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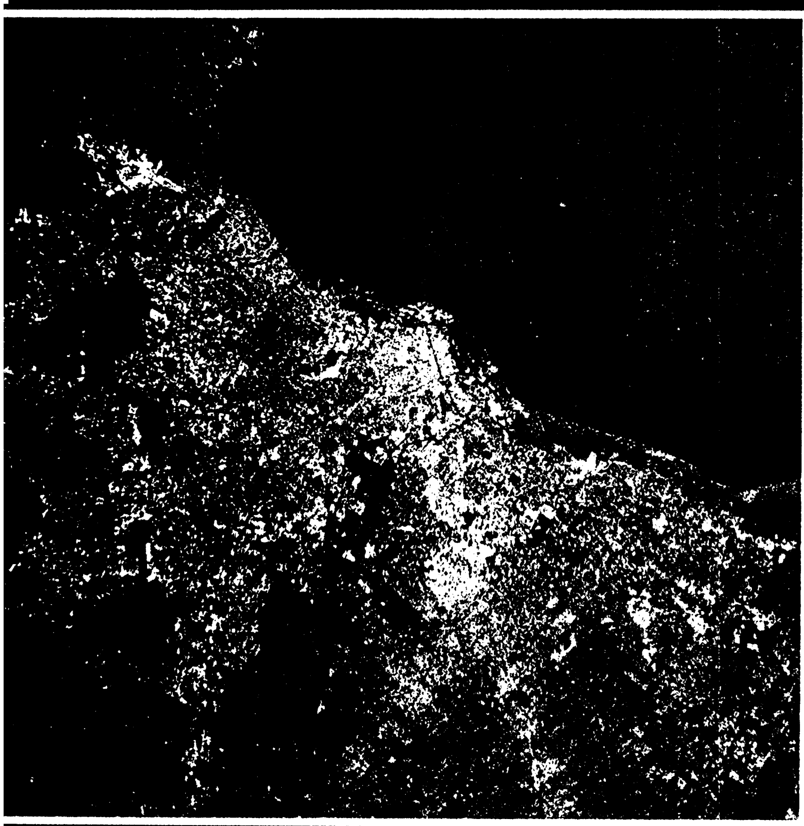

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Soil moisture retrieval from active microwave remote sensing.

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Abstract. It is well know that microwave reflectivity of agricultural targets is primarily associated with soil roughness, soil dielectric properties and the presence of vegetation. The dielectric constant of a completely dry soil is around 3 and that of pure water approaches 80. Then, as the wetness of the soil top layer increases the reflectivity will also rise. On the other hand there is a dichotomy: rough and dry soils could produce a higher backscatter (scatter in the receiving antenna direction) than smooth wet soils, since most of the fields could experience specular reflection away from the radar. This paper briefly reviews the theory and methods of retrieving soil moisture from remote active microwave systems, its application, conditions of validity and limitations as practical use is concerned. Methods based on a simple linear regression between radar backscatter and soil moisture as well as those based on the inversion of surface scattering models are presented. The validity conditions are discussed. Finally, we introduce the preliminary results on the inversion of a semi-empirical surface scattering model to retrieve top layer (first few centimeters) soil moisture using the SIR-C L and C band multipolarization imagery acquired over the Bebedouro Irrigation Project test site, in the semi-arid Sao Francisco river valley in the northeast Brazil. "In situ" soil moisture and soil roughness for some bare and low vegetated fields, were measured simultaneously with the radar data acquisition during the first flight of the SIR-C/X-SAR mission in April 1994.

Introduction

Estimates of soil moisture are of great importance in numerous environmental studies, including hydrology, meteorology, irrigation control, water resources systems planning and agriculture forecasting. In spite its importance, soil moisture information is not widely used in resource monitoring or prediction because it is difficult and costly to obtain "in situ" measurements on a routine basis over large areas (Wang et al., 1986). From theory, the dielectric constant of a completely dry soil is around 3 and that of pure water approaches 80. Then, as the wetness of the soil top layer increases the reflectivity will also rise. Based on that, there has been various experiments including aircraft, ground level truck mounted scatterometers and even satellites, showing that one can relate radar backscatter to soil top layer moisture (see for example, Ulaby et Batlivala, 1976; Ulaby et al., 1978; Wang et al., 1986; Soares et al., 1988; Bernard et al.; 1986).

