon}$$

The index of refraction also is a complex quantity composed of a real part $n'$ and an imaginary part $n''$:

$$n = n' - jn''$$

and these two parts are related to $\varepsilon'$ and $\varepsilon''$ by

$$n' = \text{Re}\{\sqrt{\varepsilon}\}$$

$$n'' = |\text{Im}\{\sqrt{\varepsilon}\}|$$

and the inverse relationships are given by

$$\varepsilon' = (n')^2 - (n'')^2$$

$$\varepsilon'' = 2n'n''$$

For a homogeneous soil medium with a flat surface, the reflectivity for nadir incidence is given by

$$\Gamma = \left| \frac{n - 1}{n + 1} \right|^2 = \left| \frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1} \right|^2$$

The reflectivity $\Gamma$ determines the fraction of the power incident upon the surface that is reflected back by the surface, and the transmissivity $T$ determines the fraction transmitted across the air–soil boundary into the soil medium. Conservation of power requires that

$$T = 1 - \Gamma$$

For incidence at angles other than normal incidence, the incidence angle $\theta$ also is involved, as is the polarization of the wave. If the soil surface is not perfectly smooth, the incident power is scattered in many directions, including the backscatter direction (Fig. 8). The component scattered in the backscatter direction provides the link between the power received by the radar and the properties of the soil medium.

The power transmitted into the soil medium decays exponentially at a rate governed by the attenuation coefficient of the soil medium, $\alpha$, which is related to $n$ and $\varepsilon$ by

$$\alpha = \frac{2\pi}{\lambda} n'' = \frac{2\pi}{\lambda} |\text{Im}\{\sqrt{\varepsilon}\}|$$

If $\varepsilon$ of the soil medium is not constant with depth, then both $\Gamma$ and $\alpha$ are governed by the depth profile of $\varepsilon$ for the layer between the surface and approximately $\delta_p$, where $\delta_p$ is the
penetration depth of the soil medium. For a homogeneous soil medium,

\[ \delta_p = \frac{1}{2\alpha} \quad (16) \]

The preceding material provided the basic relationships between the soil dielectric constant \( \epsilon \) and the reflectivity \( \Gamma \), attenuation coefficient \( \alpha \) and penetration depth \( \delta_p \). Now we shall examine the dependence of \( \epsilon \) on the soil's physical properties. This dependence is also a function of the microwave frequency \( f \). To avoid overcomplicating the picture, however, we shall limit most of the discussion to the L-band region \( f = 1 \text{ GHz} \), which is qualitatively representative of the entire frequency range usually considered for soil moisture sensing (0.4--10 GHz).
For oven-dried soil, the real part $\varepsilon'$ varies between 2 and 4 (depending on the soil bulk density $\rho_0$), and is essentially independent of both temperature and frequency. The imaginary part, $\varepsilon''$, is typically less than 0.05. In contrast, the dielectric constant of water at 1 GHz at room temperature is $\varepsilon' = 80$ and $\varepsilon'' = 4$. Consequently, the addition of water to soil causes the dielectric constant of the mixture to increase, with the increase being governed by the volume fraction of the mixture composed of water. Fig. 9 shows plots of $\varepsilon'$ and $\varepsilon''$ as a function of the volumetric water content $m$, for five soil types. In all cases, both $\varepsilon'$ and $\varepsilon''$ exhibit strong variations with $m$, and relatively weak sensitivities to soil type. Also, for $m_v > 0.05$, the soil bulk density $\rho_0$ does not influence $\varepsilon''$, as long as the water content is expressed on a volumetric basis.

Unless it changes phase into ice, water exhibits a relatively weak dependence on temperature. Hence, the soil–water mixture also is insensitive to physical temperature for $T > 0^\circ C$. A large change, however, takes place as the soil freezes, as indicated by the curves in Fig. 10.

3.2. Penetration depth

The plots shown in Fig. 11 depict the variation of the penetration depth $\delta_p$ with volumetric moisture content $m$, at three microwave frequencies for a homogeneous loamy soil. At L-band (1.3 GHz), the depth decreases from 1 m at $m_v = 1\%$ down to 6 cm at 40%. As
Fig. 10. Temperature dependence of soil dielectric constant at two moisture contents.
mentioned above, the penetration depth is a measure of the thickness of the top surface layer of the soil medium governing the backscatter observed by a radar system (or the emission in the case of passive microwave sensing). It does not follow, however, that the penetration depth is equal to the thickness of the soil layer whose moisture is measured by the radar. This is because not only is the near-surface soil moisture important, but so is the depth profile of the moisture content over the extent of the penetration depth. As a first-order approximation, we find in practice that the thickness of the layer whose moisture is estimated by L-band radar is of the order of 5 cm.

