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Use of microwave remote sensing data to monitor spatio temporal characteristics of surface soil moisture at local and regional scales

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Abstract. Hydrologic processes, such as runoff production or evapotranspiration, largely depend on the variation of soil moisture and its spatial pattern. The interaction of electromagnetic waves with the land surface can be dependant on the water content of the uppermost soil layer. Especially in the microwave domain of the electromagnetic spectrum, this is the case. New sensors as e.g. ENVISAT ASAR, allow for frequent, synoptically and homogeneous image acquisitions over larger areas. Parameter inversion models are therefore developed to derive bio- and geophysical parameters from the image products. The paper presents a soil moisture inversion model for ENVISAT ASAR data for local and regional scale applications. The model is validated against in situ soil moisture measurements. The various sources of uncertainties, being related to the inversion process are assessed and quantified.

1 Introduction

Water affects all economic, cultural, social and ecological aspects of daily life and is basic to functioning matter fluxes and hence for a clean and stable environment. Its availability, quality and allocation is largely affected by Global Change, which summarizes the complex interactions of changes not only in the global climate and water system but also changes in population, development and economy. Thus solitary sciences, with their inevitably unilateral view of the world, are neither capable to understand the complex interactions between nature, water and man nor to develop methods for a sustainable water resource management under globally changing boundary conditions. The same applies to the present state of observation systems, which often serve the very specific needs of small research communities and are often not integrated into larger and more complex approaches.

A major objective of recent Global Change research programs as e.g. the GLOWA-Danube project (Mauser and Ludwig, 2002; Ludwig et al., 2003) is therefore the development of complex integrative models which can be used as tools for scenario based decision making. A monitoring of large areas, based on remote sensing techniques, is mandatory to provide the needed spatially distributed input datasets to those models to validate and improve the model results on a regional scale. New sensors, as ENVISAT ASAR (Advanced Synthetic Aperture Radar), enable frequent observations of large areas at regional scale with an appropriate spatial resolution for mesoscale applications. The ASAR Wide Swath Mode (WSM) has a high potential in this context (ESA, 2002). The swath width of 400 km enables the acquisition of homogeneous, temporal consistent datasets of entire mesoscale river catchments at a spatial resolution of 150 m. Additionally, image acquisitions with higher spatial resolution is possible with the image and alternating polarization modes (ESA, 2002), which allow for a better comparison of the image data with ground measurements.

A key parameter for the energy and mass fluxes at the land surface is the actual water content of the soil layer. An accurate and comprehensive, spatially distributed estimation of the soil moisture content is therefore needed. The potential to quantify soil moisture patterns of the top soil layer (3–5 cm) with microwave imagery has been successfully demonstrated in numerous studies (e.g. Engman, 1998; Quesney et al., 2000; Dubois et al., 1995; Wigneron et al., 2003; Le Hégarat-Mascle et al., 2002). Contrasting earlier and rather experimental research efforts, data acquired from the ENVISAT ASAR sensor firstly enables to continuously monitor large areas with high frequency (3–4 images per week in mid-latitudes) and high spatial resolution from the local (30 m resolution/100 km coverage) to the regional scale (150 m/400 km).

The paper presents an inversion methodology for ENVISAT ASAR data to retrieve the soil moisture content of the uppermost soil layer. The semi empirical approach is validated against in situ soil moisture measurements. Despite

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the fact, that remote sensing data provide independent information about the interaction of electromagnetic waves with the land surface by means of reflected or scattered energy, each attempt to invert bio- and geophysical parameters from the data will be based on inversion models with a limited degree of accuracy. An uncertainty analysis of the presented soil moisture inversion approach is therefore conducted to assess the influences of data and model parameter induced uncertainties to the retrieved soil moisture values.

2 Testsite and datasets

The present work was conducted within the InFerno[+] project, which has been established for the assimilation of remote sensing data in operational flood forecasting systems (Schulz et al., 2002). The testsites of this project, namely the Mosel, Neckar and Ammer river catchments, are located in southern Germany. All testsites are equipped with permanently registering soil moisture stations and a dense network of meteorological weather stations. A geographical information system with a spatial resolution of 30 m is available for the entire area, including information about the actual land cover, soil texture and topography.

More than 50 ENVISAT ASAR images, acquired since the year 2002 over the testareas form the database for the analysis on local and regional scale. Extensive field campaigns were carried out during sensor passes to sample additional ground truth information about the actual soil moisture conditions on various agricultural test fields.

