

## Popular Summary

# Soil Moisture Retrieval During a Corn Growth Cycle using L-band (1.6 GHz) Radar Observations

A. T. Joseph<sup>1</sup>, R. van der Velde<sup>2</sup>, P.E. O'Neill<sup>1</sup>, R. Lang<sup>3</sup>, and T. Gish<sup>4</sup>

<sup>1</sup>Hydrological Sciences Branch/614.3, Hydrospheric and Biospheric Sciences Laboratory, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA, Tel: 301-614-5804, Fax: 301 -614-5808,  
E-mail: [Alicia.T.Joseph@nasa.gov](mailto:Alicia.T.Joseph@nasa.gov), [Peggy.E.ONeill@nasa.gov](mailto:Peggy.E.ONeill@nasa.gov)

<sup>2</sup>International Institute for Geo-Information Science and Earth Observation (ITC), Hengelosestraat 99, P.O. Box 6, 7500 AA Enschede, The Netherlands, Email: [velde@itc.nl](mailto:velde@itc.nl)

<sup>3</sup>Dept. of Electrical and Computer Engineering, George Washington University, Washington, DC 20052 USA, Tel: 202-994-6199, Fax: 202-994-0227, E-mail: [lang@gwu.edu](mailto:lang@gwu.edu)

<sup>4</sup>Hydrology & Remote Sensing Lab, USDA-ARS, Beltsville, MD 20705 USA, Tel: 301-504-8378, Fax: 301-504-8931, Email: [tgish@hydrolab.arsusda.gov](mailto:tgish@hydrolab.arsusda.gov)

New opportunities for large-scale soil moisture monitoring will emerge with the launch of two low frequency (L-band 1.4 GHz) radiometers: the Aquarius mission in 2009 and the Soil Moisture and Ocean Salinity (SMOS) mission in 2008. Soil moisture is an important land surface variable affecting water and heat exchanges between atmosphere, land surface and deeper ground water reservoirs. The data products from these sensors provide valuable information in a range of climate and hydrologic applications (e.g., numerical weather prediction, drought monitoring, flood forecasting, water resources management, etc.). This paper describes a unique data set that was collected during a field campaign at OPE<sup>3</sup> (Optimizing Production Inputs for Economic and Environmental Enhancements) site in Beltsville, Maryland throughout the complete corn growing in 2002. This investigation describes a simple methodology to correct active microwave observations for vegetation effects, which could potentially be implemented in a global soil moisture monitoring algorithm. The methodology has been applied to radar observation collected during the entire corn growth season and validation against ground measurements showed that the top 5-cm soil moisture can be retrieved with an accuracy up to 0.033 [cm<sup>3</sup>cm<sup>-3</sup>] depending on the sensing configuration.

## Significant Findings Statement

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E-mail: [Alicia.T.Joseph@nasa.gov](mailto:Alicia.T.Joseph@nasa.gov), [Peggy.E.ONeill@nasa.gov](mailto:Peggy.E.ONeill@nasa.gov)

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**Background:** The OPE<sup>3</sup> field campaign of 2002 was held to acquire a low-frequency (L-band) passive and active microwave data set in anticipation of the data availability from future spaceborne L-band radiometer and radar sensors: the Aquarius and the Soil Moisture and Ocean Salinity (SMOS) missions. One of the primary objectives of both missions is to provide soil moisture observations at a global scale. This data set provides a unique opportunity to study the impact of vegetation on scattering and emission from emergence to peak biomass. This paper reports on the retrieval of soil moisture from dual-polarized L-band (1.6 GHz) radar observations acquired during the field campaign.

**Approach:** For the retrieval of soil moisture from L-band radar observations an algorithm has been developed that includes a surface roughness and vegetation correction. The surface roughness parameterization is obtained through inversion of the Integral Equation Method (IEM) from dual-polarized (HH and VV) radar observations acquired under nearly bare soil conditions. The vegetation correction is based the relationship found between the ratio of modeled bare soil scattering contribution and observed backscatter coefficient ( $\sigma^{\text{soil}}/\sigma^{\text{obs}}$ ) and  $W$ .

**Significance:** It is found that the ratio of modeled bare soil scattering contribution over the observed  $\sigma^0$  ( $\sigma^{\text{soil}}/\sigma^{\text{obs}}$ ) can be related to the vegetation water content ( $W$ ). In the paper, it is shown that this relationship can be used to correct the observed  $\sigma^0$  for vegetation influences and soil moisture can be retrieved with an accuracy up to 0.033 [cm<sup>3</sup>cm<sup>-3</sup>]. The proposed retrieval methodology is quite straightforward and could potentially be implemented as an operational global soil moisture retrieval algorithm.

