MULTI-ANNUAL ANALYSIS OF ERS SURFACE SOIL MOISTURE MEASUREMENTS OF DIFFERENT LAND USES

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ABSTRACT

This paper describes a new approach to convert ERS backscatter signals from different test sites within Germany into surface soil moisture values over several years.

Because the radar backscatter signal depend mainly on soil type, vegetation development, vegetation structure and water content of the soil, vegetation and soil dependencies were eliminated to receive the backscatter signal only influenced by the amount of soil moisture.

To retrieve a soil type independent relationship between surface soil moisture and the radar backscattering signal, all in situ measured surface soil moisture values were converted into dielectric constant values using the relationship of dielectric constant and volumetric soil moisture established by Hallikainen et al. (1985).

The influence on the backscattering signal of different agricultural use of the test fields were corrected by using a roughness criteria for each crop type under investigation. The correction of this influence was done by including roughness parameter into this approach, based on investigations by Ulaby (1992).

The approach was successfully used for corn, barley, oat and harvested fields. A common nonlinear regression curve is now available for these crops. For m7eadows, a very common land use in the Bavarian Alpine Foreland, an additional vegetation parameter (biomass) had to be included, to compensate the attenuation effect of strong radar effective vegetation structure changes within the period of observation. On the basis of these results, an attempt was made to determine the temporal development and spatial distribution of the course of the top soil moisture, using the corrected ERS backscattering coefficients of each field in the whole test site.

1. INTRODUCTION

Point measurements of one of the most important parameters in water cycle, the soil moisture, will not lead to a realistic view of the spatial moisture distribution. Therefore, not much is known of the course of moisture in different soils and under different land uses. The reason for this is the great spatial inhomogeneity of soil moisture and the expensive, complicated and labor intensive soil moisture point measurement available now.

Therefore it is worthwhile to investigate the potential of remote sensing as a source of environmental data, which is already spatially distributed and available. Once correlations are established between remote sensing data and environmental parameters this can be used to improve the quality of model input data sets and finally to reduce the number of conventional point measurement stations, still maintaining the quality of data.

Both, theoretical considerations and measurements using ground based scatterometer and aircraft based radar systems in the 70s and 80s, have proven, that the fraction of a RADAR pulse, which is backscattered from the surface, mainly contains information on the dielectric properties and roughness of the imaged surface (HALLIKAINEN et al., 1985; ULABY et al., 1982-1986). Further influencing factors on the backscattered intensity and polarisation are the incidence angle, the wavelength of the microwave and the properties of the soil both in terms of geometry and material. The value of the dielectric constant is dominated by the water content of the soil because the dielectric constant of water has approx. 20-30 times the value of the soil matrix. Therefore, the dielectric constant of the soil water mixture changes strongly with soil water content.

The new approach is eliminating separately the effects of different soil types, different land use and for meadows the varying biomass on the backscatter signal of ERS. Then the remaining radar signal information are converted into surface soil moisture values over the test site.

2. TEST SITES

Between 1991 and 1994 two test areas were investigated within an ERS-PI-project. During the Commissioning Phase of ERS-1 in 1991 investigations were carried out in the Freiburg test site. A new test area near Munich was chosen for investigations from 1992 until 1994. This test site is situated near the town of Weilheim.

2.1 The test site near Freiburg

The Freiburg test site is situated about 20 km West of Freiburg within the Upper Rhine Valley. The geographical location of the test area is at approx. 48° North and 8° East. It covers a total area of approx. 50 km^2.

The average annual temperature in the test site is 10 °C with an average July temperature of 19.9 °C. Precipitation in the test site varies between 550 mm/a and 650 mm/a. Coarse grained sandy soils in the central part of the valley force farmers to irrigate corn fields to stabilize yield. The test site is geomorphologically situated on the lower terrace of the river Rhine (very flat area). Detailed soil information of the test area exists in the form of the Special Soil Survey of Germany (former "Reichsbodenschätzung") of 1934. The maps of these investigations were digitized and converted into GIS raster data layers with a resolution of two meters.