Because radar backscatter is also affected by surface roughness and vegetation, such that any practical application of radar must be able to account for all three of these target features. As matter as fact, there is a dichotomy: rough and dry soils could produce a higher backscatter (scatter in the receiving antenna direction) than smooth wet soils, since most of the fields could experience specular reflection away from the radar. Thus, if one were interested in monitoring soil moisture over a mixed area, the effects of surface roughness and plant canopy would have to be subtracted form the measurements of radar backscatter in order to isolate soil moisture modulation on the radar

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measured signal. Earlier results of several investigators (for example, Ulaby et al., 1978, Soares et al., 1988) showed that, at small incidence angles (between 10 ° and 20 °), soil surface roughness effects on the received radar scatter are minimized. On the other hand, these results have also pointed out that the linear relationships found between soil moisture and radar backscatter were not the same for different sites, and the optimal incidence angle to minimize roughness also fell in a rather big range. This variability suggests that many algorithms are site-specific and that there exists a need to develop portable algorithms that do not require fitting to specific site properties. Furthermore, methods that are limited to small incidence angles narrow the application of remote radar imagery to the near range of the swath. This is of course an important drawback of the technique since most SAR measurements from space generally range from 15° to 55° in incidence angle, implying that any operational algorithm to retrieve soil moisture shoal be able to provide good estimates over an as wide as possible incidence angle range. This paper briefly reviews the theory and methods of retrieving soil moisture from remote active microwave systems, its application, conditions of validity and limitations as practical use is concerned.

Soil moisture retrieval from active microwave systems.

- ***Linear relationship between radar backscatter and soil moisture***

Ulaby and Batlivala, (1976), studied the radar response to soil moisture for three bare field plots with considerably different surface roughnesses at eight frequencies in the 2-8 GHz range for VV and HH polarizations, using a truck mounted antenna located 20 m above the ground. They concluded that the effect of roughness on the radar backscattering coefficient can be minimized by proper choice of the radar parameters. An optimal combination of sensor parameters is defined such that σ° of the ground is almost independent of surface roughens while retaining an acceptable sensitivity to soil moisture. Their data led them to recommend the best radar parameters for an operational soil moisture system as being C band (4 GHz), both HH and VV operating at a range of incidence angles of 7-15°.

Soares et al. (1988), following Ulaby and Batlivala recommendation, established a linear relationship between soil moisture (m_v, cm^3cm^{-3}) and absolute radar backscatter (σ°, dB m^2m^{-2} measured with an accuracy of about 0.5 dB), using a 5.3 GHz C band scatterometer onboard an helicopter pointed at 12° incidence angle. Their data is synthesized in figure 1. The regression line is:

$$w_g = 0.015\sigma^o + 0.30 \quad (1)$$

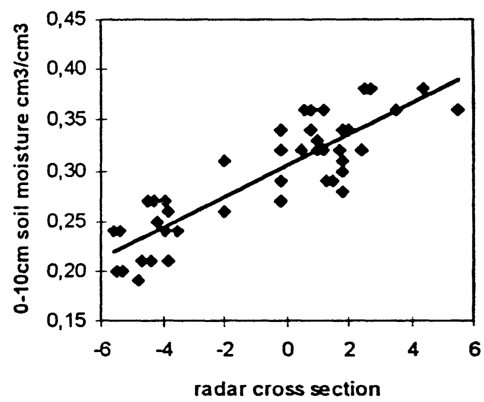

Figure 1. Radar Calibration curve against surface soil moisture, using either bare or low vegetated soils (From Soares et al., 1988).