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## ABSTRACT

This paper reports on the retrieval of soil moisture from dual-polarized L-band (1.6 GHz) radar observations acquired at view angles of 15, 35 and 55 degrees collected during a field campaign covering a corn growth cycle of 2002. The applied soil moisture retrieval algorithm includes a surface roughness and vegetation correction, and could potentially be implemented as an operational global soil moisture retrieval algorithm. The surface roughness parameterization is obtained through inversion of the Integral Equation Method (IEM) from dual-polarized (HH and VV) radar observations acquired under nearly bare soil conditions. The vegetation correction is based on the relationship found between the ratio of model bare soil scattering contribution and observed backscatter coefficient ( $\sigma^{\text{soil}}/\sigma^{\text{obs}}$ ) and vegetation water content ( $W$ ). Validation of the retrieval algorithm against ground measurements shows that the top-5cm soil moisture can be estimated with an accuracy of up to  $0.033 \text{ cm}^3 \text{ cm}^{-3}$ .

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**Abstract** — This paper reports on the retrieval of soil moisture from dual-polarized L-band (1.6 GHz) radar observations acquired at view angles of 15, 35 and 55 degrees collected during a field campaign covering a corn growth cycle of 2002. The applied soil moisture retrieval algorithm includes a surface roughness and vegetation correction, and could potentially be implemented as an operational global soil moisture retrieval algorithm. The surface roughness parameterization is obtained through inversion of the Integral Equation Method (IEM) from dual-polarized (HH and VV) radar observations acquired under nearly bare soil conditions. The vegetation correction is based on the relationship found between the ratio of modeled bare soil scattering contribution and observed backscatter coefficient ( $\sigma^{soil}/\sigma^{obs}$ ) and vegetation water content ( $W$ ). Validation of the retrieval algorithm against ground measurements shows that the top-5cm soil moisture can be estimated with an accuracy of up to  $0.033 \text{ cm}^3 \text{ cm}^{-3}$ .

## I. INTRODUCTION

Soil moisture is an important land surface variable affecting water and heat interactions between the soil column and the atmosphere [1]. Availability of the accurate soil moisture products could, therefore, be used to improve simulations of surface energy and water balances [2]-[4], which are used within many applications such as drought monitoring, flood forecasting, numerical weather prediction and agriculture. The current "state of the art" in satellite based soil moisture monitoring is at the stage where soil moisture products are provided on an operational basis by passive microwave radiometers, such as the Advanced Microwave Scanning Radiometer (AMSR,[5]) and in the future Soil Moisture and Ocean Salinity (SMOS, [6]) mission.

Also using active microwave scatterometer observations (e.g. European Remote Sensing satellites ERS-1/2) progress has been made towards global soil moisture monitoring products [7]-[9]. Soil moisture retrieval algorithms using active microwave observations, however, are still under development and satellite retrievals often suffer from large

uncertainties, especially over regions with changing vegetation conditions. Because of the launch of combined passive/active L-band microwave missions in the near future (e.g. Aquarius [10] and Soil Moisture Active Passive (SMAP, formerly the Hydrosphere State (Hydros) mission [11]), a robust soil moisture retrieval algorithm over vegetated conditions is desired.

Within active microwave soil moisture retrieval applications, the semi-empirical WaterCloud [12]-[14] and empirical change detection approaches [15] and [16] are frequently used. With the application of empirical change detection approaches, scattering induced by the vegetation cover are considered to be time-invariant, which limits the application of these approaches to areas with limited vegetation growth. The WaterCloud algorithm does take changes in vegetation biomass into account by assuming the higher order scattering contributions are negligible. The vegetation effects on the observed backscatter coefficient ( $\sigma^0$ ) are described through two mechanisms: 1) attenuation of the soil surface scattering component and 2) scattering of elements (e.g. leaves, stalks and branches) within the vegetation layer. Implementations of the WaterCloud approach parameterize both mechanisms as a function of an empirical parameter and a 'bulk' vegetation variables, such as Leaf Area Index (LAI, [13]), and vegetation water content ( $W$ , [[14], 17], [18]).

A consequence of this modelling concept is that within the limits of dense vegetation the modelled backscatter is only a function of the vegetation scattering component and the contribution of soil surface scattering becomes negligible. The soil moisture sensitivity of the WaterCloud approach becomes under dense vegetation very small. In reality, radar observations show a much higher sensitivity to changes in soil moisture over dense vegetation because of microwave interactions between the soil surface and vegetation [19]. These higher order scattering terms are not included in the

WaterCloud approach. De Roo et al. [18] extended the WaterCloud concept by including first and second order scattering components, but found for soybeans that the contribution of these components to the total  $\sigma^0$  is relatively small because an appropriate parameterization is difficult to obtain.

In this paper, a methodology is described to correct L-band radar observations for the vegetation effects through the corn growing season. The vegetation correction procedure is embedded within a soil moisture retrieval algorithm, for which the surface scattering component is formulated by the Integral Equation Method (IEM, [20]). The developed retrieval algorithm is applied to dual-polarized (HH and VV) L-band (1.6 GHz) radar observations acquired at view angles of 15, 35 and 55 degrees during a field campaign conducted during the entire corn growth cycle of 2002. Within this campaign radar observations as well as ground measurements of soil moisture and vegetation variables (e.g. canopy height, water content, wet and dry biomass) were collected once every week (weather permitting) from emerging up to harvesting of the corn crops. The data set includes a measured dynamic soil moisture range of 0.01- 0.26  $\text{cm}^3\text{cm}^{-3}$  and a vegetation water content at peak biomass was 5.1  $\text{kg m}^{-2}$ . The range in biomass and soil moisture conditions observed during this experiment forms a solid basis for a robust validation of the proposed algorithm.