The ground water table in the Freiburg test site lies between 3-10 m below surface. Therefore no contact exists between the roots of the plants (even for forests) and ground water.

The land use in the test site is very inhomogeneous. Intensive agricultural land use covers approx. 60 % of the test site whereas the forested areas cover approx. 25 %. The remaining 15 % are covered with artificial lakes, gravel pits and villages.

The agricultural land use in 1991 consisted of corn (50%), cereals (20 %, mainly barley and wheat), potatoes (4 %) and whine (17 %). The percentage relate to the total agricultural use in the test site. The average field size is 1.5 ha, which leads to a strong heterogeneity of the test area.

As conclusion the test site near Freiburg covers a large variety of natural surface and climate conditions. It ranges from very light to heavy soils, from thick forests to gravel pits without vegetation, a large variety of agricultural plants and a variety of soil moisture conditions due to different soils, plants and a gradient in rainfall across the test area.

2.2 The test site near Weilheim

The Weilheim test area is situated at 48° North and 11° East approx. 60 km South of Munich in the Upper Bavarian Forelands around the town of Weilheim and covers an area of 100 km^2.

The landscape in the test area was formed by glaciers during the ice ages. It consists of a former glacier valley, which is bound by moraines to the East and the West. In the North, Lake Ammer forms a natural boundary of the test area. In the South the geological step of the "Guggenberg Molasse" forms the border of the test site.

The average elevation of the test site is 550 m a.s. The elevation and the nearby Alps result in cool average annual temperatures of 7-8 °C in the test site. The average temperature in January is -2 °C. The average annual precipitation in the test site is 1050-1200 mm/a with a slight gradient from the North to the South. During summer, rainfall appears mainly in form of heavy thunderstorms whereas in winter time advective rainfall predominates. The distribution of the soils in the Weilheim test site were digitized from the "Bodengütekarte von Bayern, 1959" using the soil type classification of the Special Soil Survey of Germany.

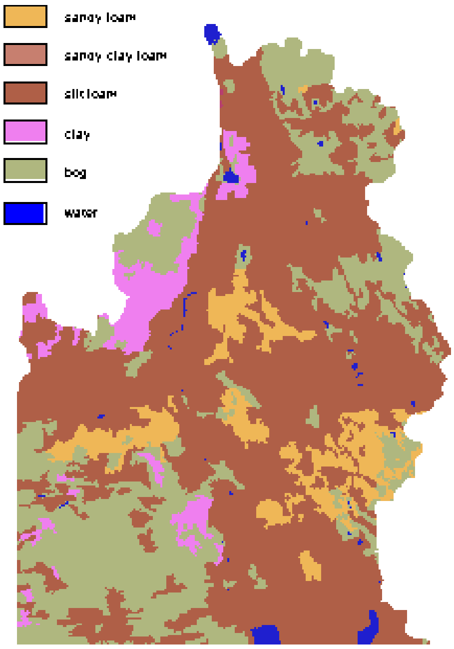

Figure 1: Digital soil type map of the test site near Weilheim (from: "Bodengütekarte von Bayern", 1959)

Figure 1 shows the distribution of the soil type in the test site. The distribution of the soils in the test site follows a general pattern. The lighter loamy gravel soils can be found to the East and West of the test site on the moraines surrounding the Ammer valley. Within the valley loamy and clay soils predominate. Where bogs developed on the clay soils today boggy soils with a high content of organic matter can be found.

The test site is predominantly covered with agriculture. The forests in the test area can be found on the moraines.

Figure 2 shows the land use distribution in the Weilheim test site in 1992 derived from Landsat TM classification (details see STOLZ & MAUSER, 1997a). As can be seen, more than half of the test area is covered with agriculture, 24 % is covered with forest and 10 % with villages. Superficially, these percentages are comparable with those in the Freiburg test site. A deeper analysis shows, that the dominance of grassland and meadows makes the Weilheim test site very different from the Freiburg one in the sense, that it is much more uniform, than the intensive agricultural region in the Rhine valley.