3.3. Radar algorithm for measuring soil moisture content

Because the soil dielectric constant exhibits a strong response to moisture content, so does the backscattering coefficient $\sigma^\circ$. Fig. 12 depicts the variation of $\sigma^\circ$ with $m$, for two soil surfaces with different roughnesses, where roughness is represented by the standard deviation of surface height $s$ (also called r.m.s. height). If the surface roughness remains approximately constant or varies over a narrow range, it is possible to use radar to monitor the change in moisture content, as a function of time for example, but it is difficult to measure $m$ on an absolute scale. In the general case, it is necessary to use a multi-channel radar to measure both $s$ and $m$. This can be done by using a single-frequency multi-polarization system capable of measuring all three linear polarization components of $u^\circ$, namely $\sigma_{hh}^\circ$, $\sigma_{vv}^\circ$, and $\sigma_{hv}^\circ$. 
The algorithm given in Fig. 13 uses two radar-derived parameters as input—(a) $p = \sigma_{hh}/\sigma_{vv}$, the co-polarized ratio; (b) $q = \sigma_{hh}/\sigma_{vv}$, the cross-polarized ratio—and provides the roughness parameters and volumetric moisture content $m_v$ as output (Oh et al., 1992). This algorithm is based on a model and extensive experimental data measured at L-band. The moisture content $m_v$ represents the average moisture content of the top 5 cm layer. The performance of the soil-moisture estimation algorithm is shown in Fig. 14, where radar-derived estimates of $s$ and $m_v$ are compared with corresponding values measured in situ.

Although this technique was derived for bare-soil surfaces, it is equally applicable to soil surfaces with modest vegetation cover. If the vegetation is less than 10–15 cm in height, the presence of the vegetation cover imparts a minor effect on the radar response of the underlying soil surface at low microwave frequencies (such as L-band). For dense or tall vegetation cover, it is necessary either to modify the estimation algorithm by accounting for the attenuation and scattering effects of the vegetation, which would require the availability of independent information about the vegetation structure and biomass, or to use a different algorithm that utilizes multi-frequency radar observations. This topic is discussed in the next section.

Fig. 12 Comparison of the backscattering response $m_v$ of a smooth surface and a rough surface for $\theta = 20^\circ$ at $f = 1.5$ GHz (Ulaby et al., 1986)
Fig. 13. Soil moisture SAR estimation algorithm for bare soil surfaces at L-band (1.25 GHz) and incidence angle 0° of 40°. The two sets of curves denote different values of \( m \) (in percent) and the m.s. height \( s \) (in mm).

Input: \( \sigma_{hh}^0, \sigma_{vv}^0, \sigma_{hv}^0 \)

Output: \( m, s \)

Fig. 14. Comparison of radar-estimated surface roughness and moisture content with in situ measurements.
4. Effects of vegetation cover

The radar backscatter for a vegetation-covered soil surface consists of three types of contributions:

$$\sigma^o = \gamma^2 \sigma^s + \sigma^d + \sigma^\text{int}$$  \hspace{1cm} (17)

where $\sigma^s$ is the backscatter contribution of the (bare) soil surface, $\gamma^2$ is the two-way attenuation of the vegetation layer, $\sigma^d$ is the direct backscatter contribution of the vegetation layer, and $\sigma^\text{int}$ represents multiple scattering involving the vegetation elements and the ground surface. These mechanisms are illustrated diagrammatically in Fig. 15. For vegetation with above-ground biomass less than 0.5 kg m$^{-2}$ and the second and third terms in Eq. (17) are negligibly small, and therefore the effect of the vegetation cover may be ignored. In the general case, $\sigma^o$ is governed by the soil properties (roughness and moisture content) as well as the structure and biomass of the vegetation cover.

