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GMES products & services, integrating **EO** monitoring capacities
to support the implementation of European directives and policies
related to "**land** cover and vegetation"

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1 BACKGROUND OF THE DOCUMENT

1.1 EXECUTIVE SUMMARY

This document reviews the algorithm used to retrieve soil moisture from ERS scatterometer data. The products are used by the OFM observatory members NEO and Alterra for crop yield and performance estimation. The model used to retrieve soil moisture is the VUT model developed at the Institute of Photogrammetry and Remote Sensing of the Vienna University of Technology and is based on radar backscatter measurements of the ERS scatterometer. The document gives an overview of the involved algorithm and its mathematical implementation. Further the limitations of the VUT model are discussed, a brief summary of validation activities is given and customization activities for the OFM users are defined.

1.2 SCOPE AND OBJECTIVES

The VUT model has been implemented in previous projects at the Institute of Photogrammetry and Remote Sensing of the Vienna University of Technology. Global soil moisture has been retrieved for the period 1992-2000 and has been made available to the Geoland partners in particular and to the scientific community in general. The data has been tested and validated by various users and in a number of projects. The scope of this document is therefore to review the VUT model in order to enable a clear definition of its hypothesis and limitations. This ATBD is also the physical baseline for setting up a customized processing line to satisfy the needs of the OFM users.

1.3 CONTENT OF THE DOCUMENT

The document consist of a brief review of the user requirements in chapter 2. The applied algorithm is described in Chapter 3 together with a discussion of the limitations the algorithm, the product quality and validation activities. Finally in Chapter 4 customization activities for the OFM users are described.

1.4 RELATED DOCUMENTS

1.4.1 Input

Overview of former deliverables acting as inputs to this document.

Document ID	**Descriptor**
CSP-0350-RP-0002	User Requirements
CSP-0350-RP-0005	Service Portfolio

1.4.2 Output

Overview of other deliverables for which this document is an input.

Document ID	**Descriptor**

2 REVIEW OF USERS REQUIREMENTS

Profile soil moisture is derived from ERS scatterometer data with a 10-day sampling and a spatial resolution of 50 km (CSP-0350-RP-ServicePortfolioWP8210). The products cover the period 1992-2001. Data is required from the OFM partners NEO and Alterra.

NEO requires the SWI to calculate the Crop Performance Index for Europe and China. NEO uses the SWI grid. There are no specific requirements about the file format.

Alterra requires the SWI to calculate the Crop Yield for Europe and China. There are no specific requirements about the data grid and file format.

3 METHODOLOGY DESCRIPTION

3.1 OVERVIEW

Soil moisture has long been a research focus in the field of remote sensing. Particularly, sensors operated in the lower part of the microwave spectrum (1-10 cm wavelength), both active (scatterometers) and passive (radiometers), hold a large potential due to their high sensitivity to soil moisture. Retrieval of soil moisture from microwave data is however confounded by the influence of vegetation and surface roughness, which need to be accounted for in subsequent processing.

Various approaches to retrieve geo-physical parameters from radar data have been discussed ion Literature, ranging from simple regression models to elaborated theoretical models. The VUT model for retrieving soil moisture from ERS scatterometer data is from its conception a change detection method [*Wagner et al.*, 1999b]. Soil moisture retrieved from ERS-1/2 scatterometer data was found to be of comparable quality with state-of-the-art modeled soil moisture products [*Wagner et al.*, 2003] with an accuracy of 0.05 m^3m^{-3} for the 0-1 m layer [*Scipal*, 2002].

3.2 THE RETRIEVAL ALGORITHM

3.2.1 Input data

The VUT model is based on input data from the ERS Scatterometer. The ERS Scatterometer is a multi-incidence angle radar operating at 5.3 GHz (C-band) VV polarization and has been flown on the European Remote Sensing Satellites ERS-1 and ERS-2 operated by the European Space Agency. The current implementation of the VUT model is based on ERS scatterometer fast delivery products (ERS.WSC.UWI). ERS Scatterometer data is available from 1991-07-30 to 2001-01-10.

After January 2001 the ERS-2 gyros failed which initially caused inaccuracies in the processing of the scatterometer raw data. To compensate for this loss in accuracy the European Space Agency (ESA) has in the meantime implemented a new processing algorithm, which is currently used to process actual ERS-2 Wind Scatterometer data acquired in zero gyro mode and to reprocess the historic data base. This data is not yet available. Detailed information about the reprocessing status is available at: http://earth.esa.int/pcs/ers/scatt/articles/.