Cognard et al. (1995, reported on the evaluation of the ERS-1 SAR capability to estimate soil moisture. ERS-1 SAR operates in C Band with an incidence angle of 23°, what makes it unlikely to sense soil moisture at filed scale using a simple universal linear algorithm, as those established in the pioneering work of Ulaby's team at the University of Kansas. They acquired SAR scenes during 1992 and 1993, concurrently with point measurements of soil moisture in the fields using both automatic tools and the gravimetric method. They found out that on a field scale the correlation between the radar signal and the surface soil moisture depends strongly on the type of cover: correlation was poor for the different cultures except for wheat. On a basin scale, they figured out that, for a period of low vegetation, there is a linear relationship between the mean radar data and the point automatic measurements, a result that open the way to hydrological applications.

The following general considerations are to be made:

1. The sensitivity of radar backscatter to soil moisture is very clear.
2. The conditions imposed as to minimize roughness effects (incidence angle) make it not practical for operational use in most cases.
3. As the incidence angle increases, the vegetation canopy attenuation of the radar power goes up, such that the sensitivity of the radar to moisture, such as expressed in equation (1), is no longer assured.
4. As stated above, the linear relationships found by many authors are site-specific.
5. Speckle noise in imaging systems is another source of uncertainty, specially for field scale.
6. Finally, one has to make sure to proceed an absolute calibration of the radar (really knowing about σ^o in dB m^2m^{-2}), for every radar data set, to produce accurate estimates of soil moisture. Scatterometers are easier to calibrate than imaging systems.

- ***Measuring Soil Moisture with Polarimetric Imaging Radar***

1. Surface scattering models

The interaction between electromagnetic waves and bare soil can be approximately described as a surface scattering problem. The scattering of electromagnetic waves by rough surfaces has been studies for many years, but no exact close-form solutions have been obtained. Numerical solutions can be used to compute the exact solution, but in general they are computationally prohibitive and are only used in evaluating the accuracy and range of validity of approximate models (Chen and Fung, 1988). When dealing with practical applications, simpler approximate models are the ones of choice. The main drawback is: they are valid only within a limited range of roughness. Three scattering models are used (Ulaby et al., 1986):

- The small perturbations method when the variations in surface height are small relative to the wavelength and the surface slope is small;
- The Kirchoff model under scalar approximation (*physical optics*), when the radius of curvature is large and the *rms* surface slope is small relative to the wavelength ;
- The Kirchoff model under stationary-phase approximation (*geometrical optics*), when the roughness is large relative to the wavelength.

The validity conditions for all the three models are summarized in Table 1 (from Ulaby et al. 1986).

Table 1. Validity conditions for surface scattering models.

$$k = 2\pi / \lambda$$

s = *rms* surface height

l = correlation length

m = rms surface slope

Model	validity conditions
Perturbation	$ks < 0.3$ and $m < 0.3$
Physical Optics	$m < 0.25$ and $kl > 6$
Geometrical Optics	$(2ks\cos\theta)^2 > 10$ and $l^2 > 2.76\, s\lambda$

Since surface scattering is a function of reflectivity and surface roughness, all models above can be represented as a product of dielectric and surface roughness functions:

$$\sigma_{pp}(f,\theta_i) = D(ff,pp,\theta_i) \times S(f,\theta_i,s,l) \quad (2)$$

where *pp* indicates polarization, *f* is frequency, *s* is the *rms* height and θ_i is incidence angle.

For the ***small perturbations model***, the dielectric functions can be described as follows:

$$D(hh,\theta_i) = \left| \frac{\varepsilon_r - 1}{\left(\cos\theta_i + \left(\varepsilon_r - \sin^2\theta_i\right)^{1/2}\right)^2} \right|^2 \quad (3)$$

and

$$D(vv,\theta_i) = \left| \frac{(\varepsilon_r - 1)\left(\varepsilon_r\left(1 + \sin^2\theta_i\right) - \sin^2\theta_i\right)}{\left(\varepsilon_r \cos\theta_i + \left(\varepsilon_r - \sin^2\theta_i\right)^{1/2}\right)^2} \right|^2 \quad (4)$$

where ε_r is the relative dielectric constant. The surface roughness function at given frequency f and incidence angle θ_i is given by:

$$S(f,\theta_i,W) = 8\kappa^4 cos^4 \theta_i W(2\kappa sin\,\theta_i) \qquad (5)$$

where $W(2\kappa sin\,\theta_i)$ is the normalized roughness spectrum, which is given (for the Gaussian correlation function) by:

$$W(2\kappa sin\,\theta_i) = \frac{1}{2} l^2 exp\left[-(\kappa l\, sin\,\theta_i)^2\right] \qquad (6)$$