## II. OPE<sup>3</sup> FIELD CAMPAIGN

### A. Site description

The presented investigation is based on field measurements collected in a campaign conducted at USDA's<sup>1</sup> Optimizing Production Inputs for Economic and Environmental Enhancement (OPE<sup>3</sup>) experimental site [21]. The site consists of four adjacent watersheds with similar surface and sub-surface soil and water flow characteristics and covers an area of 25 ha near Beltsville, Maryland. The soil textural properties are classified as sandy loam with 23.5% silt, 60.3% sand, 16.1% clay, and bulk density of 1.25  $\text{g cm}^{-3}$ . A detailed description of the research activities can be found at <http://hydrolab.arsusda.gov/oep3>. (Verified April 20, 2007)

<sup>1</sup>USDA ~ United States Department of Agriculture

### B. Ground measurements

The ground measurements were collected in conjunction with radar data acquisition, which took place on every Wednesday (rainy days excluded). During the field campaign, representative soil moisture, soil temperature, vegetation biomass and surface roughness measurements were taken around the radar footprint; this characterization was conducted around the periphery of the footprint to preserve the integrity of the footprint.

Soil moisture measurements were collected using a gravimetric sampling technique and portable impedance probes (Delta-T theta probe) at twenty-one sites located at the edge of a 67.1m x 33.5 m rectangular area situated around the radar footprint. At the beginning of each sampling day, gravimetric soil samples were collected in conjunction with the theta probe observations and radar observations. Simultaneous to the other radar observations acquired during the sampling day, soil moisture was measured using the theta

probe. Using the gravimetric measurements, the theta probe observations are calibrated to provide a soil moisture measurement representative for each radar observation. Details on the calibration of the theta probe observations can be found in Joseph et al. [22].

Vegetation biomass and surface roughness measurements were taken around study area at locations representative for the footprint. The vegetation biomass was quantified through the destructive measuring technique applied to a 1m<sup>2</sup> area (approximately 12 plants) once every week. On April 17<sup>th</sup>, the corn was planted, which emerged around May 10<sup>th</sup>, reached peak biomass at July 24<sup>th</sup> and was harvested on October 2<sup>nd</sup>. At peak biomass, a vegetation water content of 5.1  $\text{kg m}^{-2}$  and a crop height of 2.2 meters were measured. Fig. 1 shows the vegetation water content, wet and dry biomasses measured throughout the growing season.

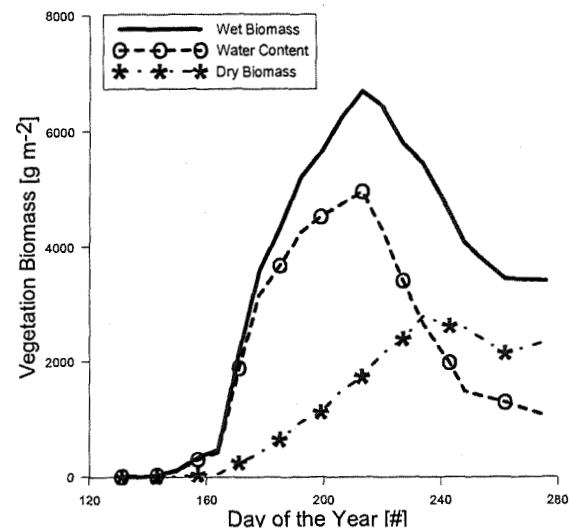


Fig. 1. Illustration of the crop conditions during the corn growing season in 2002 at the OPE<sup>3</sup> test site.

At the beginning of the experiment, the surface roughness was characterized using a 2-meter long grid board. In total, ten surface roughness profiles were acquired around the footprint. These profiles were digitized at a 0.5 cm interval and the digitized profiles were used to compute the root mean square height (*rms* height), and the correlation length ( $\rho$ ). Based on the ten surface roughness profiles, the averaged *rms* height and  $\rho$  of 1.62 and 12.66 cm were found with a standard deviation of 0.64 and 7.7 cm, respectively.

### C. Radar observations

One of the microwave instruments operated during the field campaign was a multi-frequency (C-band (4.75 GHz) and L-band (1.6 GHz)) and quad-polarized radar (HH, HV, VV, VH), which is mounted on a 20 meter long boom. Since the early 1990's, this instrument has provided reliable backscatter observations during field experiments across the United States [23]. The data collected during these field experiments has been used successfully for the validation of scattering models developed by Chauhan and Lang [24] and others.

In the OPE<sup>3</sup> field campaign, radar data was collected on one day a week at nominal times of 8 am, 10 am, 12 noon and 2 pm. During each data run the radar acquired six independent measurements within an azimuth of 120 degrees from a boom height of 12.2 m and at three different incidence

angles (15, 35, and 55 degrees). The six observations in the azimuth direction were averaged to provide one backscatter ( $\sigma^\circ$ ) value for the study area. The accuracy of these radar measurements is estimated to be 1 dB [39]. For this investigation, only, the L-band observations are used.