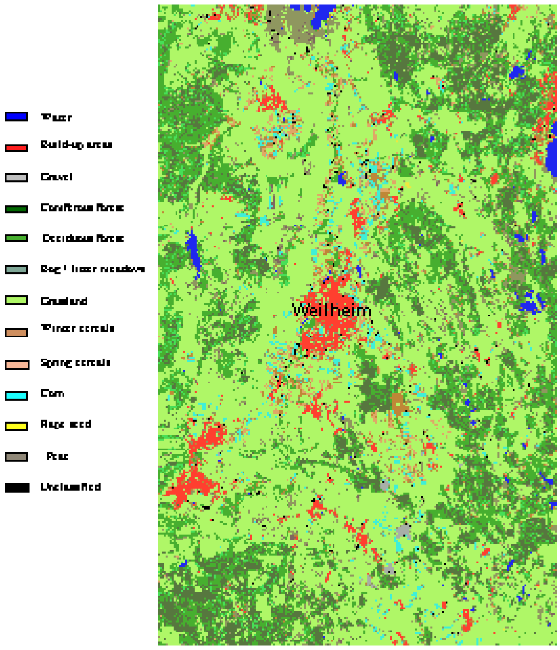

Figure 2: Digital land use map of the test site near Weilheim derived by TM classification (STOLZ & MAUSER, 1997a)

3. GROUND TRUTH
3.1 Soil moisture

To determine the amount of soil moisture in the first 2-4 cm of a test field, it is necessary to proof all data sets, taken at the field. First because of the principal problems of the measurement (different sensor techniques measure different soil moisture), second because of the nearly unlimited interference factors (registration of extreme events, influence of animals in the area near the station of measurement, different quantity of irrigation of a field, impairment of the electronic registration of data, mistakes in calibrations, etc.). Therefore it is very important to use different measurement techniques, to measure soil moisture and to use them on different places in the test fields to control themselves as well (tensiometer, electrical resistors (gypsum blocks), Time Domain Reflectometry (TDR), gravimetrical measurements, electrical capacity measurements, etc.).

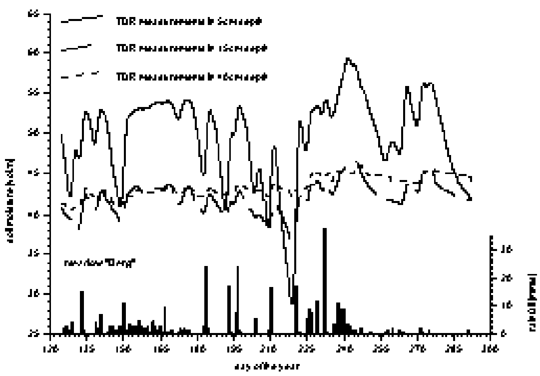

Figure 3: Measured soil moisture courses (TDR) of a meadow in three different depths

This was done for both test sites during the vegetation periods (April to October) of the years 1991 until 1994 (see Figure 3). Almost 30 different test fields with different land use were monitored for temporal and spatial soil moisture development together with other permanent soil physical parameters (porosity, soil bulk density, soil suction curves, grain size distribution, a.o.).

3.2 Meteorological data

Additional to hourly measurements of radiation, wind speed and direction, temperature (wet and dry), rainfall data were collected by rain gauges installed through the research group of the Institute of Geography (hourly measurements) and from meteorological stations of the German Weather Service (DWD) three times a day.

3.3 Plant Parameters

The aim of the detailed measurement of plant parameters on selected test fields is to acquire sufficient data to verify models for the backscattering behavior of natural surfaces and to deliver synchronious data of plant canopy parameters during the overflights of ERS.

During the vegetation period of the years 1991 until 1994 plant parameters were measured on almost 45 test fields.

Measurements took place once every week not taking into account the actual dates of the overpass of the satellite. The following parameters were measured on each selected field on a regular basis: phenology, plant height, leaf area index, wet/dry biomass and plant density.

4. RADAR DATA

All radar data were received either from the German or EECF Processing and Archiving Facility.