The vegetation-related quantities depend on the radar wave parameters: the wavelength $\lambda$, polarization configurations of the transmit and receive antennas, and the incidence angle $\theta$, and on the vegetation geometry and dielectric properties. As with soil, the dielectric constant of vegetation is strongly influenced by the moisture content. Vegetation geometry includes both the macrostructure of a vegetation canopy, such as the height of the canopy and the number of plants or trees per unit area, and the microstructure, which refers to the stalks and leaves. For well-characterized canopies, it is possible to use electromagnetic scattering models to compute the radar backscattering coefficient $\sigma^o$ and its constituent components, as given in Eq. (17), for any radar wavelength, polarization configuration and incidence angle. These models are highly complex, owing primarily to the complex nature of the vegetation scattering medium, and therefore it is not possible to describe them in any adequate detail in this paper. Instead, we will examine the effects of vegetation cover from the standpoint of sensing soil moisture through a combination of model calculations and experimental observations. The model calculations are based on the MIMICS code (Michigan Microwave Canopy Scattering Model), which is a vector radiative transfer formulation that accounts for single scattering mechanisms involving single
Fig. 16. Backscatter variation with biomass for a grass canopy.
interaction between the vegetation elements and the underlying soil surfaces (Ulaby et al., 1990).

4.1. Backscatter response

Fig. 16 depicts the variation of $\sigma^o$ with biomass for a layer of grass above a soil surface, for each of several soil moisture conditions, and Fig. 17 shows the soil moisture response of $\sigma^o$ for three types of vegetation cover. For each vegetation cover, the vegetation parameters were selected to represent fully mature conditions, and therefore the most difficult from the standpoint of wave penetration through the vegetation layer. The plots given in Fig. 16 and Fig. 17 are based on model calculations performed using the MIMICS code. It is clear from these figures that to measure soil moisture content with radar, it is necessary to have information about the vegetation cover. A possible approach for obtaining this information is to use a multi-frequency radar system that can simultaneously estimate both the soil and vegetation parameters of interest. Different frequencies exhibit different transmissivities through a vegetation canopy (as illustrated by Fig. 18) as well as different scattering responses.
4.2. Experimental observations

Extensive experimental evidence supports the conclusion that radar waves can penetrate through vegetation, particularly in the longer-wavelength segment of the microwave band ($\lambda > 5$ cm). Two examples are provided in Fig. 19 and Fig. 20, with the former showing measured values of $\sigma^0$ as a function of soil moisture content for fields planted in soybeans and millet, and the latter showing similar plots based on SIR-B measurements for various types of covers, individually, for each of the vegetation covers, $\sigma^0$ exhibits a good response; however, the response curves have different slopes and intercepts, again pointing out the need to determine the vegetation parameters in conjunction with the soil sensing problem. This may be accomplished through the use of multi-frequency multi-polarization observations to simultaneously estimate both the soil and vegetation-cover parameters governing the radar backscatter. Such an approach is being pursued by both the University of Michigan and JPL.

5. Soil moisture maps from AIRSAR and SIR-C

In 1992, the JPL AIRSAR system was flown on eight different days from 10 June to 18 June over the Little Washita watershed in southwestern Oklahoma. The SAR observations, which were part of a major NASA-supported hydrology field investigation known as the Washita '92 Experiment, were made from a nominal flight altitude of 7.9 km. This section
provides a brief description of the SAR system, followed by a presentation of multi-date soil moisture maps generated on the basis of the radar images. Only a cursory description of the Washita test site is given in this paper, as it has already been well characterized in the paper by Jackson and Le Vine (1996).

5. AIRSAR Instrument

The AIRSAR instrument is a fully polarimetric multifrequency SAR system mounted onboard a DC-8 aircraft operated by NASA-Ames (Van Zyl et al., 1992). The radar acquires data on the left of the nadir track as the aircraft flies at an average velocity of 420 knots. It measures the full scattering matrix by transmitting alternately H- and V-polarized waves and receiving with two antennas of perpendicular polarization orientations. It operates at C-band (5.7 cm), 1.-hand (24 cm) and P-band (68 cm) simultaneously, producing three sets of overlapping data.

The recorded raw data return must be processed on the ground into SAR imagery. The standard processed frame size (for 20 MHz data) is 12 km in the along-track direction by 8.5 km in the across-track direction with a pixel size of 6.6 m x 12.1 m in the across-track and along-track directions, respectively. The calibration of the data is performed in the processor by using both the calibration parameters derived for the flight campaign and routine system tests. Fifteen trihedral corner reflectors, each measuring 2.4 m on a side, are deployed on the Rosamond dry lake bed in California to cover the full radar swath. The calibration site is imaged at the beginning of the radar campaign and calibration parameters are derived matching the radar cross-section of the trihedral reflector to its
Fig. 20. Radar response to soil moisture, as measured by the Shuttle Imaging Radar-B in corn, (b) cut corn and tilled bare soil. (From Dobson and Ulaby(1986))

(a) Corn

harvest-ready corn
N = 51
$r^2 = 0.79$

(b) Cut corn and tilled bare soil
N = 18
$r^2 = 0.81$
AIRSAR - Chickasaw 92 - AG002 Site: Soil Moisture Maps

The AIRSAR data is used in the soil moisture inversion algorithm to estimate the soil moisture content of the field. The algorithm takes into account various factors such as the soil type, terrain, and weather conditions. The resulting soil moisture maps are then used to evaluate the health of the field and to inform crop management decisions.