### III. DEVELOPMENT OF THE RETRIEVAL ALGORITHM

The proposed retrieval algorithm is based on the concept that the ratio of the bare soil scattering component over observed  $\sigma^\circ$  ( $\sigma_{\text{soil}}/\sigma_{\text{obs}}$ ) is influenced by the vegetation cover and the sensing configuration, according to.

$$\frac{\sigma_{pp,s}^\circ}{\sigma_{pp}^\circ} \sim f(\text{vegetation, antenna configuration}) \quad (1)$$

where,  $\sigma_{pp}^\circ$  is  $pp$ -polarized radar observed  $\sigma^\circ$  and  $\sigma_{pp,s}^\circ$  is the bare soil scattering contribution [ $\text{m}^2\text{m}^{-2}$ ].

At first sight this modelling concept seems to be an over simplification of reality because as other scattering approaches [25]–[27] and soil retrieval methods [12] and [18] do, no specific individual scattering mechanisms (e.g. surface scattering, vegetation scattering and higher order scattering components) is provided. The purpose of the proposed retrieval algorithm is not to accurately represent the individual scattering mechanisms, but to provide a workable framework for radar based soil moisture retrieval. From this perspective, the presented concept may prove to be useful because the soil moisture sensitivity within this retrieval concept is preserved over all vegetation densities, for the  $\sigma_{\text{soil}}/\sigma_{\text{obs}}$  is a function of bare soil scattering and, thus, also the soil moisture. Implementation of this concept within a soil moisture retrieval framework requires: 1) parameterization of the bare soil scattering, and 2) parameterization of a relationship that describes the influence of the vegetation cover on the ratio  $\sigma_{\text{soil}}/\sigma_{\text{obs}}$ .

#### A Bare soil scattering

For the presented soil moisture retrieval application, the bare soil scattering component is provided by the physical Integral Equation Method (IEM, [20]). Parameterization of the surface roughness within the IEM approach (e.g. root mean square ( $rms$ ) height and correlation length ( $\rho$ )) is obtained through a look-up-table (LUT) inversion technique introduced by Van Oevelen and Hoekman [28] for the retrieval of soil moisture. To derive the surface roughness, the LUT inversion procedure of Van Oevelen and Hoekman has been slightly adjusted. Here, the  $rms$  height and  $\rho$  are inverted from radar observations acquired over nearly bare soil conditions using the measured soil moisture.

The IEM is used to simulate the bare soil  $\sigma^\circ$  for a wide range of surface roughness conditions [ $rms$  height: 0.05 – 2.0 cm, with a 0.05 cm increment;  $\rho$ : 1.0 – 18 cm, with a 0.5 cm increment]. A unique solution is found for the combination of  $rms$  height and  $\rho$  values, for which the error between the IEM modelled and observed  $\sigma^\circ$  is smallest. Fig. 2 illustrates the inversion of the surface roughness parameters from L-band  $\sigma^\circ$  observations acquired at a view angle of 55 degrees.

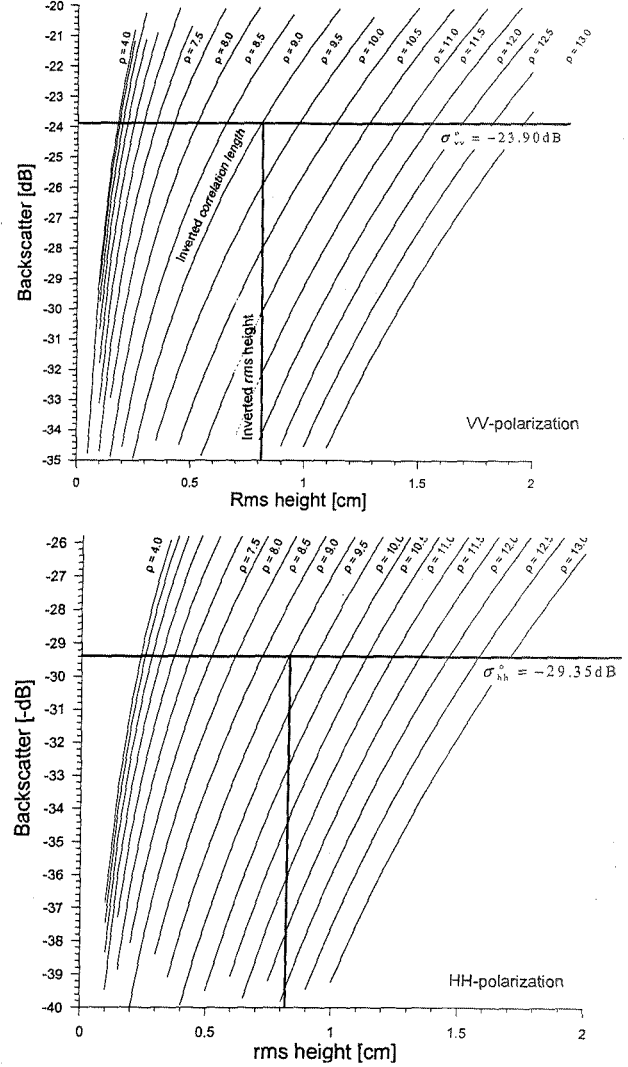


Fig. 2. Integral Equation Method (IEM) simulations for a broad range of surface roughness conditions and inversion of the  $rms$  height and  $\rho$  based on observations acquired at a view angle for 55 degrees.