Test site Freiburg (1991):

38 ERS-1 SLC quarterscenes (descending mode)

37 ERS-1 SLC quarterscenes (ascending mode)

03 ERS-1 PRI full coverage (ascending mode)

Thus an almost complete data set of the images of the Commissioning Phase 1991 (August until October) is available.

Test site Weilheim (1992):

06 ERS-1 SLC quarterscenes (descending mode)

05 ERS-1 PRI full coverage (descending mode)

The images were taken between April 27 and November 23 1992 during the Mapping Phase.

Due to sensor problems no data of the test site were acquired at August 12 1992.

Test site Weilheim (1993):

06 ERS-1 SLC quarterscenes (descending mode)

04 ERS-1 SLC quarterscenes (ascending mode)

The data were acquired during the period from February 1 to November 24 1993.

Test site Weilheim (1994):

04 ERS-1 SLC quarterscenes (descending mode)

02 ERS-1 SLC quarterscenes (ascending mode)

The data were acquired during the period from May 11 to October 6 1994.

5. PREPARATION OF THE DATA SETS

5.1 Ground truth data

All field data (soil moisture, plant parameter, rainfall, radiation, wind speed, photographs, a.o.) are stored in a digital database after a careful check of their correctness.

When analysing the soil moisture values of meadows, we had to face the problem of measuring the water content of organic material as well, if taking probes from the top soil layer. This was leading to very high values (up to 80 vol. %) of soil moisture. Per definition these are no *soil* moisture values. By comparing the measurements of a lower horizon (15 cm depth) of the same soil at full saturation, we were able to calculate the real soil moisture values for the top soil layer. A special analysis of the organic content of the top soil layer confirmed this procedure.

5.2 Remote sensing data

The existing ERS SLC data were, converted into intensity (power) images, coregistrated and then calibrated (algorithm published by LAUR, 1993). No geometrical changes were made with these images.

For the test site near Freiburg images with per field averaged backscatter coefficients were generated. This was done with the help of a digital field number map of the test site and a statistical software package implemented within the image processing software FAP, developed at the Institute for Geography (MAUSER & BACH, 1993). For the test site near Weilheim the ERS images were averaged by using a gaussian and afterwards a median filter (each with a 3x3 box). They are produced to calculate the backscattering behavior on a field size raster, when field boundary maps does not exist, but averaged backscatter values per field are needed. No radiometric correction of local incidence angle influence on to the backscatter signal were applied, because in both test sites only flat test fields were investigated.

6. DESCRIPTION OF THE APPROACH

The backscatter of the ERS radar system is basically influenced by the soil type, vegetation development, vegetation structure, the water content of soil and the surface roughness. To retrieve the surface soil moisture from radar data, all influences contributing to the main signal, apart from the water content must be eliminated. This was done by finding the corresponding relations between each ground truth parameter and the backscatter signal for different land use classes. The next step is the correction of the main radar signal performed with the knowledge of existing ground truth data and their contribution to the signal. Afterwards the remaining signal is only sensitive to surface soil moisture content and can be converted.

7. IMPLEMENTATION OF THE APPROACH

Results of investigations based only on the test site near Freiburg in 1991 are documented in several publications (DEMIRCAN et al., 1993 a/b; ROMBACH et al., 1993; MAUSER & ROMBACH, 1994). It was not possible to generalize these results and use them straight forward on the test site near Weilheim. Therefore this new approach was developed.

All ground measured surface soil moisture values of both test sites, for each overflight of ERS, were converted into dielectric constant values (DC). This was done using the algorithm published by Hallikainen et al. (1985) (see Figure 4).

First all soil type classes had to be transformed into grain size distribution functions as input in the transformation formula. Problems occurred, when finding the necessary grain size distribution curves for soils with high organic content. To overcome this problem, the function of volumetric soil moisture vs. dielectric constant published by Roth et al. (1992) was used when bog soils were found within the test sites (added in Figure 4). After this procedure of converting soil moisture into dielectric constants, the soil type effects on the backscatter signal are eliminated.