The AIRSAR data is collected over a wide area, allowing for a comprehensive view of the field conditions. This information is valuable for farmers and researchers alike, as it provides insight into the water availability and potential yield for the crops being grown. By analyzing the data, farmers can make informed decisions about when to water and what crops to plant, leading to more sustainable and productive farming practices.

The AIRSAR data is also useful for environmental monitoring, as it can provide information about changes in the landscape over time. By comparing data from different seasons or years, researchers can study the impact of climate change and other environmental factors on soil moisture and crop growth.

In conclusion, the AIRSAR data is a valuable resource for farmers, researchers, and environmentalists alike. By providing a detailed view of soil moisture conditions, it enables more informed decisions and better management of agricultural resources.
2 weeks. No additional precipitation occurred between 10 June and the final flight on 18 June, leading to continuous dry-down between those two dates. This dry-down pattern is clearly reflected in the soil-moisture estimated maps shown in Fig. 21, with the 10 June map being predominantly dark blue, denoting high moisture content, and the maps corresponding to succeeding dates exhibiting progressively larger segments that are yellow, denoting low moisture states. These results are particularly significant in view of the fact
that the moisture maps were generated by an algorithm that had been developed on the basis of radar measurements for bare-soil surfaces, with no attempt made to correct or account for vegetation cover (detailed land-use and soil-type maps are available in the paper by Jackson and Le Vine, 1996). Scattering from vegetation will result in a higher $\sigma_v/\sigma^0$ ratio than scattering from a bare surface alone. This will cause the algorithm to underestimate soil moisture over the vegetated field. The effect can be seen in the 10 June map, where the areas in yellow (dry) correspond to the more heavily vegetated surfaces. Fig. 21 includes a typical example of a quantitative comparison between the in situ measurements of soil moisture for one of the bare-soil fields and the corresponding values estimated by the radar algorithm.

5.3. SIR-C SAR observations

During its April 1994 mission, the SIR-C instrument aboard the Space Shuttle acquired SAR imagery of the Washita test site on 11 April. Fig. 22 shows an L-band single-polarization image of a 25 km x 25 km area, and soil moisture maps for 12 and 15 April. The soil moisture maps were generated by applying the same SAR algorithm as described above in conjunction with Fig. 21. The average soil moisture over the site was estimated to be in the neighborhood of 20% on 12 April, compared with only 10% on 15 April. This is because no rain had occurred over this time period. The significant change in moisture is reflected in the color change towards yellow between the two moisture maps.

Fig. 23 provides a summary of the quantitative analysis derived from both the AIRSAR and SIR-C SAR observations over the Washita test site. Comparison of soil moisture values estimated using the SAR inversion algorithm with their field counterparts based on direct in situ measurements reveals good agreement between them. With volumetric soil moisture expressed in percent, correlation analysis indicated that the overall r.m.s. error is 3.5%.

The results of the Washita 1992 AIRSAR and 1994 SIR-C SAR campaigns, which are based on only L-band observations, are strong testimony to radar’s potential as a soil moisture mapper. Current research aims to use both L- and C-band observations to simultaneously estimate both soil moisture and vegetation biomass of vegetation-covered areas, thereby providing more accurate soil moisture maps over a wide range of cover conditions.

6. Concluding remarks

The highlights of this overview presentation are as follows:

1. the combination of L- and C-band polarimetric SAR observations can provide Level-1 terrain classification accuracies of the order 90% or better for tall vegetation (trees), short vegetation (grasses and crops), and bare surfaces (water, roads, and bare soil).

2. For bare-soil surfaces, multi-polarization L-band observations can be used to estimate...
the soil moisture content of the topsoil layer and the surface roughness with a high degree of accuracy. The estimation algorithm is equally applicable for vegetation-covered surfaces if the vegetation height is less than 1 cm.

3. For vegetation-covered surfaces, the radar response is governed by both soil and vegetation parameters. Strong evidence exists to suggest that it should be possible to develop a radar algorithm for estimating soil moisture in the presence of vegetation cover. Such an algorithm is currently under development.

References