Through this inversion methodology, the surface roughness parameters are obtained for HH-and VV-polarized backscatter observations acquired at view angles of 15, 35 and 55 degrees. The resulting surface roughness parameters are presented in table 1. The Root Mean Square Error (RMSD) is for each of the three view angles lower than 0.41 dB, which is comparable to the estimated uncertainty of the radar observations. Compared to roughness measurements, the retrieved roughness values are somewhat low. However, the influence of surface roughness on the radar measurements is also affected by the view angle and the wavelength (Ulaby et al. 1986). It is, therefore, difficult to interpret the validity of the retrieved roughness based on measurements. The dependency of the effective roughness to view angle also explains the varying  $rms$  height for view angles of 15, 35 and 55 degrees.

TABLE I  
INVERTED SURFACE ROUGHNESS PARAMETER USING IEM AND HH-  
AND VV-POLARIZED RADAR OBSERVATIONS ACQUIRED UNDER NEARLY  
BARE SOIL CONDITIONS.

	15 degrees	35 degrees	55 degrees
rms height [cm]	0.30	0.55	0.80
correlation l [cm]	9.0	9.5	9.0
RMSD [dB]	0.42	0.27	0.41

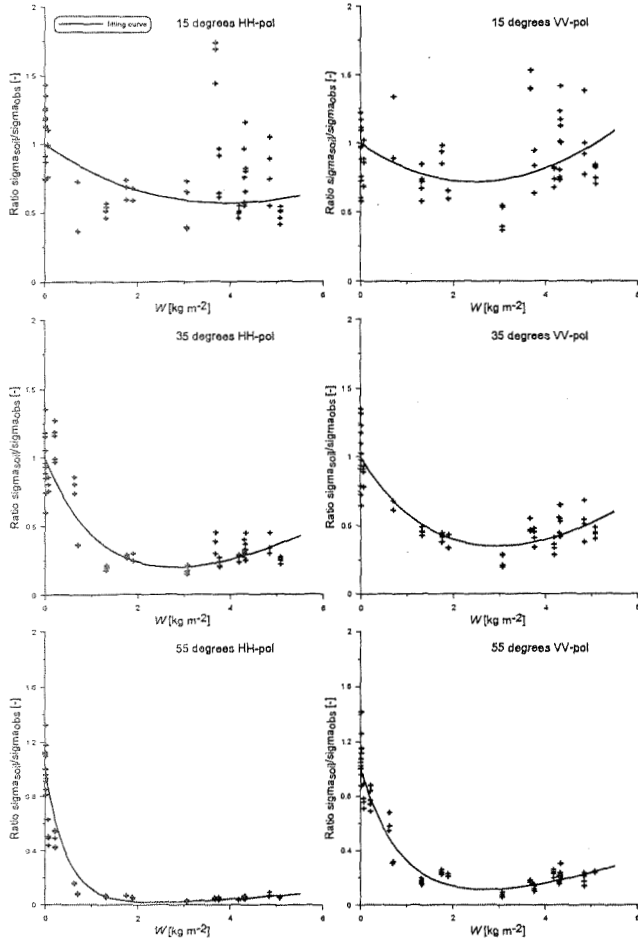


Fig. 3. The ratio  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  plotted against the vegetation water content  $W$  for HH- as well as VV-polarization and view angles of 15, 35 and 55 degrees.

#### B Relationship between $\sigma^{\text{soil}}/\sigma^{\text{obs}}$ and $W$

In this section, relationships that describe the influence of the vegetation cover on the ratio  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  is presented. The vegetation water content ( $W$ ) has been selected as the input variable to parameterize changes in vegetation effects on the observed  $\sigma^0$ . The reasoning for this is that the  $W$  can be retrieved from readily available remotely sensed vegetation indices [29]. Moreover, the vegetation water content and related remotely sensed vegetation indices are frequently used within passive microwave soil moisture retrieval algorithms [30]–[32].

To find the relationships between the  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  and  $W$ , both variables are plotted against each other in Fig. 3 for each view angle and both polarizations, separately. The bare soil scattering component for  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  is obtained through IEM

simulation with input of the inverted roughness parameters from the previous section and the measured soil moisture. Application of the surface roughness parameters inverted from radar observations collected at the beginning of the growing season is justified by assuming the surface roughness does not change a lot over this period.