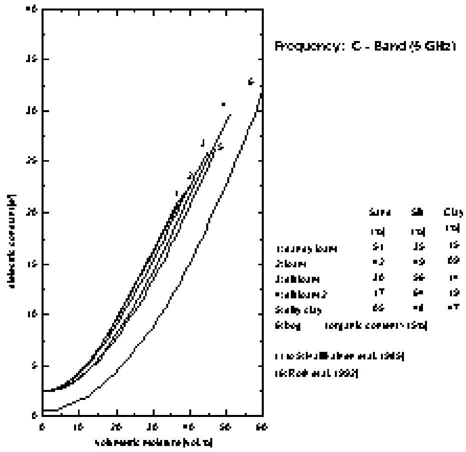

Figure 4: Relations between volumetric soil moisture and dielectric constant for one frequency on different soil types (from: HALLIKAINEN et al., 1985 and ROTH et al., 1992)

Vegetation development (roughness) effects are taken into account by establishing separate relations between dielectric constant and the backscattering signal depending on each land use under investigation. This is possible, due to the fact, that images are only taken into the analysis, where crops reached a growing development, from which onwards, no radar effective roughness changes appear (for example: when the height of corn plants are greater than 1 m). Therefore only the crop type is responsible for a different backscatter behavior when all other influencing parameters are stable. Harvested fields are treated as a different "land use" class. As an example for other crops under investigation, Figure 5 shows a resulting regression curve for corn fields. The bold line shows a MIMICS simulation (Michigan Microwave Canopy Scattering Model) of the backscattering behavior on bare soils for the ERS configuration (ULABY, 1992). The measured soil moisture values (converted in DC) of corn fields (plant height is already above 1 m) agree well to the simulation. The meaning of the equal course of these curves is, that for corn fields from a certain phenology stadium onwards, the ERS signal reflect almost like a bare soil with a roughness (RMS) height of 0.7 cm. This behavior can be found on rye, barley, oat and fallow fields but, of course, with different roughness agreements calculated by the MIMICS model.

These roughness parameters were assigned to the corresponding crop type.

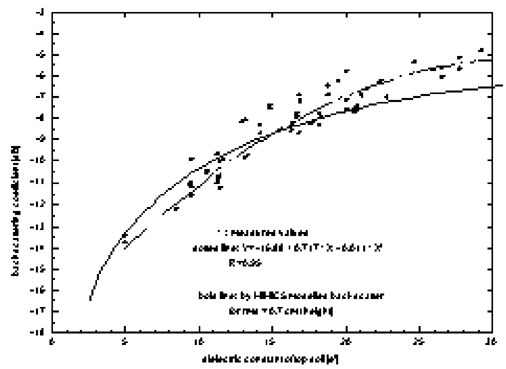

Figure 5: Regression analysis between dielectric constant and backscatter coefficient for corn fields

To eliminate the roughness influence on the backscatter signal, all backscatter coefficients were shifted from their estimated roughness class (crop type dependent) to the radar ineffective roughness class (RMS height > 2.4 cm).

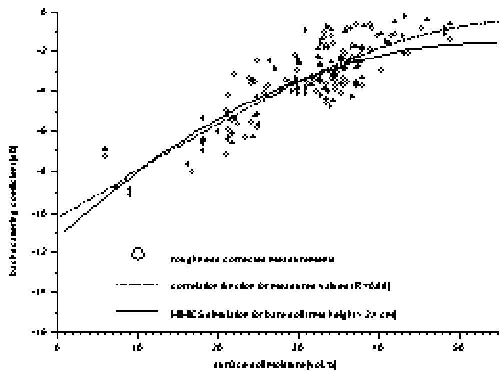

Figure 6: Roughness corrected relation between surface soil moisture and backscattering coefficient for all crop types under investigation

Figure 6 shows the results of this correction for over 200 measurements calculated for a standard soil (sand: 40 %, silt: 40 %, clay: 20 %) The dotted line is the nonlinear regression curve for these measurements with a correlation coefficient of 0.88. The bold line indicates the same relation derived by Ulaby (1992) for bare soils with a roughness height greater than 2.4 cm.