From January 2006 onwards scatterometer data from the METOP satellite series, which has a nominal lifetime of 14 years, will be used for soil moisture retrieval.

3.2.2 Methodology

The VUT method for retrieving soil moisture from ERS scatterometer data is from its conception a change detection method [*Wagner et al.*, 1999b]. A reference backscatter value σ^0_{dry} representing backscatter from the vegetated land surface under dry soil conditions is subtracted from the actual incidence-angle normalized σ^0 measurements to account for roughness and heterogeneous land cover. In [*Wagner et al.*, 1999a] the method has been refined to account for the effects of plant growth and decay by exploiting the multi-incidence capabilities of the ERS Scatterometer. As a result, time series of the topsoil moisture content m_s (< 5 cm) are obtained. It is a relative quantity ranging between 0 (dry) and 1 (saturated). In order to retrieve soil moisture in the root zone (up to about one meter) a two-layer water balance model, which only considers the exchange of soil water between the topmost remotely sensed layer and the “reservoir” below, was used to establish a relationship between the m_s series and the profile soil moisture content [*Ceballos et al.*, 2005; *Wagner et al.*, 1999b]. The resulting quantity is called the Soil Water Index (*SWI*) and ranges between 0 (wilting level) and 1 (field capacity).

The VUT model comprises an initialization module used to set up a backscatter knowledgebase containing parameters quantifying the effect of vegetation, roughness, heterogeneous land cover and the incidence-angle dependency and a retrieval module used to calculate surface and profile moisture using the backscatter knowledgebase as input. The necessary processing steps are summarized in the following:

3.2.2.1 Regridding

In a preprocessing step scatterometer data are rearranged from an image format to a time series format without altering the data. In this way, multi-year time series of scatterometer measurements are built up over a predefined global grid. Eq. 1 defines a grid with a grid spacing of approximately 28 km (Figure 1) for the entire globe.

$$\lambda_j = -90 + 0.25 \cdot (j - 0.5) \qquad 0 \le j < 4 \cdot 90$$

$$\varphi_{i,j} = -180 + 0.25 \cdot \frac{(i - 0.5)}{\cos\lambda} \qquad 0 \le i < 4 \cdot 360 \cdot \cos\lambda \qquad \textbf{(Eq. 1)}$$

$$i, j \;\forall\; N$$

In Eq. 1, φ defines the longitude and λ the latitude of each grid point i, j, where i ranges from 0 to 360 and j from 0 to 1440*cosλ. Constant spacing involves that the number of points in longitude direction decreases with increasing latitude. For each grid point, ERS scatterometer measurements collected within 36 km distance are extracted and stored in a time oriented structure spanning the entire analysis period.

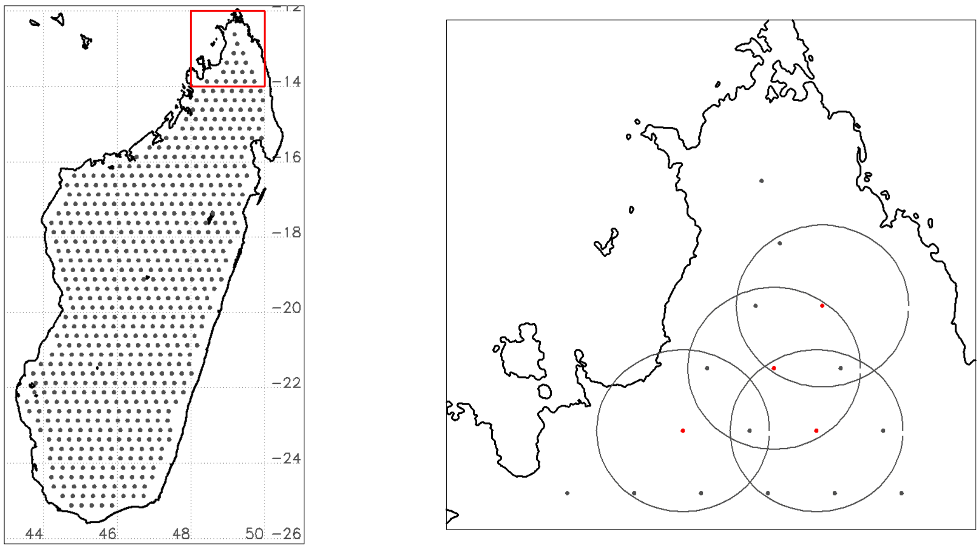

Figure 1: Left: Defined Scatterometer Analysis Grid for Madagascar. Right: Grid point resolution for selected points.