In Fig. 3, clear relationships are observed between the  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  and  $W$ , specifically for the radar observations collected at view angles of 35 and 55 degrees. Under low biomass conditions [ $W < 0.5 \text{ kg m}^{-2}$ ], the ratio  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  is close to one and decreases exponentially up to a  $W$  value of  $3.0 \text{ kg m}^{-2}$ . Above a  $W$  of  $3.0 \text{ kg m}^{-2}$  the ratio  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  increases again. The magnitude of the ‘exponential decay’ of  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  at low biomass and magnitude of the ‘increase’ at high biomass is specific for each polarization and view angle. An inter-comparison of the scatter plots of Fig. 3. shows that for VV-polarized observations acquired at a view angle of 15 degrees the ‘exponential decay’ and the ‘increase’ of  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  are smallest and largest, respectively. This means that the vegetation effects on  $\sigma^0$  are smallest for this antenna configuration. This is expected because at a low view angle the observed vegetation volume is smaller and VV-polarized radiation has less interaction with the vertically oriented vegetation than HH-polarized radiation [38].

The scatter plots (HH as well as VV-polarization) for the 15 degrees view angle show only a poorly defined relationship between the  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  and  $W$ . At a view angle of 15 degrees vegetation effects are smaller than for 35 or 55 degrees, because a smaller vegetation volume is observed. Then, the assumption of a fixed surface roughness parameterization for the entire growing season becomes a significant source of uncertainty in the determination of a unique  $\sigma^{\text{soil}}/\sigma^{\text{obs}} - W$  relationship.

The physical interpretation of the exponential decrease of  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  at low biomass conditions can be attributed to attenuation of the bare soil scattering component by vegetation and the increase in vegetation scattering. The increase in  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  above a certain biomass density ( $W > 3.0 \text{ kg m}^{-2}$ ) could be considered to be induced by microwave interactions along vegetation-soil and soil-vegetation-soil pathways.

Based on the observations made with respect to Fig. 3, the following general fitting equation is proposed to describe the  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  in terms of  $W$ ,

$$\frac{\sigma^{\text{soil}}}{\sigma^{\text{obs}}} = \left[ a W^2 + \exp(-b W) \right] \quad (2)$$

where,  $a$  and  $b$  can be considered to be site-specific vegetation parameters [ $\text{m}^2 \text{kg}^{-1}$ ]. In eq. (2) the first term on the right-hand side represents the increase in  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  under dense vegetation and the second term on the right-hand side accounts for the absorption of bare soil scattering/increase in vegetation scattering.

TABLE II  
FITTED VEGETATION PARAMETERS TO THE  $\sigma^{\text{soil}}/\sigma^{\text{obs}} - W$   
RELATIONSHIP PLOTTED IN FIG. 3.

	$a [\text{m}^2 \text{kg}^{-1}]$	$b [\text{m}^2 \text{kg}^{-1}]$	RMSD [dB]
15 deg. VV	0.0272	0.241	1.55
15 deg. HH	0.0118	0.243	1.18
35 deg. VV	0.0183	0.562	0.89
35 deg. HH	0.0139	0.861	0.98
55 deg. VV	0.0094	1.151	1.38
55 deg. HH	0.0027	2.181	1.18

For this investigation, the  $a$  and  $b$  parameters are fitted through the scatter plots shown in Fig. 3. The resulting parameter values and Root Mean Squared Difference (RMSD) between modelled and observed  $\sigma^0$  are presented in table II. The obtained RMSD might seem somewhat large as compared to the uncertainty of the radar measurements. The large RMSD values can be explained by a combination of uncertainties, which consist of 1) assuming a constant surface roughness parameterization throughout the growth cycle, 2) soil moisture measurement uncertainties, 3) vegetation water content measurement uncertainties, and 4) uncertainties in radar observations itself. However, from the soil moisture retrieval perspective the accuracy, at which the observed  $\sigma^0$  can be reconstructed, is not of primary interest. More important is the ability of model concept to describe the bare soil scattering component. The RMSD values given in Table II are representative for the differences between observed and modelled  $\sigma^0$ , which consist of two parts: 1) differences between the modelled and observed vegetation scattering contribution and 2) differences between the modelled and observed bare soil scattering contribution.

#### V. SOIL MOISTURE RETRIEVALS

In this section, the soil moisture retrievals estimated for L-band radar observations collected during the entire corn growing season are discussed. The applied retrieval procedure includes a surface roughness and a vegetation correction. The influence of surface roughness on  $\sigma^0$  is accounted for through IEM simulations with input of surface roughness parameters inverted from radar observations acquired under nearly bare

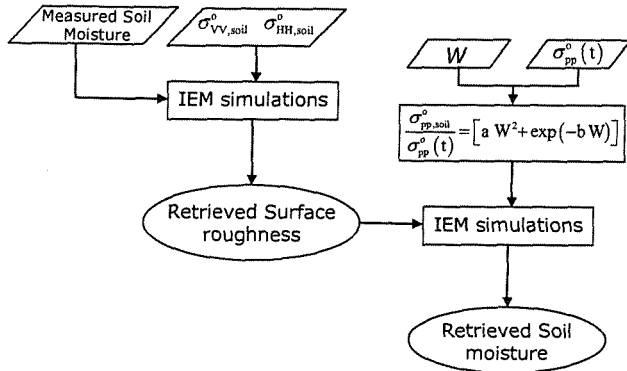


Fig 4. Schematization of the soil moisture retrieval algorithm

soil conditions and is assumed to be constant throughout the growing season. The vegetation correction is based on the

obtained  $\sigma^{\text{soil}}/\sigma^{\text{obs}} - W$  relationships. For potential operational application, the algorithms could be outlined as follows: First, the surface roughness parameters are inverted using IEM and dual-polarized radar observation acquired over nearly bare soil conditions. Second, the bare soil scattering contribution is computed using Eq. (2) with the input  $W$ . The soil moisture content can, then, be inverted from the bare soil scattering contribution using the IEM with input of the roughness parameters obtained under the first step. This retrieval procedure is schematically illustrated by the flowchart shown in Fig. 4.