The influence of vegetation structure changes on the backscattering behavior is very strong within the major land use in the test site near Weilheim. Meadows change their phenotype within a vegetation period, not only, but also through cultivation activities of farmers. This structure change can be quantified by dry biomass measurements in the fields. Comparing this biomass changes and the transmissivity of the backscatter for meadows in the test site, two relations of different meadow types can be distinguished. A stronger attenuation was observed, especially for extensive cultivated meadows. This kind of meadows seem to absorb the signal stronger than intensive cultivated meadows (see STOLZ & MAUSER, 1997b).

Ulaby et al. (1996) derived a transmissivity function depending on dry biomass per square meter for a radar system configuration with 5 GHz frequency, 20 degrees incidence angle and HH polarization with the MIMICS model. The graph in Figure 3 shows the estimated attenuation effects of extensive and intensive cultivated meadows measured in the test site near Weilheim, compared to the modeled results derived by Ulaby.

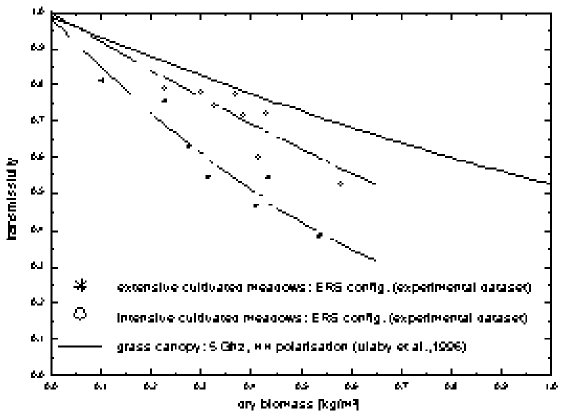

Figure 7: Transmissivity behavior of meadows in the test site compared to MIMICS simulation results with grass canopy

The simulated transmissivity is higher than the observed values. This can be explained by the different radar system parameters of ERS and the model and by different meadow types observed.

Using the temporal biomass measurements of meadows in the test site, all backscattering coefficients of meadows were corrected for vegetation structure changes with the transmissivity function of Figure 7.

8. RESULTS OF THE APPROACH

For corn, barley, oats, harvested and fallow fields nonlinear relations between the backscattering coefficients of ERS and the soil type independent dielectric constants are established. With these curves the roughness height (RMS) were estimated, based on the results of the Michigan Empirical Model. The offset from the ineffective ERS radar roughness height (< 2.4 cm) were calculated for each land use. The effects of vegetation structure changes on the backscattering signal of meadows are eliminated with relations between dry biomass and transmissivity.

A common regression curve between soil moisture and radar backscatter for crops under investigation were found, which is independent of vegetation and roughness effects (see Figure 6). A summary of the results can be found in Table I at the end of this paper.

9. SURFACE SOIL MOISTURE MAPS

For the purpose of hydrologic modeling, especially for floods and water yield, the knowledge of the spatial distribution and temporal change of the top soil moisture is essential to bring the existing models to a new level of accuracy and applicability. Recently hydrologic models are emerging, which explicitly model the spatio-temporal distribution of soil moisture from rainfall, meteorological data (radiation, temperature etc.) and runoff. Presently there is a considerable lack in methods for the validation and calibration of these models. To conduct a first test of the applicability of the proposed method to determine soil moisture for model validation purposes the model PROMET (MAUSER & SCHÄDLICH, 1997a; MAUSER et al., 1997b) was used. PROMET is based on a SVAT (Soil-Vegetation-Atmosphere-Transfer) scheme and was developed to determine the spatial water balance on different scales using as much remote sensing data as possible. It considers meteorology, plant development, soil differentiation and relief. PROMET models the spatial distribution of soil moisture on hourly basis. To be able to compare the results of PROMET with the measured soil moisture from ERS surface soil moisture maps are generated using the unified relation between backscattering coefficient of ERS images and soil moisture (Figure 6).

