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Soil moisture assessment at a basin scale using active microwave remote sensing: the Agriscatt '88 Airborne Campaign on the Orgeval watershed

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Abstract. In June and July 1988, the European Space Agency organized in five European countries the Agriscatt '88 campaign. For this campaign two airborne scatterometers were used, including the French dual-frequency (*C* and *X* band) dual-polarization (*HH* and *VV*) forward-looking radar ERASME. For the French site, the Orgeval hydrological basin, one of the aims of the experiment was to develop a soil moisture retrieval algorithm from radar data. It is shown, from comparison with the ground-truth data, that the use of a multiconfiguration radar improves the capacity of imaging radar for soil moisture mapping. In particular, an algorithm based on a vegetation absorption index and a soil moisture one is tested over wheat fields.

1. Introduction

As it has been recently shown (Loumagne *et al.* 1991), substantial improvements in flow modelling and forecasting can be obtained by integrating information about point soil moisture measurements in a hydrological conceptual model. So, soil moisture data appear to be useful for hydrologists and climatologists trying to understand and to model water transfer processes at the basin scale.

It is possible that active microwave remote sensing could lead to a better knowledge of watersheds soil surface moisture (i.e., average values and time-space variations), in order to progress with flow forecasting. Many studies have been conducted to perfect this remote sensing method, which has the advantage of being insensitive to weather conditions and attempts have been made to explore the soil superficial layer and the plant canopy (Bernard *et al.* 1982, Dobson and Ulaby 1986, Ulaby *et al.* 1986).

In this framework, the Agriscatt '88 campaign was organized and supported by the European Space Agency (ESA) to test the capability of using this technique in agricultural and water resources fields. Its aim was, first, to build a data base containing radar and ground measurements obtained in natural conditions and, second, to test the capability of active microwave remote sensing in agricultural and water resources monitoring.

The analysis presented here is devoted to the experimental determination of the optimum multiconfiguration radar measurements to infer surface soil moisture.

2. Description of the experiment

2.1. *The Agriscatt '88 campaign*

Two airborne radars were operating during the Agriscatt '88 campaign, the DUTSCAT (Dutch) and ERASME (French) scatterometers. Five test sites were chosen located in five European countries, (the United Kingdom, Netherlands, Germany, Italy and France). This paper relates to the first results obtained with the ERASME radar on the French site. Each experiment consisted of two flights. The first flight was performed with an incidence angle of 23° from the nadir and the second one with an incidence angle of 38°. Four experiments were carried out on 16 and 30 June, 12 and 28 July, 1988. Simultaneously, ground-truth operations were conducted to collect soil moisture, roughness and vegetation data.

2.2. *The ERASME radar*

The ERASME scatterometer is a *C/X* band (5·35 GHz and 9·65 GHz) Frequency Modulated Continuous Waves radar designed as a research tool for the development of radar remote sensing for sea and land applications and as a calibration tool for ERS-1 satellite equipment. This scatterometer is a low power, small radar which can easily be carried on a small fixed-wing aircraft or helicopter (Bernard *et al.* 1986).

During the Agriscatt '88 campaign, ERASME was mounted on the B17 aircraft of the Institut Géographique National and operated as a forward-looking radar. The radar footprint is about 20 m by 20 m given by the characteristics of the antenna patterns, the altitude of the aircraft, about 350 m during the flights, and the range resolution is about 1 m.

The accuracy has been estimated better than 1 dB at the vicinity of the antenna axis and between 1 and 2 dB at the edges of the angle range (±10° across the axis).

Two polarizations were available, *HH* polarization for the *C* band, *HH* and *VV* polarizations for the *X* band. The incidence angles of the antenna axis were 23° and 38° from the nadir.