3.2.2.2 Incidence Angle Normalisation

To account for incidence angle variations of the ERS scatterometer (ranging from 18 to 59°), σ^0 measurements are extrapolated to a reference incidence angle taken at 40°. The mean annual cycle of the incidence angle behavior of σ^0 is described by taking advantage of the instantaneous multi-incidence angle measurements of the ERS scatterometer. Finally, the average $\sigma^0(40)$ based on the backscatter triplet is calculated.

The incidence angle variation is described according to Eq. 2, where σ' is defined as the first derivative of $\sigma^0(\theta)$ and σ'' as the second derivative of $\sigma^0(\theta)$. σ' and σ'' are calculated according to (Eq. 3 and Eq. 4).

$$\sigma^0(\theta,t) = \sigma^0(40,t) + \sigma'(40,t)(\theta-40) + \tfrac{1}{2}\sigma''(40,t)(\theta-40)^2 \qquad \textbf{(Eq. 2)}$$

$$\sigma'(40,t) = C' + D' \cdot \Psi'(t) \qquad \textbf{(Eq. 3)}$$

$$\sigma''(40,t) = C'' + D'' \cdot \Psi''(t) \qquad \textbf{(Eq. 4)}$$

In Eq 3 C' is the annual minimum slope value, D' is the annual dynamic range of σ' and $\Psi'(t)$ is an empirical periodic function describing the annual variation of σ'. In Eq 4 C'' is the annual minimum curvature value D'' is the annual dynamic range of σ'' and $\Psi''(t)$ is an empirical periodic function describing the annual variation of σ''. Based on the Eq. 2, Eq. 3 and Eq. 4, $\sigma^0(\theta)$ can be extrapolated to a reference angle of 40° by applying Eq. 5. The parameters C', D', $\Psi'(t)$, C'', D'' and $\Psi''(t)$ are retrieved for each grid point from a multi annual backscatter series. Based on these parameters, $\sigma^0(\theta)$ can be extrapolated to a reference angle of 40° by applying Eq. 5.

$$\sigma^0(40) = \frac{1}{3}\sum_{i=1}^{3}\sigma_i^0(\theta,t) - \sigma'(40,t)(\theta-40) - \tfrac{1}{2}\sigma''(40,t)(\theta-40)^2 \qquad \textbf{(Eq. 5)}$$

3.2.2.3 Determine a dry/wet backscatter reference considering vegetation scattering effects

Despite the VUT model uses different parameters, it is similar in functionality to simple radiative transfer models like the Cloud Model [*Ulaby et al.*, 1982]. In these latter models, the effect of vegetation is to a large extent controlled by the optical depth which weights the relative contributions of volume and surface scattering to total backscatter. When vegetation grows, the optical depth increases and the volume scattering term becomes more important. But this does not necessarily mean that backscatter increases. In situations where the reduced contribution from the underlying ground is more important than the enhanced volume scattering, σ^0 decreases. The first situation is typically encountered at high incidence angles and dry soil conditions; the second at low incidence angles and wet soil moisture conditions. This implies, that depending on the soil moisture content, there is an incidence angle where the effect of vegetation growth is minimal. In the VUT model, this is taken into account by assuming that the effect of vegetation is negligible at the so called "cross over" angles θ_{dry} and θ_{wet}, which differ for dry and wet soil conditions [*Wagner et al.*, 1999a]. As a result, when the ERS scatterometer observes a flattening of the backscatter curve due to vegetation growth then σ^0 decreases at incidence angles lower than the crossover angles and increases at higher incidence angles. In a first step values for the cross over angles θ_{dry} and θ_{wet} where the effects of vegetation growth and decay on σ^0 are assumed to be negligible are selected empirically. Given that the values which were used in previous studies over the Iberian Peninsula, Ukraine and Western Africa (θ_{dry} = 20°, θ_{wet} = 40°) also produced reasonable results in other areas, it was decided to use these values globally. In a second step the effect of vegetation phenology and the exact positions of the dry and wet soil backscatter reference curves, $\sigma^0_{dry}(t)$ and $\sigma^0_{wet}(t)$ given in Eq. 6, are determined by fitting the curves to the $\sigma^0(40)$ time series;

$$\sigma^0_{DRY}(40,t) = C^0_{DRY} - D'\Psi'(t)(\theta_{DRY} - 40) - \frac{1}{2} D''\Psi''(t)(\theta_{DRY} - 40)^2$$