2.1 Data characteristics

The ENVISAT ASAR sensor allows for image acquisitions in different imaging geometries, which enables to monitor an area of interest from different sensor pathes and thus increases the temporal repetition frequency significantly. Due to the different imaging geometries, the incidence angle (angle between ellipsoid normal and incident beam) changes, which affects the amount of backscattered energy. The large swath width of a WSM image corresponds to incidence angles ranging from 15° to 45°. Thus, parameter inversion models have to account for this incidence angle change and its effect on the backscattering coefficient.

For mesoscale image products, as the WSM mode, image pixels can not be treated as homogeneous. The backscattering coefficient of a resolution cell is a function of different land cover types within the image pixel. To allow for a quantitative estimate of land surface parameters from those image products, it is mandatory to care for the subscale heterogeneity of the image pixels (Löw et al., 2003; Schneider and Oppelt, 1998). Using a high resolution (30 m) land use classification developed by Stolz et al. (2004), the fractions of each land use can be determined for each mesoscale image pixel. This ancillary information is used for the preprocessing of the image data and the derivation of quantitative parameters from mesoscale ENVISAT ASAR imagery.

3 Determination of surface soil moisture from ENVISAT ASAR data

To derive quantitative information about the surface soil moisture from ENVISAT ASAR data, an appropriate preprocessing of the image data is crucial to obtain reliable estimates of the backscattering coefficient. These can be used to invert land surface parameters from the image. The principle methodology to derive soil moisture of the upper soil layer from ENVISAT ASAR data is outlined in the following. It has been described in more detail by Löw et al. (2004). The methodology is applicable at local as well as at regional scales. Figure 1 shows the principle data flow for soil moisture inversion from SAR data and the sources of model uncertainties to be discussed later on in Sect. 4.

3.1 Geocoding

The image geometrical and radiometrical properties are distorted due to changes in local topography. The image pixels are displaced due to topography and the changing local scattering area results in significant backscatter changes up to several decibels. This has to be compensated to obtain reliable estimates of the backscattering coefficient as a function of surface characteristics. The SAR images are therefore precisely geocoded using the Range-Doppler approach after calibrating the ENVISAT ASAR data to image brightness values (β^0). It has been shown, that SAR images can be normalized by taking into account ancillary information about local topography (Löw and Mauser, 2003; Small et al., 2004) and that significant improvements of the radiometric accuracy of the data can be achieved in this way (Riegler and Mauser, 1998; Löw, 2004). The local scattering area is calculated by taking into account the local slope and aspect with respect to the incident wave. The normalized backscattering coefficient σ^0, being comparable to the backscatter from flat earth is obtained by normalizing the image brightness value by the local scattering area.

3.2 Incidence angle normalization

The terrain corrected backscattering coefficients are mainly a function of surface characteristics and the incidence angle.

Figure 2 shows an example of the incidence angle dependency of the backscattering coefficient on crop and grassland, as derived from multitemporal analysis of image statistics. Clearly can be seen, that the backscattering coefficient decreases with increasing incidence angle. Due to the large possible incidence angle range of ENVISAT ASAR data, a normalization of the incidence angle effects on the signal is mandatory for quantitative image analysis. This ensures the comparability between multiple image datasets. This normalization is achieved by using land use dependant linear incidence angle models as those shown in Fig. 2 to normalize a measured backscattering coefficient to a reference imaging geometry (Löw et al., 2004). It is shown that the normalization model only accounts for part of the variability of the
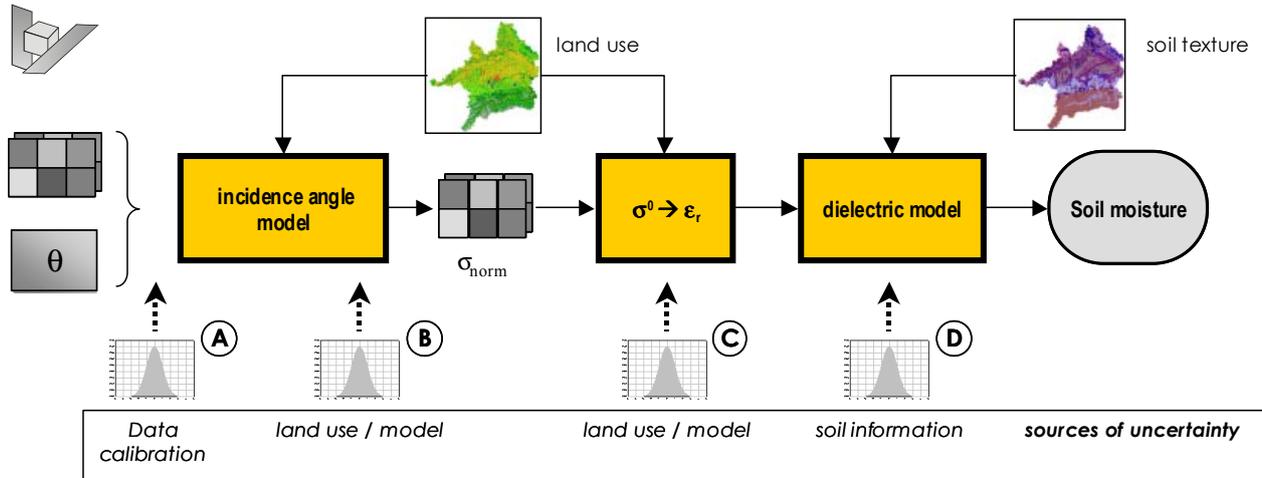
Fig. 1. Principle of soil moisture inversion from ENVISAT ASAR data and sources of uncertainties.