When processing the data, the classical radar equation has to be solved according to the antenna pattern, the helicopter flight parameters (pitch, roll, altitude), and the incidence angle. The backscattering cross-section σ_0 is then derived from the radar equation as a function of the incidence angle. The backscattering cross-section is given at the same time, i.e., for a same ground cell at four incidence angles (15°, 20°, 25° and 30°, 35°, 40°, 45°) averaged over 2° around these values.

The two main interests of such an airborne forward-looking scatterometer are the capability to study the spatial variability of soil moisture and vegetation canopy (airborne) and to derive a backscattering cross-section for the same target at different incidence angles (forward-looking).

2.3. *The French test site and the ground measurements: the experimental Orgeval basin*

The French test site is the Orgeval hydrological basin located about 70 km east of Paris, in the agricultural BRIE region (figure 1). It has been managed by CEMAGREF (Centre National du Machinisme Agricole, du Génie Rural, des Eaux et des Forêts) for 25 years as an experimental and representative basin for hydrological research purposes. The watershed surface is equal to 104 km^2. The relief is rather flat. Except for a small residual hill, the main part of the basin is covered over by a thick table-land loess (up to 10 m thick), characterized by a low permeability. The soil is a very homogeneous leached-out brown soil and the texture of the upper layer is a silt loam. The particle-size distribution of the 0–5 cm surface layer of 17 plots distributed along the experimental radar axis crossing the basin is given in table 1. The basin is situated entirely in rural areas: 80 per cent of the total area is covered by crops (wheat, corn, flax, peas, coleseed, sugar-beet . . .). Approximately 80 per cent of the basin's arable land has already been drained.

Precipitation and outflow discharge data are collected by rainfall recording stations and water-level recorders. Additional data are recorded at the Boissy-le-Chatel hydrological base: meteorological data and soil water content by depth gamma neutron probes. In addition, preliminary experiments have been conducted with the first version of the C-band ERASME airborne radar during the 1985–1986 period (Jarry *et al.* 1988).

During the Agriscatt '88 campaign, the flight line crossing the watershed had an E–W direction and was 17 km long. It is representative of the different basin soil occupation. Seventeen fields corresponding to the two main crops, wheat (11 fields)

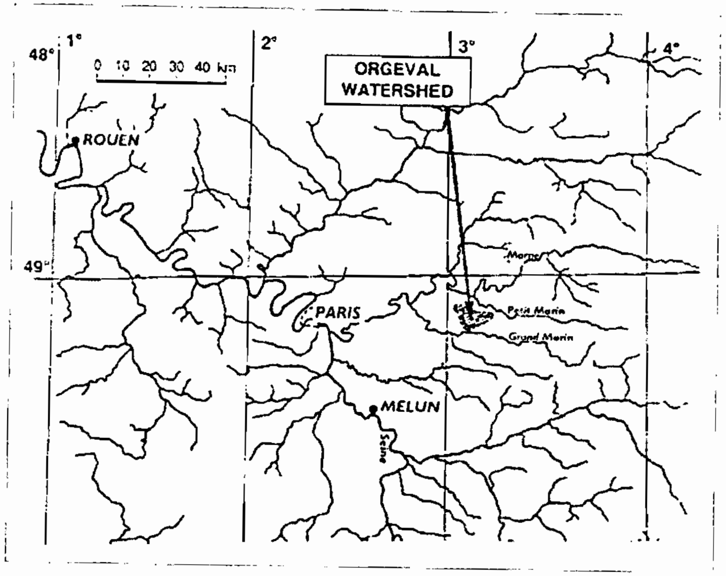

Figure 1. Geographical location of the Orgeval watershed, the French site for Agriscatt '88.

Table 1. Particle-size distribution of the 0–5 cm surface horizon of 17 fields.