(Eq. 6)

$$\sigma^0_{WET}(40,t) = C^0_{WET} - D'\Psi'(t)(\theta_{WET} - 40) - \frac{1}{2} D''\Psi''(t)(\theta_{WET} - 40)^2$$

In Eq 6. σ^0_{dry} and σ^0_{wet} are backscatter from the dry and saturated canopy, θ_{dry}, θ_{wet} are the crossover angle for dry and wet soil conditions (at this angle vegetation has no influence) C^0_{dry}, C^0_{wet} are the annual minimum and maximum backscatter $D'\Psi'(t)$ describe the annual variation of σ^0 due to the influence of vegetation. Given that in dry climates there may never be enough rainfall to thoroughly wet the soil surface layer [*Wagner and Scipal*, 2000], an empirical correction approach was developed which estimates $\sigma^0_{wet}(t)$ corresponding to a wet, saturated soil surface based on the observed slope [*Scipal*, 2002].

3.2.2.4 Calculate Surface Soil Moisture

Surface (< 5 cm) soil moisture $m_s(t)$ is calculated by comparing σ^0(40, t) to the dry $\sigma^0_{dry}(t)$ and wet $\sigma^0_{wet}(t)$ reference curves according to Eq 7. The resulting quantity is a relative meassure ranging between 0 (dry) and 1 (saturated).

$$m_s = \frac{\sigma^0(40,t) - \sigma^0_{dry}(40,t)}{\sigma^0_{wet}(40) - \sigma^0_{dry}(40,t)} \qquad \textbf{\textit{(Eq. 7)}}$$

3.2.2.5 Mask measurements affected by snow and/or frozen soil

Under snow and/or frozen soil retrieval of soil moisture is not possible, these measurements are therefore masked. Currently, a simple masking procedure which is based on mean monthly temperature data extracted from a climate data base prepared by Leemans and Cramer (1991) is employed.

3.2.2.6 Calculate Profile Soil Moisture

In order to retrieve soil moisture in the root zone (up to about one meter) a two-layer water balance model, which only considers the exchange of soil water between the topmost remotely sensed layer and the "reservoir" below, was used to establish a relationship between the m_s series and the profile soil moisture content [*Ceballos et al.*, 2005; *Wagner et al.*, 1999b]. Solving the differential water balance equation showed that the water content in the reservoir at time t is related to the measurements of m_s at times $t_i < t$, whereby the influence of $m_s(t_i)$ decreases with increasing time lag $t - t_i$. Under the assumption that the effective large-scale soil hydraulic conductivity is constant, an indicator of the water content in the reservoir layer is obtained by convoluting the m_s time series with an exponential function (Eq 8). The resulting quantity, the Soil Water Index (*SWI*), ranges between 0 (wilting level) and 1 (field capacity).

$$SWI(t) = \frac{\sum_i m_s(t_i) e^{-(t-t_i)/T}}{\sum_i e^{-(t-t_i)/T}} \qquad \text{for } t_i \le t \qquad \textbf{\textit{(Eq. 8)}}$$

In the VUT model the SWI is calculated considering all measurements taken within a period 3*T* if at least 4 measurements have been recorded within the most recent time period *T* and if the ground was snow free and not frozen. In cold climates, the calculation of *SWI* is in principle not possible at the beginning of the thawing period due to the lack of physically meaningful m_s data in the previous few weeks. However, to enable the calculation of *SWI* right from the onset of thawing, the preceding m_s values are set equal to the maximum observed m_s. The underlying assumption is that the soil moisture status is high at the end of the winter season due to snow melt. This assumption is not valid for dry cold climates and will be revised in the future; Typically, the temporal variability of soil moisture decreases with increasing layer thickness. Therefore, given that the parameter *T* controls the degree of smoothing of the m_s series, higher *T* values are representative of deeper layers. In a study over the Ukraine, the best comparison of *SWI* with field measurements of the 0-20 cm layer was observed for *T* set equal to 15 days, respectively *T* = 20 days for the 0-100 cm layer [*Wagner et al.*, 1999b]. For the global processing *T* was kept constant at 20 days. Given that the temporal variability of the soil moisture field is dependent on climate and soils [*Entin et al.*, 1999], this implies that the *SWI* data may represent layers of variable thickness in different parts of the world.