For the ***physical optics model***, the coherent part can be neglected for incidence angles that are not near the normal. When we consider the non-coherent term only, the dielectric functions become:

$$D(f,pp,\theta_i) = \left|R_{pp}(\theta_i)\right|^2 \qquad (7)$$

where

$$R_{vv}(\theta_i) = \frac{(\varepsilon_r - 1)(\varepsilon_r cos^2\theta_i - sin^2\theta_i)}{\left(\varepsilon_r cos\,\theta_i + (\varepsilon_r - sin^2\theta_i)^{1/2}\right)^2} \qquad (8)$$

and R_{hh} is the same as in equation (3).

When one considers the backscattering from both the non-coherent term and the one due to slope, the equations are:

$$D(f,pp,\theta_i) = \left|R_{pp}(\theta_i)\right|^2 (1 + sin^2\theta_i) + Re\left[R_{pp}(\theta_i) R^*_{pp1}(\theta_i)\right] sin\,2\theta_i \qquad (9)$$

where,

$$R_{hh1}(\theta_i) = -\frac{2\,sin\,\theta_i R_{hh}(\theta_i)}{cos\,\theta_i + (\varepsilon_r - sin^2\theta_i)^{1/2}} \qquad (10)$$

and

$$R_{vv1}(\theta_i) = \frac{sin\,\theta_i\left[R_{vv}(\theta_i)(\varepsilon_r + 1) - \varepsilon_r + 1\right]}{\varepsilon_r cos\,\theta_i + (\varepsilon_r - sin^2\theta_i)^{1/2}} \qquad (11)$$

Assuming again a Gaussian correlation form, the surface roughness function is as follows:

$$S(f,\theta_i,\sigma,l) = (\kappa l)^2 exp(-K_0) \times \sum_{n=1}^{\infty} \frac{(K_0)^n}{n n!} exp\left(-\frac{(\kappa l\, sin\,\theta_i)^2}{n}\right) \qquad (12)$$

where $K_0 = 4k^2 s^2 cos^2\theta_i$.

For both the perturbation and physical optics models, the dielectric formulation include the dependence on incidence angle, frequency, polarization and the dielectric properties themselves. They do not depend on the correlation function and *rms* roughness. The surface roughness parameterization are a function of frequency, incidence angle, surface roughness correlation form and rms surface height. They are independent of polarization. The measured ratio expressed by equation (13) (see bellow), is expected to be independent of the surface roughness function.

$$\frac{\sigma^o_{hh}}{\sigma^o_{vv}} = \frac{D(f,hh,\theta_i)}{D(f,vv,\theta_i)} \qquad (13)$$

Since single surface scattering models physics indicate that the relative phase difference between HH and VV polarizations approaches 0, the imaginary part of the dielectric function is very small. Therefore, one can either use the magnitude of the dielectric constant to replace the complex dielectric constant or express the dielectric function as a function of the incidence angle θ_i and the refractive angle θ_t at a given frequency and polarization through Snell's law, as in Shi et al., (1992). For example, for the perturbation model the dielectric function ratio between the HH and VV polarizations can be written as:

$$\frac{\sigma^o_{hh}(f,\theta_i)}{\sigma^o_{vv}(f,\theta_i)} = \frac{cos^4(\theta_i - \theta_t)}{sin^2\theta_i + cos^2\theta_t} \qquad (14)$$

Then, the refractive angle is the only unknown in the ratio and can be easily solved for. Consequently, the magnitude of dielectric constant can be obtained through Snell's law, and finally volumetric soil moisture can be derived following the dependence of the soil dielectric constant on soil type and the volumetric constant (see, for example, appendix E of Ulaby et al., 1986).