	Test fields																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
% clay (0–2 μm)	15·2	12·7	14·8	20·3	19·3	19·6	17·9	15·3	21·8	19·5	14·2	17·4	16·1	17·2	19·6	17·2	21·6
% silt (2–50 μm)	78·7	83·3	79·5	71·7	74·7	74·1	74·2	78·7	72·8	75·7	79·7	76·1	74·8	76·1	73·1	76·4	72·1
% sand (50–2000 μm)	4·1	2·3	4·4	4·3	4·5	4·6	5·3	4·5	3·8	2·6	4·8	5·2	7·6	5·1	5·9	4·9	4·7

and corn (6 fields), have been selected to derive models relating radar measurements to ground parameters (figure 2). The airborne scatterometers had to fly over a cultivated area without bare soils at this period of the year.

Ground measurements were related to soil and vegetation and had to satisfy several conflicting constraints:

(*a*) the distance between the test fields deliberately distributed throughout the flight line;
(*b*) the rapidity of ground measurements, in order to reduce the gap between these measurements and radar measurements (rain hazard or, at the opposite, drying up of the soil surface);
(*c*) the possible deviation of the aircraft with regard to the theoretical flight line;
(*d*) the necessity of obtaining a significant mean value of the soil surface moisture in the part of the fields corresponding to the flight axis;
(*e*) the small number of people available to carry out the measurements in the fields.

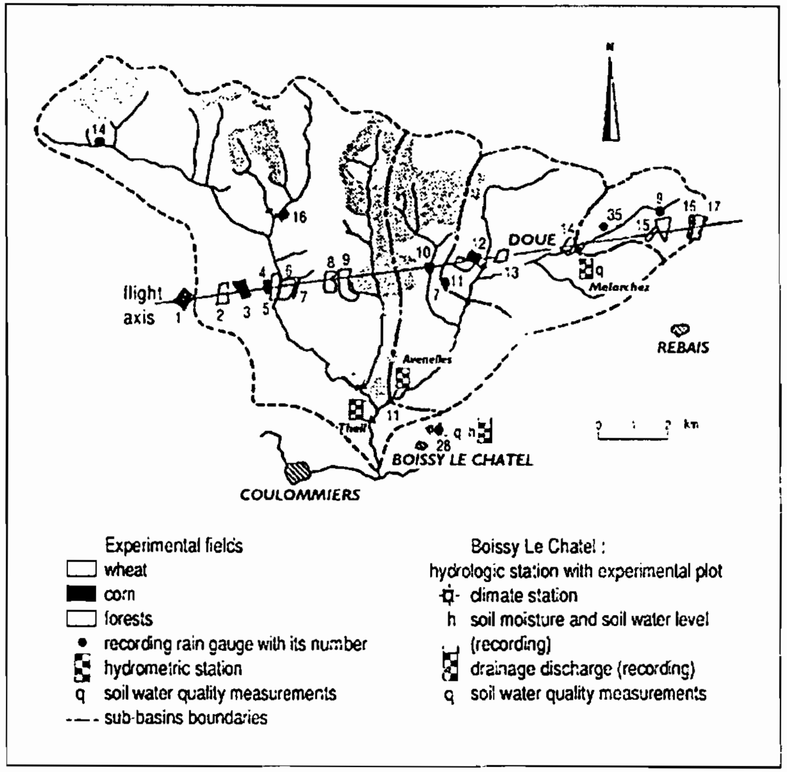

Figure 2. The flight axis and the 17 test fields used for Agriscatt '88.

Soil moisture in the upper layer was measured in every test field by gravimetric and gamma neutron methods. The first method was used to determine the soil water content of disturbed samples on the 0–5 cm plane, along three lines parallel to the flight axis: a central line corresponding to the theoretical flight axis, and two lines distant from 100 m (figure 3). Soil samples were taken about 50 m apart: a constant sampling step was preferred to a fixed number of measurements per field. Field lengths ranged from 50 to 700 m: hence the number of soil samples ranged from 6 to 33.

