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Using Multi-Angular Radar Data to Discriminate the Influence of Rough Surface Scattering on Soil Moisture Inversions over Bare Soils

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Abstract: It is well known that the angular response of radar backscattering is strongly influenced by surface roughness. Attempts to exploit this result in soil moisture or roughness inversions are however practically non-existent, maybe because multi angular satellite data are only starting to be available. Experimental data shows how the difference between signals at 20° and 30° incidence angles is 10x more sensitive to surface roughness degradation than is the difference between hh and vv polarizations at same incidence and 5. 3 or 9.4 GHz. Extensive simulations with IEM show that this result can be exploited for soil moisture inversions, if the surface correlation function is close to exponential.

1. INTRODUCTION

Retrieving soil moisture from radar data over bare soils is an outstanding challenge due to the influence of rough surface scattering (RSS). The range of sensitivity of the radar signal to RSS over natural soils is more than twice that due to soil moisture variations. Moreover, the number of surface parameters that are necessary to quantify the effect of RSS is shown to be a minimum of three, whereas only a single variable parameter is necessary to quantify the effect of soil moisture.

Numerically, RSS can be quantified if the entire surface geometry as viewed by the radar is known with sufficient resolution [1]. Analytically, the state of the art model to date, IEM [2, 4], gives an alternative theoretical approach that relies only on a few input parameters. The IEM, in its practical version, however remains dependent on the statistical laws that are used to describe random roughness as well as various approximations inherent to its analytical form, which greatly restrict its domain of validity.

Experimentally, the clear dependence of radar signal to soil moisture (see § 3) makes it tempting to propose empirical models that reproduce the observations. It is however generally admitted that existing empirical models are valid only over the range of surface roughness characteristics over which they were developed. Moreover, because of the multiple surface roughness parameters, it is difficult to find simple models that cover a wide range of surface characteristics. This is made clear below with IEM simulations over a wide range of surface roughness parameters.

Since multiple parameters influence the radar signal, it seems inevitable to have recourse to multiple measurements of the same surface, viewed under different conditions, to discriminate the different effects. The difference between signals measured at two view angles is presented here as a potential candidate to eliminate the influence of RSS on the radar signal, thus opening the possibility of inverting the corrected signal to retrieve soil moisture.

Experimentally, the potential of this method seems promising. From IEM simulations however, it is shown that the method is not practical unless the surface correlation function is close to the exponential. This was investigated for a wide range of surface parameters and incident angles from 20° to 40°, which are typical of satellite remote sensing,

2. MODEL FORMULATION

In a practical approximation, the effects of RSS and soil moisture on the radar signal can be written as

$$\sigma_0 = f_1(\theta_i, \mathrm{RSS}) + f_2(\theta_i)\cdot f_3(m_v) \quad [\mathrm{dB}] \qquad (1)$$

where RSS represents the combined surface roughness parameters, θ_i is the incidence angle and m_v is the soil moisture. The separation of functions f_2 and f_3 is based on our simulated and experimental results, see § 3. The separation of f_1 from $(f_2\cdot f_3)$ has been used before [3] and is confirmed by our experimental and IEM-simulated results.

Based on (1), it is easy to show :

$$\begin{aligned}\Delta\sigma &= \sigma_0(\theta_1) - \sigma_0(\theta_2) f_2(\theta_1)/f_2(\theta_2) \\ &= f_1(\theta_1, \mathrm{RSS}) - f_1(\theta_2, \mathrm{RSS}) f_2(\theta_1)/f_2(\theta_2)\end{aligned} \qquad (2)$$

Thus, if (1) is respected, it is possible, from two measurements at different angles, to obtain a quantity in [dB] which is dependant only on surface roughness parameters and not on soil moisture.

In § 3, (1) and (2) are validated with both experimental and simulated data. The proposed method can be divided in 3 steps: *i)* estimate $\Delta\sigma$ from measurements at two angles; *ii)* determine f_1 from $\Delta\sigma$ and *iii)* estimate the soil moisture m_v from (1), with the knowledge of f_1, f_2 and σ_0.