Regarding the geometrical optics model, the dielectric and surface roughness functions are given by:

$$D(f) = |R_{hh}(0)|^2 = |R_{vv}(0)|^2 = \frac{\varepsilon_r^{1/2} - 1}{\varepsilon_r^{1/2} + 1} \quad (15)$$

and

$$S(\theta_i) = \frac{1}{2m^2 \cos^4 \theta_i} \exp\left(-\frac{\tan^2 \theta_i}{2m^2}\right) \quad (16)$$

which show that the dielectric function depends only on the dielectric properties of the surface at a given frequency. It is independent of both polarization and incidence angle. The surface roughness formula is done as a function of incidence angle and mean random surface slope. It is independent on both polarization and frequency. In this case, the ratio of co-polarization signals does not provide any information about surface dielectric properties and roughness because both functions are the same for the co-polarization signals.

Shi et al., (1992), have attempted to use these surface scattering models using data collected during an experiment carried out in 1989 with the NASA/JPL AIRSAR in an agricultural are near Fresno, Ca. Soil moisture measurements were obtained for three plots, showing low values corresponding to dielectric constant within the 3.0 - 5.5 range. They were assumed to represent the whole area because all the fields were flat, essentially uniform in texture, none of them had been irrigated for several weeks, the whether conditions were high temperatures and low humidity. Based on the "a priori" condition that the roughness function *S(f, θ, s, l)* is independent of polarization, they used the ratio of co-polarization channels to indicate which surface scattering model should be used as follows:

- For the small perturbation model the ratio $\sigma^o_{hh}/\sigma^o_{vv}$ is always less than one except at near-normal incidence.
- For the physical optics model, the ratio is greater than one, except at near nadir incidence.
- For the geometrical optics model, the ratio is always equal to one.

Therefore, one can "say" something about the surface roughness condition using the co-polarization ratio and automatically choose the model to be applied for each pixel (or plot). Their results showed that the co-polarization ratio has good potential for measuring soil moisture for bare fields, particularly when soil moisture was less 30% in volume and incidence angle is above 40°. The inversion algorithm performed well at L Band but not at C Band. The geometric model could not be evaluated because the validity conditions were not met.

The main drawbacks of using the purely analytical surface scattering models are:

- The validity conditions are hardly met in the practical world;
- The co-polarization ratio is very noisy on a pixel by pixel basis;
- Absolute calibration is needed.

2. Semi-empirical models

Oh et al., (1992,1994), developed semi-empirical expressions for the two co-polarized backscattering coefficients σ^o_{hh} and σ^o_{vv} and the cross-polarized backscattering coefficient, σ^o_{hv}, as a function of the incidence angle θ, the radar wavelength λ, and two soil parameters, the relative dielectric constant ε_s and the *rms* surface roughness. The models, valid over the angular range defined by $20° \leq \theta \leq 70°$, are given by:

$$\sigma^o_{vv} = \frac{g \cos^3 \theta_i}{p^{1/2}} \left[\Gamma v(\theta) + \Gamma h(\theta) \right] \quad (17)$$

$$\sigma^o_{hh} = p \sigma^o_{vv} \quad (18)$$

$$\sigma^o_{hv} = q \sigma^o_{vv} \quad (19)$$

$$p = \left[1 - \left(\frac{2\theta}{\pi} \right)^{[0.314/\Gamma o]} \cdot \exp(-\kappa s) \right]^2 \quad (20)$$

$$q = 0.25(\Gamma o)^{1/2}(0.1 + \sin^{0.9}\theta_i) \cdot \left[1 - \exp[-(1.4 - 1.6\Gamma o)\kappa s] \right] \quad (21)$$

$$g = 0.7\left[1 - \exp\left(-0.65(\kappa s)^{1.8}\right) \right] \quad (22)$$

$$\Gamma o = \left| \frac{\varepsilon_s^{1/2} - 1}{\varepsilon_s^{1/2} + 1} \right|^2 \qquad (23)$$