We checked with soil moisture measurements made 1 m apart that the range of the resulting variogram (20 m) was smaller than the interdistance of measurement in this experiment (50 m minimum). This interdistance has been chosen in order to find a good compromise for the above constraints of the experiment, knowing also that the soil moisture was very homogeneous at field scale: the standard deviations of the mean gravimetric water content in each field (or part of field) were very low (0·015 g g^{-1} to 0·020 g g^{-1} approximately).

Moreover, soil bulk density and moisture measurements were collected every 50 m along the theoretical flight axis by surface gamma neutron gauges. The probes had been previously calibrated with standard blocks for the density (gamma) and with soil *in situ* measurements for the water content (neutron).

For each site, three apparent soil density measurements were done: the first one using gamma rays backscattering to sense the surface layer, the second and the third using gamma transmission for 0–5 cm and 0–10 cm layers. The volumetric water content was measured only by backscattering.

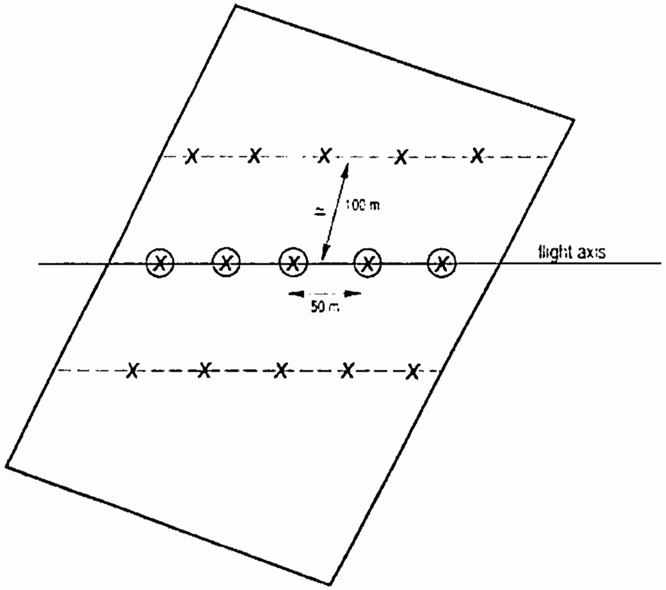

Figure 3. The soil moisture test plots within a field. X = soil sampling, O = surface gamma–neutron probe.

These data were intended essentially to characterize at each measurement date, the average dry bulk density of the part of each test field, and to obtain volumetric water content from dry mass basis water content calculated with soil samples.

In order to characterize plant canopy, the principal vegetation parameters were measured in the test fields (wheat and corn) during each of the four flight weeks: i.e., plant height, plant biomass and water content, leaf area index, growth stage (Prévot *et al.* 1992).

The aim of all these measurements was to calibrate the radar, using for each measurement day and for each test field, the mean backscattering cross-section data and the mean volumetric soil water contents simultaneously acquired.

3. Results and discussion

3.1. *Ground truth data*

A large range of variation for the different parameters measured *in situ* was observed during the campaign.

3.1.1. *Vegetation parameters*

Corn. The corn height has increased from 20 cm to 2 m. The green leaf area index has increased from 0·5 to 4 m^2 m^{-2}. The corn water content has increased from 0·5 to 3·5 kg m^{-2}.

Wheat. The wheat height has stayed quite constant around 90 cm. The green leaf area index has decreased from 5 to 0 m^2 m^{-2}. The wheat water content has decreased from 3 to 1 kg m^{-2}.

Table 2 gives for each flight day the mean and standard deviation for the vegetation height (*H*) and the green leaf area index (*LAI*) for the corn and wheat fields. For the same measurement date, one can observe a large variability of the LAI values for

Table 2. Mean and standard deviation of the vegetation height and green leaf area index for the test fields.