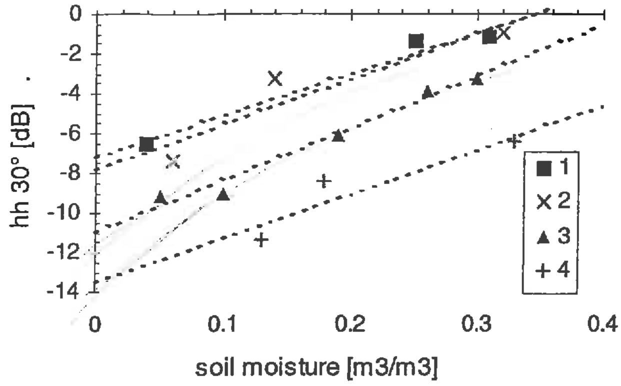

Figure 1: Measured signal versus measured soil moisture. Radar on crane. Pixel area ~10x10 m. Four data sets = four periods consecutive to rain or irrigation. rms height ~1.4, 1.2, 1.0 and 0.8 cm for periods 1-4. Frequency is 9.4 GHz.

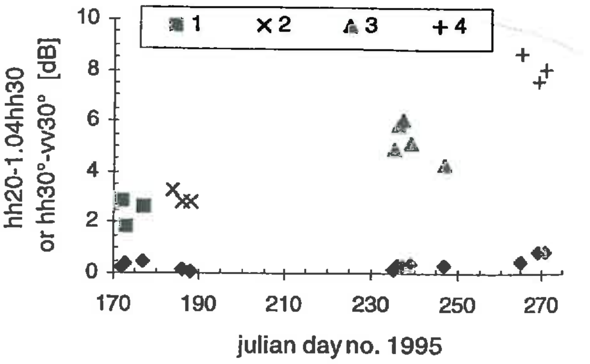

Figure 2: Difference between radar signals measured at two incidence angles (red) and two polarizations (blue) versus day number. Same sets of data as Fig. 1. The increase is due to smoothing under the action of rain or irrigation before each of the four periods.

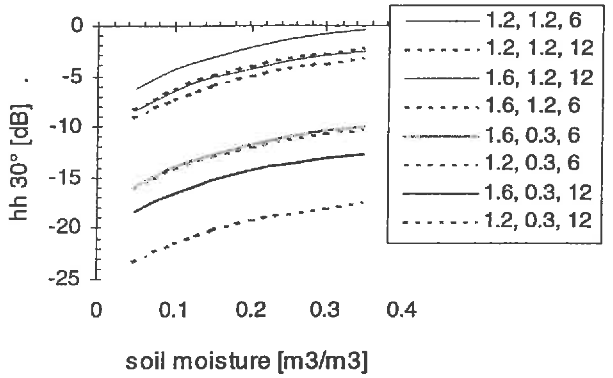

Figure 3: IEM simulated radar backscatter versus soil moisture. The triplets represent D, *ks*, and *kl*, where D is the fractal dimension, *k* is the wave number and *s*,*l* are the surface rms height and correlation length.

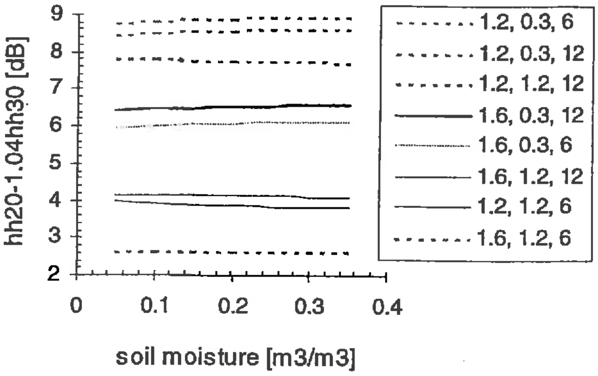

Figure 4: $\Delta\sigma$ as simulated by IEM versus variable surface characteristics - D, *ks*, *kl* - as in Fig. 3. Note that D=1.6 to1.0 represents a variation from exponential to gaussian correlated surface [5] and $k = 1$ cm^{-1} if the frequency is 4.77 GHz.