For the calculation of surface soil moisture maps two distinct ERS images from 1992 were chosen: one at the end of a drought period in spring (June 1) and one five weeks later after intensive rainfall (July 6) to test the sensitivity of the approach. The night before June 1 a small rainfall event of about 8 mm occurred, most of which evaporated from the wetted vegetation cover before the overpass of the satellite. The rest infiltrated into the top soil layer and partly filled it up. Before July 6 of the same year, rainfall was quite regular and intensive with a heavy rainfall the day before the overpass. After masking of forested areas, for which no relation between the ERS signal and soil moisture was derived, the backscatter was converted into soil moisture using the existing land use information for a selected test site near Weilheim.

The result is shown at the bottom of Figure 8. At the top of Figure 8 the model results from the days of the satellite overpass are shown. They are cut out from a continuous stream of hourly model calculations, which started on March 1, 1992.

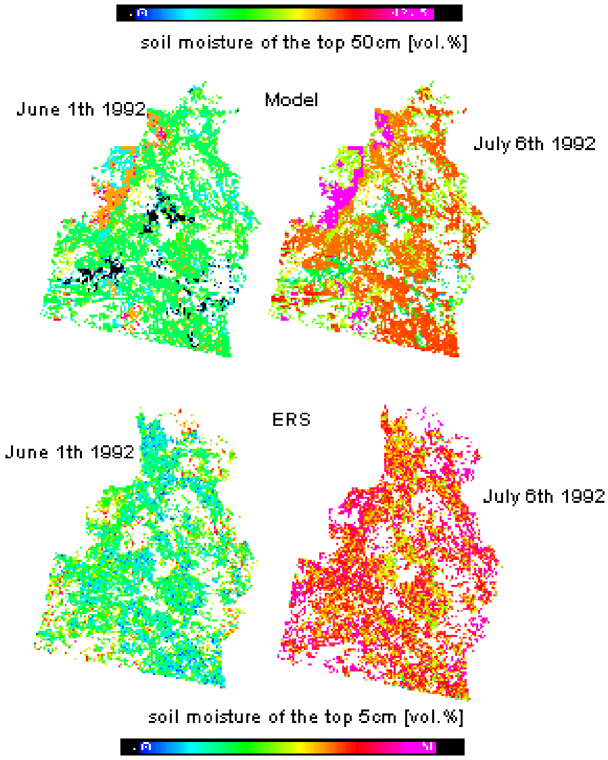

Figure 8: Soil moisture maps derived with the model PROMET and extracted from ERS radar data of the test site near Weilheim for two days in 1992.

The change in soil moisture between both days is clearly visible in both image pairs as much as differences in scale between satellite derived and modeled soil moisture allows. This is mainly due to the different depths for which the model and the satellite considers soil moisture (50 cm in the model vs. approx. 5 cm from ERS). Due to the light rainfall before the first overpass the surface is slightly wetter in the ERS image in June. This tendency even increases in July because the antecedent rainfall has filled up the top soil layer. The deeper layers of the soil are still drier than usual due to the drought in spring. The average surface soil moisture of the test site measured by ERS is about 20 vol. % in the June and 42 vol. % in the July image. The corresponding model results are 14 vol. % for June and 26 vol. % for July respectively. The larger changes in the topsoil moisture measured by ERS show the much larger soil moisture dynamics at the surface than in the deeper soil layers. Still the overall trend is visible.

For easier comparison Figure 9 shows the over and under estimation of soil moisture, calculated with ERS data in percentage relative to the soil moisture values received from the model.