$$\Gamma h(\theta_i) = \left| \frac{\cos\theta_i - (\varepsilon_s - \sin^2\theta_i)^{1/2}}{\cos\theta_i + (\varepsilon_s - \sin^2\theta_i)^{1/2}} \right|^2 \qquad (24)$$

$$\Gamma v(\theta_i) = \left| \frac{\varepsilon_s \cos\theta_i - (\varepsilon_s - \sin^2\theta_i)^{1/2}}{\varepsilon_s \cos\theta_i + (\varepsilon_s - \sin^2\theta_i)^{1/2}} \right|^2 \qquad (25)$$

and is the relative complex dielectric constant of the soil:

$$\varepsilon_s = \varepsilon_s' - j\varepsilon_s'' \qquad (26)$$

According to this surface scattering model, the three magnitude quantities measured by a polarimetric radar, σ^o_{hh}, σ^o_{vv} and σ^o_{hv}, provide three measured quantities, from which it should be possible to determine the *rms* height *s* and the dielectric constant ε_s, since θ_i and κ are known. The dielectric constant is in turn a function of the soil volumetric moisture m_v and the soil type. Using this model, Ulaby et al., (1995) provide two algorithms for estimating *s* and ε_s from polarimetric radar observations:

- The first one, the *p-q* Inversion Algorithm uses the equations (17)-(26). The advantage of this algorithm is that it is insensitive to absolute calibration of σ^o_{hh}, σ^o_{vv} and σ^o_{hv}, relying only on good relative calibration one to each other. Its potential disadvantage is when vegetation is present since whereas σ^o_{hh} and σ^o_{vv} are only weakly sensitive to the presence of modest vegetation, σ^o_{hv} (and *q*) is quite sensitive to vegetation cover.
- The second one is the p-σ^o_{hh} inversion algorithm that does not use the cross-polarized channel, but requires good absolute calibration of the co-polarized channels.

Ulaby et al., (1995) compared radar-estimated surface roughness and soil moisture using JPL AIRSAR data with ground truth data, and obtained very good agreements with correlation coefficients as high as 0.96.

Dubois et al., (1995), developed an algorithm that also employs only the co-polarized channels to estimate *s* and m_v. Their equations are:

$$\sigma^o_{hh} = 10^{-2.75} \frac{\cos^{1.5}\theta_i}{\sin^5\theta_i} 10^{0.028\varepsilon \tan\theta_i} \cdot (\kappa s \sin\theta_i)^{1.4} \lambda^{0.7} \qquad (27)$$

$$\sigma^o_{vv} = 10^{-2.35} \frac{\cos^3\theta_i}{\sin^3\theta_i} 10^{0.046\varepsilon \tan\theta_i} \cdot (\kappa s \sin\theta_i)^{1.1} \lambda^{0.7} \qquad (28)$$

Here ε is the real part of the complex dielectric constant. According to the authors, the algorithm is optimized to work at a frequency between 1.5 and 11 GHz and gives best results for $\kappa s \le 2.5$, $m_v \le 35\%$, and $\theta \ge 30^o$. They used a simple criteria based on the $\sigma^o_{hv}/\sigma^o_{vv}$ ratio to select the areas where the inversion is not impaired by the vegetation. To test their algorithm, they used several SAR data sets taken between 1991 and 1994 from airborne (AIRSAR) and spaceborne (SIR-C) for bare surfaces, under a large range of sampling conditions. They found an RMS error in the estimated soil moisture to be less than 4.2%.

The following general statements can be made:

- The models require polarimetric data, not always available;
- The models work better at lower frequencies (L band);
- Absolute calibration accuracy is a problem, since the model is quite sensitive to uncertainties in the backscattering;
- The models are of a semi-empirical nature, such that a lot of independent data throughout the world must be tested for before being certified as operational.