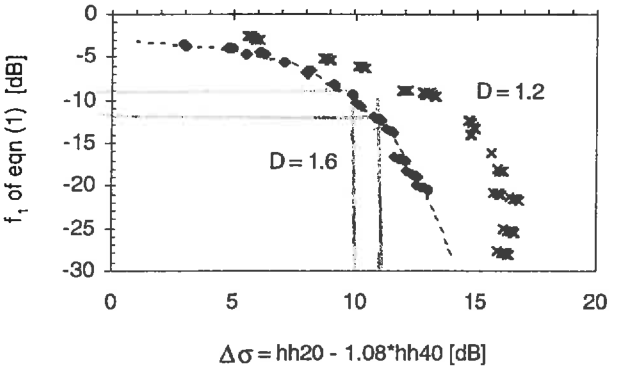

Figure 5: IEM simulation, f_1 of (1) versus $\Delta\sigma$ of (2) for ks = 0.3 to 1.5, kl = 6 to 12 and two surface correlation functions symbolized by D, the fractal dimension. The smallest values of f_1 (largest $\Delta\sigma$) occur when the rms height is smallest.

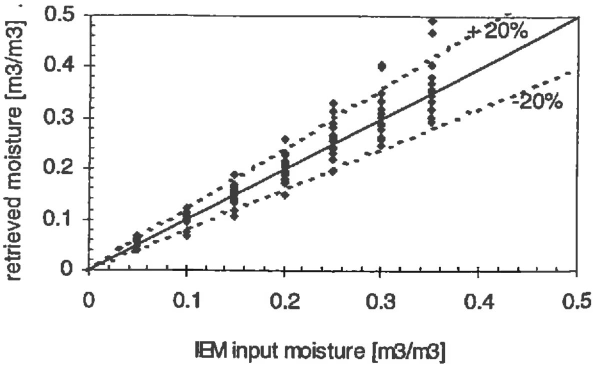

Figure 6: Simulated moisture retrieval using (1-3), over the same data set as used in Fig. 5, assuming an exponential surface correlation, see text. Note that the largest errors occur when the soil is "smoothest" and f_1 is minimal, see Fig. 5.

WATER FLOW AND SOIL WATER CONTENT VARIABILITY IN GRASS-COVERED HEAVY CLAY AND PEAT SOILS OF THE NETHERLANDS

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In the Netherlands many grass-covered heavy clay and peat soils are susceptible to drought and difficult to wet after a dry period. A major proportion of precipitation can flow rapidly through shrinkage cracks towards the subsoil, bypassing the matrix of the soils. However, trenches studied in these soils revealed that preferential flow is not limited to macropore flow: irregular and fingerlike wetting patterns are also formed through the small pores of the matrix. The diameter of the patterns exceeded the width of individual cracks, indicating that the surrounding matrix was participating in the vertically directed flow as well. These preferred pathways are thought to form at places with cracks which receive relatively large amounts of water, due to water moving over the surface and through the surface layer towards slightly lower places. Hence, the surrounding small pores in the matrix can be wetted as well, resulting in irregular wetting patterns. As a consequence of these patterns, variability in soil mois-ture content is high. We found large differences in soil moisture content in the heavy clay and peat soils in all layers sampled at all the sites and for all measurements. Large differences in wettability exist between wet and dry soils, due to water repellency being induced at low water contents. Resistance to wetting was determined by measuring the wetting rate of field-moist samples with varying water contents.

MODELLING OF WATER INFILTRATION AND SOIL SWELLING IN A VERTISOL FROM GUADELOUPE.

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Models of water infiltration in undisturbed swelling soils rely on a dual porosity concept: Darcy flow in the micro (matric) porosity and by-pass flow in cracks. In vertisols from the humid tropics, a third component must be added: the structural porosity, excluding cracks, formed by the soil microfauna activity and containing water easily available for plants. A model was implemented to study the mecanisms of water infiltration: (i) water infiltration in the matric porosity is modelled by the Darcy law, (ii) the flow in the structural porosity is a gravity-dominated flow, (iii) water entering cracks is instantaneously added at the bottom of the cracks. Water movement from structural to matric porosity and from crack's wall into soil matrix are accounted for. Cracks opening is a function of soil matrix moisture. Shrinkage curve, retention curve and hydraulic conductivity of the matrix were measured in the laboratory. The anisotropy ratio of soil deformation was measured *in situ*. Experiments were conducted *in situ* to fit some soil structure parameters and test the model. Although not wholly validated because of a poor modelling of infiltration in structural porosity, the model already shows that infiltration in this soil is a 3D process and that water infiltration in structural porosity is the main factor of rainfall partition between vertical infiltration in the soil matrix and water flow into the cracks. Therefore, new researches should fócus on water flow in structural porosity.