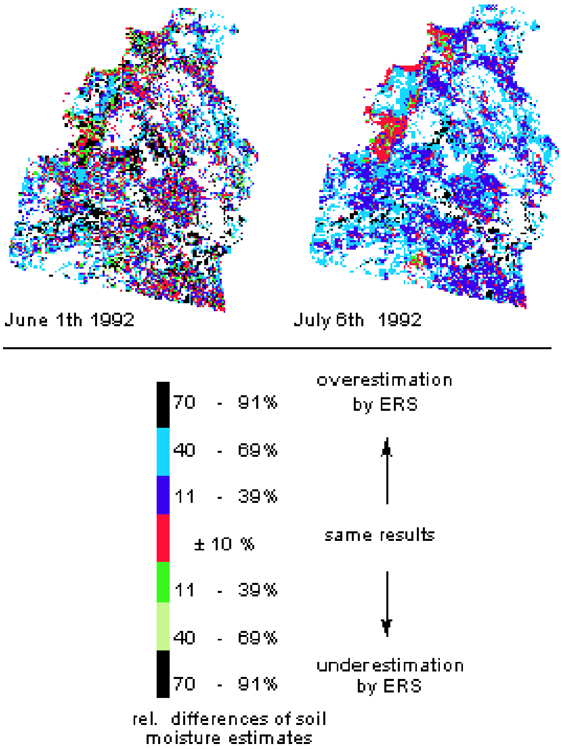

Figure 9: Comparison of ERS (top 5 cm) and modeled (top 50 cm) soil moisture results

The absolute soil moisture difference, calculated from the image in Figure 9, varies for June within 0.4 vol. % and 6 vol. % and for July from 1.5 vol. % up to 14 vol.%.

11. CONCLUSIONS

The principle possibility to measure surface soil moisture with the ERS radar system can be confirmed by the approach of this paper. Several limitations have to be taken care of. These are:

- existence of a land use map

- existence of a soil type map

- knowledge of the actual biomass of meadows

- soils under crops can only be monitored, when these crops passed a vegetation developing stadium from which onwards no radar effective changes take place.

- the approach is only validated for the crops investigated within this survey (corn, barley, rye, harvested and fallow fields and meadows).

If these additional information are available, surface soil moisture maps can be calculated, for all temporal and spatial coverage of ERS. To use these surface soil moisture maps for modeling (as a starting parameter and for verification purposes), a multi layer soil moisture module must be implemented within the used SVAT model.

TABLE I

	dB vs. DC	**R**	**RMS height (cm)**	**dB offset (approx.)**	**transmissivity vs. biomass**
corn	$dB = -16.88 + 0.71\,DC - 0.0011\,DC^2$	0.95	0.7	4.6	-
barley	$dB = -24.07 + 1.17\,DC - 0.0020\,DC^2$	0.94	0.45	7.5	-
oats	$dB = -25.20 + 1.20\,DC - 0.0180\,DC^2$	0.94	0.43	7.9	-
harvested fields	$dB = -15.44 + 0.42\,DC - 0.0047\,DC^2$	0.90	0.65	5.3	-
fallow fields	$dB = -14.57 + 0.33\,DC - 0.0045\,DC^2$	0.97	0.55	6.5	-
meadows intensive	$dB = -16.53 + 0.53\,DC - 0.0055\,DC^2$	0.96	0.68	4.9	$transm. = 1.0 - 0.84\,biom. + 0.15\,biom.^2$
meadows extensive	$dB = -16.53 + 0.53\,DC - 0.0055\,DC^2$	0.96	0.68	4.9	$transm. = 0.98 - 1.46\,biom. + 0.67\,biom.^2$

dB vs. DC: function for the relation between backscatter and dielectric constant; *R*: correlation coefficient for the "dB vs DC function"; *RMS height:* estimated roughness; *dB offset*: approximated offset for roughness correction; *dB:* backscattering coefficient; *DC:* dielectric constant; *biom.*: dry biomass; *transm.*: transmissivity;

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ACKNOWLEDGEMENT

The authors would like to thank the Deutsche Agentur fhr Raumfahrtangelegenheiten (DARA) for making this study possible through their funding of the projects "Land-Use, Pedology and Soil Moisture from Multitemporal ERS-1 Data" and AThe Pre-Operational Use of ERS-Data in Hydrology and Agriculture@. The authors also want to thank ESA for providing the necessary ERS images through its PI-program.