3.2.3 Underlying Assumptions

The underlying assumptions of the VUT model are:

- At the resolution of the scatterometer, roughness and landcover are temporal invariant. The measurement process, due to the low resolution of the sensor, suppresses local fluctuations.
- Vegetation phenology influences σ^0 on an annual scale. The measurement process, due to the low resolution of the sensor, suppresses local short-term fluctuations.
- There exist distinct incidence angles θ_{dry} and θ_{wet}, where the backscattering coefficient σ^0 is relatively stable despite seasonal changes in above ground vegetation biomass for dry and wet conditions.
- The relationship between soil moisture and σ^0 is linear.

3.3 LIMITATIONS

Soil Moisture can not be estimated if the fraction of dense vegetation, open water surfaces or snow/frozen soils dominate the scatterometer footprint. Additionally the VUT model does not explicitly model the azimuthal geometry of the ERS scatterometer. Under certain condition azimuthal viewing effects can dominate the measurement process and make a retrieval impossible.

3.3.1 Dense Vegetation

One often alluded limitation of the ERS and METOP scatterometers for soil moisture retrieval is their operation frequency of 5.3 GHz (C-Band) which, according to some theoretical models, is believed to be insufficient for penetrating vegetation. However the empirical evidence that C-band is sensitive to changes of surface soil moisture even under a vegetation cover (grassland and agricultural vegetation) based on scatterometer [*Wagner et al.*, 1999a; *Wagner et al.*, 1999c] was recently confirmed by 3D-laboratory measurements [*Brown et al.*, 2003; *Picard et al.*, 2004].

The backscattering coefficient measured by C-band radars saturates over forests with about 20–30 tons/ha above-ground biomass [Le Toan et al., 2001]. For the case of the ERS scatterometer this means that the measured signal is relatively stable if a significant portion of the radar footprint is covered by forests. Since in such a situation there are not enough soil moisture sensitive areas (e.g. grassland or agriculture) within one ERS footprint, soil moisture retrieval is not possible. To identify these regions, pixels where the difference $\sigma^0_{wet} - \sigma^0_{dry}$ is less than 2 dB were masked. The resulting forest mask covers an area of roughly 9.6 Mio km^2 and only occurs in the equatorial rainforest belt.

3.3.2 Water Surfaces

The effect of open water surfaces is not considered in the VUT model. Principally measurements taken over water are rejected during the regriding of scatterometer data using a water flag delivered with the original scatterometer files. Meassurments from wetland areas, rice cultivation areas and small lakes are not flagged. Soil moisture retrieval over these areas can be biased.

3.3.3 Snow and Frozen Soil

The effect of Snow and Frozen Soil is not considered in the VUT model. Under snow and/or frozen soil retrieval of soil moisture is not possible, these measurements are therefore masked. Currently, only a simple masking procedure which is based on mean monthly temperature data extracted from a climate data base prepared by Leemans and Cramer (1991) is employed.

3.3.4 Azimuthal Effects

The VUT model assumes that σ^0 measurements are independent of the azimuth viewing direction. In areas with systematic roughness patterns the VUT model can not be applied. These areas are therefore masked. The masking criterion is based on the difference between the fore and aft beam measurement of the ERS scatterometer which are taken at different azimuth angles. If the estimated standard deviation based on this difference is above 1 dB and if the reasons for this high noise could be attributed to azimuthal effects, e.g. caused by sand dunes, then the corresponding pixel was masked. The masked areas cover an area of about 4.7 Mio km^2 and can mainly be found in the Sahara, the Rub'al Khal and the Takla Makan

3.4 THE PRODUCT QUALITY

During the entire processing chain strict quality control is applied. Based on error propagation of the instrument noise, measurements that fall outside the noise threshold are removed from the data set.