The Bebedouro SIR-C Hydrology Supersite

We introduce here the preliminary results of testing the empirical model of Dubois et al., (1995), over the Bebedouro SIR-C/X-SAR Supersite (JPL Publication 93-29). The area is located on the left bank (9°07'S, 40°18'WGr) of the São Francisco River, a major north-south trending flowing river system. The river crosses a vast semi-arid region in northeast Brazil, where a government sponsored development program will irrigate over 1 million hectares for agriculture, of which 200,000 have already been irrigated. In the Bebedouro Irrigation Project, BIP, individual farms range from 5 to 12 ha and the total irrigated area is 1750 ha (Soares et al., 1988). Crops and orchards in the BIP include mango, vine, tomato, melon and water melon. Other types of land cover (found at the time of the SIR-C April'94 flight) are pasture, pasture with bushes, and bare soil. We used a total of 6 scenes taken on April 9, April 10, April 13, April 14 (two, ascending and descending) and April 15.

Soil moisture and roughness measurements were taken over 13 fields scattered all over the test site. Soil moisture sampling were done at two layers: 0-5 cm and 5-10 cm, on a daily basis, during the SIR-C/X-SAR April'94 flight. Four sampling points were done for each field, with five repetitions each. Over 2000 samples were collected, weighted, dried out and weighted again. There was a rainfall of 80 mm the night before the first SIR-C overpass (April, 8, 1994), and it did not rain for the rest of the experiment. Because top 30 cm of the dominant soil are sandy , some fields were irrigated for planting 5 days after the rainfall. Surface roughness was estimated using photographs of a gridded panel oriented both parallel and perpendicular to radar swaths. Photographs were digitized and the *rms* height was calculated.

We tested the inversion of equations (27) and (28) to derive both *rms* height and the dielectric constant ε and compared them with the "in situ" measured values. Soil moisture was calculated from dielectric constant using soil texture information as in Hallikainen et al., (1985). The results for soil moisture obtained from using both co-polarized L Band channels are plotted in figure 2 against the measured values. Only the averages are used in this case. Although the sensitivity of radar backscatter is very clear, the derived values are in general underestimated and the correlation coefficient is only moderate, indicating that this empirical model could not be used to map soil moisture with an acceptable accuracy. On the other hand if the *rms* height is previously known, we could use only one co-polarized data set (either equation (27) or (28)). This situation is realistic in many cases, for which no agricultural practices are happening to change the surface roughness. Also, in the near future, for technical reasons, multipolarimetric spaceborne SAR are not likely to fly, what brings the problem of "a priori" knowledge of soil roughness if one are interested in estimating soil moisture. Figure 3 displays the comparison between model derived and measured values, using L band VV polarization (equation (28)). In this case, the underestimation is minimized and the correlation coefficient is higher. One can notice that the variance tends to be higher when m_v is higher than 25% in volume, which is in agreement with the findings of Dubois et al., (1985). There may be situations where realistic estimates of roughness could be done over a stable region, after days of continuous rainfall that saturates the soil; in this case soil moisture is an input and *rms* height is obtained from inversion of equation (28). On the other hand, when the HH polarization is used (figure 4), the correlation coefficient is smaller indicating that there may be problems of fitting for equation (27). Dubois et al., (1995) did not compare VV and HH polarization for their sensitivity to soil moisture. It appears, though, from this preliminary results, that the VV polarization are less sensitive to uncertainties on rms height, a result to be investigated as a follow up of this survey. To confirm these results, we show, in figures 4 and 5, the plots of the theoretical values for σ^o_{vv} and σ^o_{hh} corresponding to a range of m_v going from 0 to 40% and two *rms* height (0.3 to 1.4 cm). When *rms* height is 0.3 cm, σ^o_{vv} goes from -24 to -14 dB σ^o_{hh} varies between -27 and -21 dB as m_v changes from 0 to 40%.. If the *rms* height of 1.4 cm is used, σ^o_{vv} goes from - 17 to -7 dB and σ^o_{hh} varies between -18 and -11 dB in the same range of m_v. Ulaby et Siquiera, (1995), show that, for their model, σ^o_{vv} rises from -23 to -13 dB as soil moisture goes from 0 to 40% in volume, a 10 dB change, while σ^o_{hh} increases from -23 to -18, a 5 dB change (1.25 GHz, s=1.5cm, θ_i=40°). It is clear that, for both semi-empirical models, σ^o_{vv} is approximately twice as much sensitive to volumetric moisture variation.