TABLE III  
SOIL MOISTURE RETRIEVAL STATISTICS COMPUTED BASED ON SOIL MOISTURE MEASUREMENTS.

	RMSD [cm <sup>3</sup> cm <sup>-3</sup> ]	bias [cm <sup>3</sup> cm <sup>-3</sup> ]	R <sup>2</sup> [-]
15 deg. VV	0.046	-0.001	0.697
15 deg. HH	0.055	-0.001	0.738
35 deg. VV	0.033	0.001	0.811
35 deg. HH	0.053	-0.020	0.739
55 deg. VV	0.037	0.003	0.651
55 deg. HH	0.064	-0.015	0.322

The retrieval procedures, described above, has been applied to HH- and VV-polarized radar observations acquired at view angles of 15, 35 and 55 degrees. The obtained retrievals are plotted against the soil moisture measurements in Fig. 5. Statistics describing the uncertainty of the soil moisture retrievals with respect to the measurements are given in Table III.

As can be observed in Fig. 5, for each sensing configuration (e.g. polarization and view angle) positive relationships are found between the retrieved and measured soil moisture. The maximum and minimum soil moisture retrieval errors (see RMSD given in Table III) are 0.064 and 0.033 cm<sup>3</sup>cm<sup>-3</sup>, respectively. Considering that the soil moisture is retrieved over the entire corn growth cycle with a maximum  $W$  of 5.1 kg m<sup>-2</sup>, even the highest retrieval error is comparable to previous investigations. Taconet et al.[33] and Prevot et al. [13], for example, reported soil retrieval error of 0.060 and 0.065 cm<sup>3</sup>cm<sup>-3</sup> for winter wheat, respectively. However, considerable lower retrieval errors are systematically obtained, here, for radar observations acquired in the VV-polarization. The obtained RMSD from observations acquired at  $\theta_v$  of 35 and 55 degrees are 0.033 cm<sup>3</sup>cm<sup>-3</sup> and 0.037 cm<sup>3</sup>cm<sup>-3</sup>, respectively, which are error levels that are comparable to uncertainties obtained within passive microwave soil moisture retrieval applications ([30], [31], [34],[35]).



The relatively large difference in soil moisture retrieval error between HH and VV-polarized is somewhat peculiar, but can be explained by the difference in soil moisture sensitivity of surface scattering component between the HH- and VV-polarization. In Fig. 6, the soil moisture sensitivity of the IEM modeled  $\sigma^0$  is plotted for both polarizations and all three view angles. For all three view angles, the soil moisture sensitivity of the VV-polarization is larger than for the HH-polarization. Therefore, uncertainties in the soil moisture retrieval procedure, as described in the previous section, have a larger impact on the soil moisture error for the HH-polarized observations than for the VV-polarized observations. Further, the strong decreasing soil moisture sensitivity of the IEM modeled  $\sigma^0$  under wet soil moisture conditions (see Fig. 6) is also an explanation for the larger scatter above soil moisture contents of  $0.200 \text{ cm}^3 \text{ cm}^{-3}$ .