	Wheat (11 fields)		Corn (6 fields)	
Flight day	H (m)	LAI (m^2 m^{-2})	H (m)	LAI (m^2 m^{-2})
1	0·91	3·53	0·43	0·63
mean std	0·06	1·15	0·08	0·23
2	0·91	2·84	0·83	2·28
mean std	0·07	1·44	0·19	0·52
3	0·89	0·40	1·39	3·25
mean std	0·06	0·44	0·22	0·32
4	0·84	0·00	1·78	3·28
mean std	0·07	0·00	0·19	0·66

wheat. This variability is due to the mixing of fields with senescent or still green wheat.

3.1.2. *Soil water content*

Table 3 gives for each flight day the mean and standard deviation of the surface soil water content for the corn and wheat test fields. For the wheat fields, the mean volumetric water content exhibits a temporal variation of about 0·2 cm^3 cm^{-3}. At the same date, the wheat fields have a similar behaviour: the standard deviation is about 0·02 cm^3 cm^{-3}. In the corn fields, the dispersion of the data is larger (up to 0·045 cm^3 cm^{-3}) due to the partial plant canopy. In conclusion, the range of variation of soil moisture during the measurement period appears to be quite large in order to try to calibrate the radar.

3.2. *Radar calibration against soil moisture*

The linear correlations between σ_0, function of frequency (C and X), polarization (HH and VV) and angle of incidence (from 15° to 45°), and the field mean surface moisture have been calculated.

Two trials of data processing are presented here. The first one, listed in table 4, presents the correlation if all the fields are taken into account (corn and wheat). The main features are that the correlation is very high at C band even for large incidence angles (up to 40°). The sharp decrease of the coefficient for 45° can be attributed to a less effective correction of the radar signal due to a bad knowledge of the antenna's lobes. At X band, the correlation is generally very poor even at low angles. Table 4 is in general agreement with previous results (see, for example, Ulaby *et al.* 1986).

Secondly, recalling that the surface soil water contents in the corn fields exhibit a large variability, the linear correlation has been tested over the wheat fields only. Table 5 depicts the results. At C band, the correlation coefficients are comparable in magnitude with those obtained previously with the first pattern of the scatterometer (Jarry *et al.* 1988, Soares *et al.* 1988). They decrease with the angle of incidence, which may be attributed to the effect of the vegetation attenuation. The coefficient is slightly greater at 20° than at 15° which may due to radar signal correction difficulties (even if the difference is not statistically significant, the correlation being calculated only for 31 points).

Table 3. Mean and standard deviation of the surface soil moisture for the test fields.

Flight day	Wheat (11 fields) (cm^3 cm^{-3})	Corn (6 fields) (cm^3 cm^{-3})	Wheat and corn (17 fields) (cm^3 cm^{-3})
1			
mean std	0·207 0·02	0·21 0·03	0·207 0·027
2			
mean std	0·139 0·015	0·191 0·043	0·157 0·037
3			
mean std	0·309 0·028	0·286 0·027	0·301 0·027
4			
mean std	0·327 0·018	0·318 0·045	0·324 0·029

Table 4. Correlation coefficients for all available frequencies and polarizations for the test fields.

	15	20°	25°	30°	35°	40°	45
$C-HH$	0·67	0·73	0·73	0·71	0·67	0·66	0·34
$X-HH$	0·33	0·36	0·40	0·44		—	—
$X-VV$	0·30	—	—		—	—	

At X band, the correlation coefficients are always very poor, even if they are larger than those listed in table 4. This has to be attributed to the vegetation attenuation. The lower values for $X-VV$ are compatible with that explanation, since it is known that wheat is more visible for VV polarization (Le Toan *et al.* 1983). Figures (4) and (5) show the correlation between σ_0 (C band, 20°, HH) and the surface soil moisture for the wheat fields (4) and for the corn fields (5). From tables 4 and 5 and figures 4 and 5 it is clear that, for this particular experiment, it is impossible to obtain a meaningful calibration of the radar over the corn fields.