Measured "in situ" rms height used in our tests were between 0.33 and 1.4 cm. They correspond to ks from 0.087 and 0.37 for L band and from 0.37 and 1.57 for C band.

According to Dubois et al.,(1995), the science requirements for the SIR-C Calibration accuracy at both L and C bands are ± 2.0 dB / ± 0.4 dB for absolute and relative calibration, respectively. It is obvious that, since as much as 4 dB change could happen due only to calibration problems (in the worst case), absolute calibration errors are an important source of scattering in the cluster. Obviously, since the *hh* polarization is less sensitive to soil moisture changes, it is more affected by absolute calibration inaccuracy.

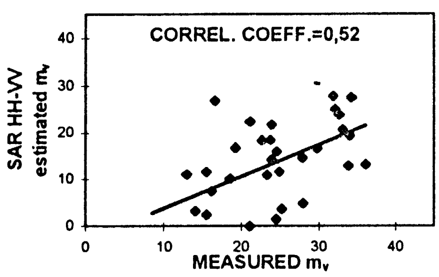

Figure 2. SAR derived soil moisture using the two co-polarized bands (L Band) versus measured soil moisture.

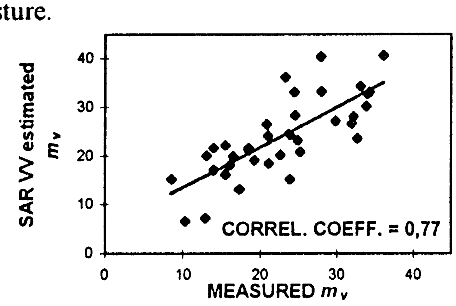

Figure 3. SAR derived soil moisture using the one co-polarized band (VV, L Band) versus measured soil moisture.

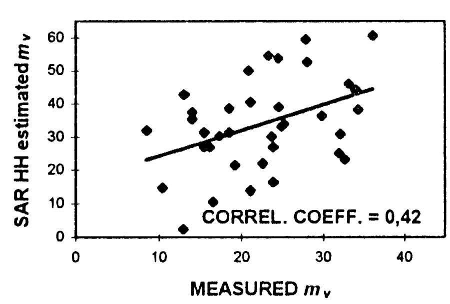

Figure 4. SAR derived soil moisture using the one co-polarized band (HH, L Band) versus measured soil moisture.

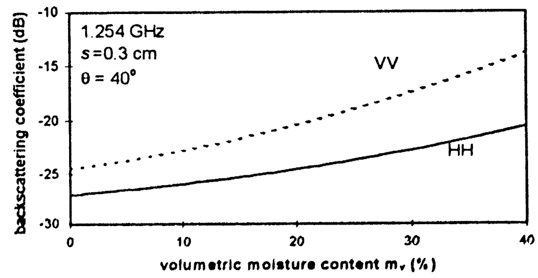

Figura 5. Plots of σ^0_{vv} and σ^0_{hh} as a function of m_v (L band, s=0.3 cm, θ=40°).

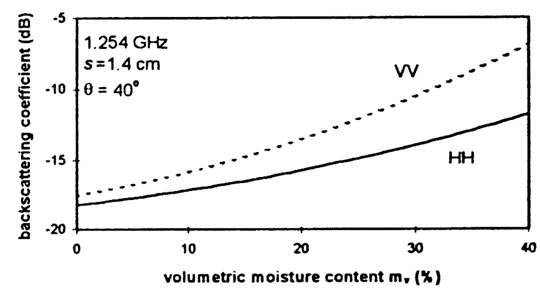

Figura 6. Plots of σ^0_{vv} and σ^0_{hh} as a function of m_v (L band, s=1.4 cm, θ=40°).

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