INFILTRATION OF WATER INTO SOIL WITH CRACKS: MODEL DESCRIPTION AND RESULTS OF MODELING.

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Results of modeling of precipitation water infiltration into soil with cracks are presented, as well as short description of the model FRACTURE which is a part of the SPAC model HYDRUS - ET, developed previously by joint effort of the U.S. Salinity Laboratory and by the Institute of Hydrology Slovak Academy of Sciences. The model FRACTURE is based on the two simultaneously running infiltration processes: infiltration into soil through soil surface calculated by the Richards equation and filling up of soil cracks and following infiltration of this water horizontally into soil matrix, using Green - Ampt approach. This process is involved in Richards equation as a source term. To quantify cracks infiltration two additional information are needed: so called *shrinkage curve*, which is the relation between crack porosity and soil water content and *specific length of soil cracks* on the soil surface. The next task in improving of the model application will be parametrization of the cracked soils properties (specific cracks length l_c and relationship $P_c = f(w)$) needed as input data to the model FRACTURE, thus making possible routine modelling of infiltration into cracked soils.

SIMULATION MODELLING OF VARIABLE SOIL WATER RESPONSES TO RAINFALL IN A CRACKING CLAY SOIL, BRIMSTONE FARM, UK.

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This paper will make use of an extended data-set comprising readings of soil water tension from an area of $9m^2$ which has been instrumented with 4 nests of 3 tensiometers for an 18 month period at Brimstone Farm, near Faringdon in the UK. The tensiometers have been connected with a Scanivalve fluid switch, and read sequentially every 2,5 minutes over a 45 minute interval. Supplementary data include soil moisture readings from a Neutron Moisture Probe, precipitation, net radiation, temperature and relative humidity. The soil at this site is a cracking clay characterised by the seasonal development of shrinkage cracks which inhibit any generalisation of soil water flow. A summary of field-work result will be provided, which clearly indicate the influence of macropores in determining soil water response to rainfall of varying magnitude. The way in which theses data are able to direct the development of a process-response model for specific tensiometer nests will be described, and their general applicability will be

MANAGEMENT OF SOIL WATER IN TEMPERATE CLAY SOILS: MOLE DRAINAGE AND THE ROLE OF STRUCTURE.

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Clay soils in temperate environments present difficulties in mangement, although rewarded by high agricultural yields. Artificial drainage is essential for the successful cultivation of such soils. In the UK this is most commonly achieved by the use of mole drainage, which has the effect of both improving the structure and providing an unlined drainage channel in the soil. However, the successful drainage of soils also leads to the prospect of rapid leaching of pollutants.
This paper will review experience in the experimental techniques required to study the hydrology and water quality of such soils; and the development of models to predict the leaching of pesticides and nitrates from these soils.

DERIVING PARAMETERS FOR THE DETERMINATION OF MACROPORE FLOW IN CLAY SOIL

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Field investigations carried out in Sjökulla Experimental Station located south of Finland have shown that only the macropore flow of the soil is significant due to the extremely low permeability of clay soil. Field experiment was carried out to investigate the geometrical configuration of the macropores using the dye agent Brilliant Blue ($C_{47}H_{48}N_3O_7S_2Na$) as a tracer to map the macropores. Evidences gathered have shown that water entrapment in cracks may reach up to 70% of the total rainfall. That amount of water losses depends mainly upon the dryness of the topsoil which initiates the opening of the "crack's mouth". A method for calculating the macropore flow in clay soil has been developed. Drain flow records, surface runoff, evapotranspiration and rainfall measurements over a considerable period of time have been used to construct the model. Physical characteristics of the catchment were lumped in one parameter called a retardation factor (κ). In addition, another parameter (Γ) was used to describe water entrapment in cracks and other macropores. These two parameters were both described as a function of rainfall and incorporated in a mathematical model that describes soil continuum as a vertical cylinder. Conventional models, which do not consider water entrapments in cracks, may overestimate water discharge from the catchment and ultimately overestimate pollution impact on rivers and lakes. In light of the testing results, the model can serve as a useful tool for calculating water and solute balance in agricultural clay soil. However, further field investigations are still being carried out to establish a better parameterization to the water losses in discontinuous cracks.

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