One of the advantages of the ERASME scatterometer is that it provides multiple radar configurations over strictly the same target. Then, it allows multiconfiguration algorithms to be tested in order to derive surface soil moisture. Such a capability has been used by Prévot *et al.* (1992) to derive information about the wheat canopy. Prévot *et al.* shows that if the surface soil moisture is provided by C band low incidence angle measurements, then the canopy dry weight may be obtained using X band measurements at two incidence angles, a low one (20°) and a high one (40°). The principle of such an algorithm is based on the differential attenuation of the soil signal by the canopy. The same approach may be used for the soil moisture. If one calculates a multiple linear regression between

$$\sigma_0\,(20^\circ, HH, X) - \sigma_0\,(40^\circ, VV, X) \qquad \text{(value 1)}$$

which may be related to the vegetation attenuation and

$$\sigma_0\,(20^\circ, HH, C) \qquad \text{(value 2)}$$

a correlation coefficient of 0·9 is reached for the wheat fields. It is then obvious that if an estimation of soil moisture at field scale is necessary, the use of multiconfiguration radars may answer to the question. The demonstration from space will soon be possible thanks to the launch of the SIR-C/X-SAR experiment in 1993 by the U.S. Space Shuttle.

Table 5. Correlation coefficients for all available frequencies and polarizations for wheat fields only.

	15	20	25	30°	35°	40	45
$C-HH$	0·80	0·85	0·87	0·85	0·65	0·66	0·38
$X-HH$	0·63	0·68	0·71	0·69	0·47	0·36	
$X-VV$	0·58	0·46	0·44	0·36	—		

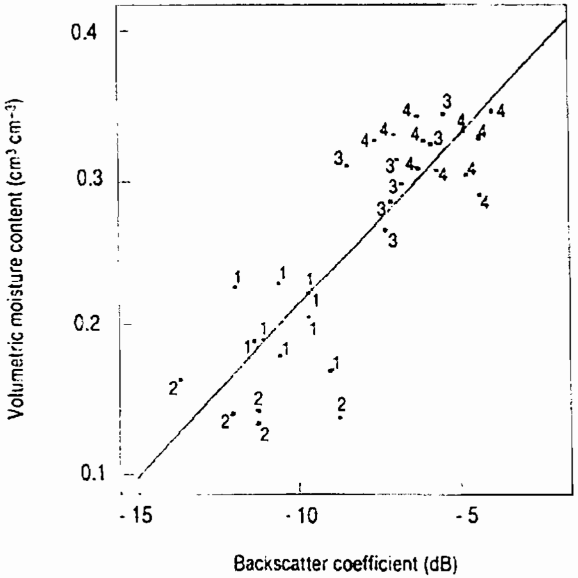

Figure 4. Scatter-plot showing the linear relation between the radar σ_0 at *C* band, *HH* polarization and 20° incidence angle and volumetric soil surface content in cm³ cm⁻³ for wheat fields. The numbers are for the different flight days (1 = 16 June, 2 = 30 June, 3 = 12 July, 4 = 28 July). The correlation coefficient is 0·85. The numbers at the points indicate the day of the experiment.

3.3. *ERS-1 large-scale soil moisture measurements*

Recently, in July 1991, the first ESA Earth observation satellite was launched. Among its payload ERS-1 carries a *C* band SAR. The angle of incidence of this instrument is of the order of 23°. The difficulty of measuring soil moisture at field scale over a variety of canopies, shown in this paper (i.e., it works for wheat but not for corn), indicates that it will be difficult to use this instrument at its highest resolution (between 20 and 30 m). In order to overcome this drawback it was proposed that we should follow the moisture state at regional scale rather than at field scale, by averaging the signal over an entire watershed. Figure 6 illustrates this possibility. The mean σ_0 (*C*, *HH*, 20°), excluding the forested and urban areas (which will be possible because of the high resolution of the ERS-1-SAR), is plotted against the mean soil moisture calculated using all test fields (table 3).