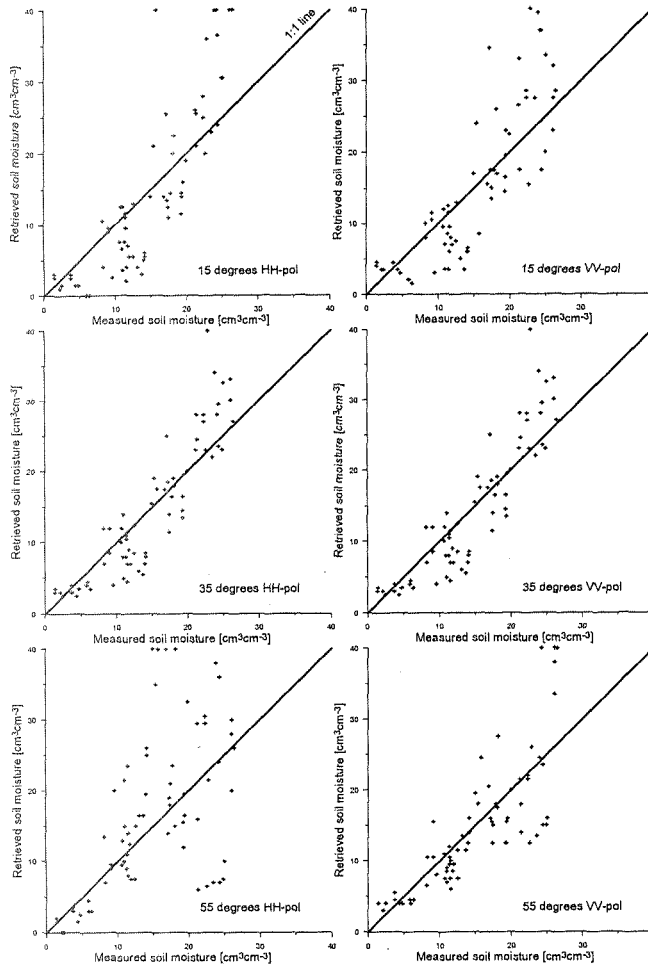


Fig 5. Validation of the soil moisture estimates retrieved using L-band radar observations acquired during the entire corn growing season at HH- and VV-polarization and view angle of 15, 35 and 55 degrees.

The retrieval errors presented in Table III should be viewed in this context and in combination with the calibration error given in Table II. For a  $\theta_v$  of 35 degrees, the calibration errors are small and the sensitivity of the bare soil  $\sigma^0$  to soil moisture is relatively high. This combination results in the lowest soil moisture retrieval errors. On the other hand, for HH-polarized observations acquired at a  $\theta_v$  of 55 degrees, the calibration error is relatively large and the sensitivity of the

bare soil  $\sigma^0$  to soil moisture is relatively high, which results in the largest soil moisture retrieval errors. The soil moisture retrieval accuracy of the proposed retrieval procedure is determined in part by the soil moisture sensitivity of the bare soil scattering component as well as the calibration error between the modeled and observed  $\sigma^0$ .

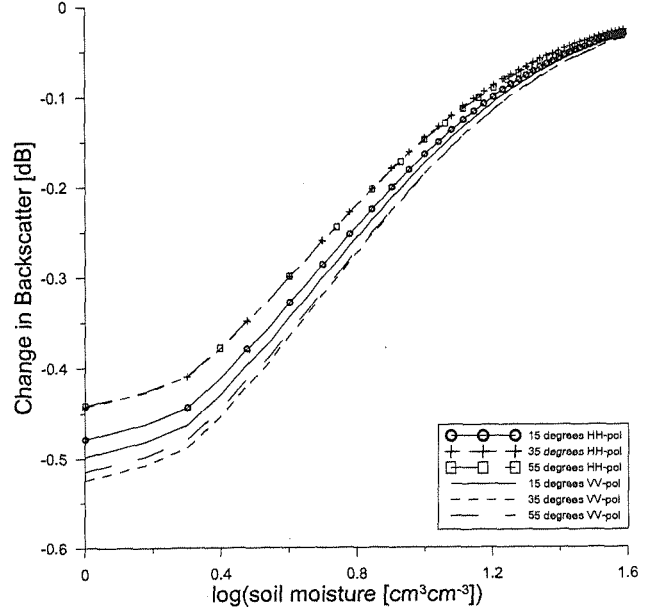


Fig 6. Soil moisture sensitivity of the surface scattering contribution.

## VI CONCLUSIONS AND DISCUSSION

Surface soil moisture is retrieved from L-band radar observations acquired during a corn growth cycle at view angles of 15, 35 and 55 degrees. The applied retrieval algorithm includes a surface roughness correction and a vegetation correction. The roughness correction is based on the Integral Equation Method (IEM), for which the surface roughness parameterization is obtained through inversion from dual-polarized radar observations acquired over nearly bare soil conditions. It is found that the ratio of bare soil scattering contribution over the observed  $\sigma^0$  ( $\sigma^{\text{soil}}/\sigma^{\text{obs}}$ ) can be related to the vegetation water content ( $W$ ). This relationship is used to correct the observed  $\sigma^0$  for vegetation influences. The retrieval of soil moisture is, then, based on the derivation of the bare soil scattering component from the radar observations using a semi-empirical relationship between  $\sigma^{\text{soil}}/\sigma^{\text{obs}}$  and  $W$ .

Validation of the soil moisture retrievals against ground measurements yields errors varying between  $0.033$  and  $0.064 \text{ cm}^3 \text{ cm}^{-3}$ . The retrieval errors obtained for VV-polarized radar observations were systematically lower than for HH-polarized observations. This difference is explained by the soil moisture sensitivity of bare soil scattering component, which is smaller for the HH-than for the VV-polarization. Due to the low soil moisture sensitivity of the bare soil scattering component, larger errors are found under wet conditions (soil moisture  $> 0.20 \text{ cm}^3 \text{ cm}^{-3}$ ).

The strength of the applied retrieval procedure is the estimation of soil moisture contents between  $0.01$  and  $0.20 \text{ cm}^3 \text{ cm}^{-3}$  over a range of vegetation densities ( $0.0$ -  $5.1 \text{ kg m}^{-2}$ ).

Parameterization of the crop dependent parameter is, however, important for the accuracy of the soil moisture retrievals, but is not available at larger scales. More research should, therefore, be conducted to determine the vegetation parameters for other land covers as has been done for the  $b$  parameter ([37] and [38]), which is used for the vegetation correction within passive microwave soil moisture retrieval applications.

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