3.5 THE VALIDATION PROCEDURE

The SWI product has been validated using in-situ data from large agrometeorologic networks [*Scipal*, 2002], insitu data from an experimental catchment [*Ceballos et al.*, 2005], global model data [*Dirmeyer et al.*, 2003] and global gridded precipitation data and model data [*Wagner et al.*, 2003]. Results of the validation can be summarized as follows:

1. Comparison with 40000+ gravimetric insitu soil moisture measurements from 360 agrometeorologic stations in Russia, Ukraine, China, USA and India indicated a RMS error of the SWI of 17% which is equivalent to an RMS error of 6 vol%.
2. Comparison with global model data and global gridded precipitation data indicated that the SWI is a consistent reliable measure of soil moisture over temperate, cold and tropical climates. In extreme climates such as deserts and arctic regions the SWI is biased.

3.6 RISK OF FAILURE

Cuurently no risks of failure are identified.

4 COSTUMISATION METHODS

4.1.1 Costumisation for OFM

- A quality flag has been added to the SWI. The quality flag consists of a reliability indicator for each single SWI measurement and the correlation coefficient between the SWI and gridded rainfall data from the from the Global Precipitation Climatology Centre (GPCC).
- Missing values have been replaced by the long term average.

5 REFERENCES

Brown, S.C.M., S. Quegan, K. Morrison, J.C. Bennett, and G. Cookmartin, High-Resolution Measurement of Scattering in Wheat Canopies - Implications for Crop Parameter retrieval, *Ieee Transactions on Geoscience and Remote Sensing*, *41* (7), 2003.

Ceballos, A., K. Scipal, W. Wagner, and J. Martinez-Fernandez, Validation and downscaling of ERS Scatterometer derived soil moisture data over the central part of the Duero Basin, Spain., *Hydrological Processes*, 2005.

Dirmeyer, P.A., Z. Guo, and X. Gao, Validation and forecast applicability of multi-year global soil wetness products, *COLA Technical Report*, 2003.

Entin, J.K., A. Robock, K.Y. Vinnikov, V. Zabelin, S.X. Liu, A. Namkhai, and T. Adyasuren, Evaluation of Global Soil Wetness Project soil moisture simulations, *Journal of the Meteorological Society of Japan*, *77* (1B), 183-198, 1999.

Le Toan, T., Picard, G., Martinez, J.-M., Melon, P., and Davidson, M., On the relationships between radar measurements and forest structure and biomass. In Proceedings of the 3rd International Symposium on Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications, ESA SP-475, Sheffield, UK, , 3-12, 2001.

Leemans, R. and W. Cramer, The IIASA database for mean monthly values of temperature, precipitation and cloudiness on a global terrestrial grid, Research Report RR-91-18 of the International Institute of Applied Systems Analyses, Laxenburg, Austria, 1991.

Picard, G., T. Le Toan, and S. Quegan, A three-dimensional radiative transfer model to interpret ranging scatterometer measurements from a pine forest, *Waves in Random Media*, *14* (2), S317-S331, 2004.

Scipal, K., Global Soil Moisture Monitoring using ERS Scatterometer Data, PhD thesis, Vienna University of Technology, 2002.

Ulaby, F.T., R.K. Moore, and A.K. Fung, Radar Remote Sensing and Surface Scattering and Emission Theory., *Microwave Remote Sensing: Active and Passive. Vol. II*, 1982.

Wagner, W., G. Lemoine, M. Borgeaud, and H. Rott, A study of vegetation cover effects on ERS scatterometer data, *Ieee Transactions on Geoscience and Remote Sensing*, *37* (2), 938-948, 1999a.

Wagner, W., G. Lemoine, and H. Rott, A method for estimating soil moisture from ERS scatterometer and soil data, *Remote Sensing of Environment*, *70* (2), 191-207, 1999b.

Wagner, W., J. Noll, M. Borgeaud, and H. Rott, Monitoring soil moisture over the Canadian Prairies with the ERS scatterometer, *Ieee Transactions on Geoscience and Remote Sensing*, *37* (1), 206-216, 1999c.

Wagner, W., and K. Scipal, Large-scale soil moisture mapping in western Africa using the ERS scatterometer, *Ieee Transactions on Geoscience and Remote Sensing*, *38* (4), 1777-1782, 2000.

Wagner, W., K. Scipal, C. Pathe, D. Gerten, W. Lucht, and B. Rudolf, Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data, *Journal of Geophysical Research-Atmospheres*, *108* (D19), 2003.