As the mean soil moisture using all test fields shows increasing soil surface moisture from 30 June, 16 June, 12 July and 28 July, the same evolution clearly is obtained by the averaged radar measurements over the whole watershed, even if attenuated. Although the number of points is not very large, it is apparent that such an approach will be possible with ERS-1. It is the aim of an ESA-Pilot Project to demonstrate it.

4. Conclusion

Active microwave remote sensing is considered a very promising technique to infer information related to renewable resources. Among this information, surface

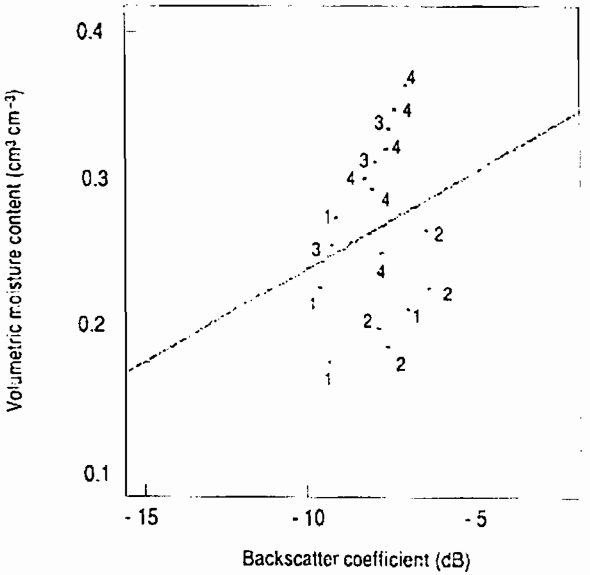

Figure 5. Same as figure 4 but for corn fields. It is clear here that no correlation exists between the two variables.

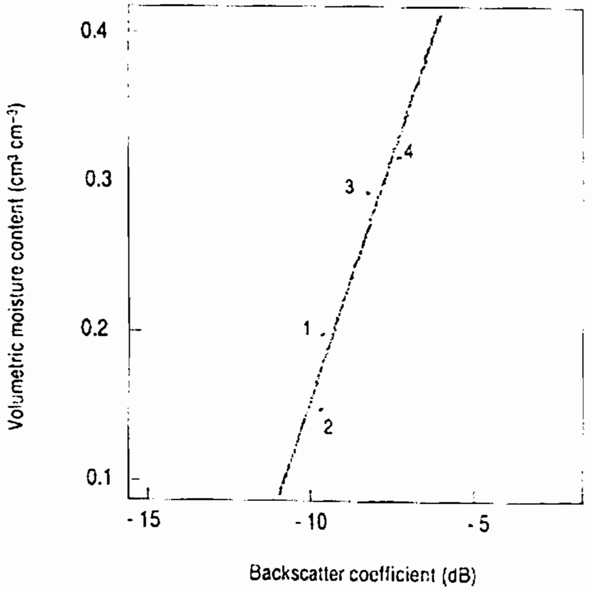

Figure 6. Same as figure 4 but for the mean radar data (excluding urban and forested areas) and mean soil water content.

soil moisture is one of the most important. It has been shown on several occasions that a knowledge of this parameter at field scale, or at basin scale, would improve our capability in hydrological modelling considerably.

The paper which is presented here is directed to the construction of soil moisture retrieval algorithms using multiple configuration radars of the type which will be available at the end of the century (e.g., the EOS-SAR proposal).

From the analysis of an airborne experiment using a forward-looking calibrated non-imaging scatterometer it has been shown that the use of a multifrequency, multi-incidence angle radar may improve our capability to retrieve the soil moisture greatly. The best algorithm deduced from the data makes use of a vegetation absorption index (the ratio between the *X* band measurements at 40° and 20° incidence angles), and a soil moisture one (*C* band, 20°). Furthermore, it has been shown that the soil moisture index may be used alone at the basin scale as an indicator of the surface hydric state.

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