data. The backscattering coefficient is as well influenced by soil moisture, vegetation effects and surface roughness which should be theoretically be taken into account in the normalization procedure. This can not be achieved for larger areas due to missing data. The estimated angular backscatter variability is therefore an approximation to the land surface microwave interactions as function of incidence angle. The uncertainty which is induced by the normalization model is assessed in Sect. 4.

3.3 Soil moisture inversion

The developed soil moisture inversion approach is based on a semiempirical model which was formerly developed for ERS data (Rombach and Mauser, 1997). It has been shown in different test sites in Europe, that the model can be used to invert soil moisture with an accuracy of 4 vol.% (Bach and Mauser, 2003) and that it can also be applied for mesoscale SAR data (Löw et al., 2003). The model is mainly validated for vegetated areas and different crop types. The backscattering coefficient is known to be very sensitive to surface roughness as well as to soil moisture (Oh et al., 1992; Zribi and Dechambre, 2002). The bare soil contribution is attenuated by the vegetation canopy and the influence of surface roughness therefore decreases. If additional surface roughness information is available it can be used to improve soil moisture inversion results (Zribi and Dechambre, 2002; Löw, 2004). Vegetation effects on the signal are treated to remain constant after a certain phenological stage which has been shown to be valid as a first approximation (Rombach and Mauser, 1997). Nevertheless soil moisture inversion results can be significantly improved if vegetation growth dynamics is taken into account in the inversion process by means of vegetation biomass and water content (Löw, 2004; Quesney et al., 2000; Mattia et al., 2003)

This model is adapted for ENVISAT ASAR data by compensating for the changing incidence angles and subpixel heterogeneities.
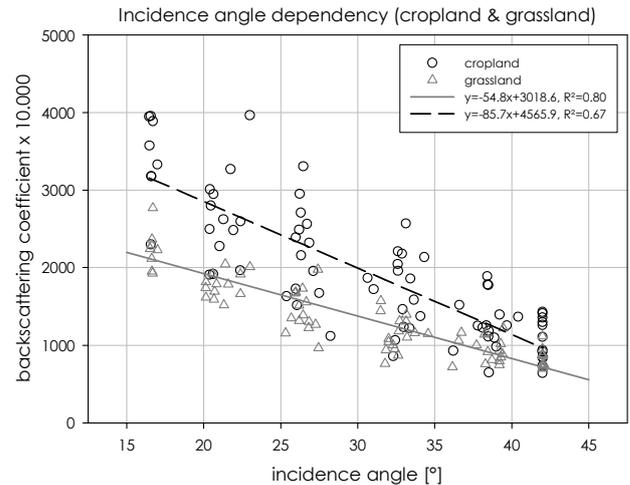

Fig. 2. Incidence angle dependency of SAR backscatter for grassland and crop land.

The approach consists of basically two steps. In a first step, the radar backscatter σ^0 is related to the dielectric constant of the soil by a 2nd order polynomial. The empirical relationships between the backscattering coefficient and the dielectric constant ε_r are dependant on the land use (Fig. 3). Detailed information about the actual land use is therefore required to obtain best inversion results. If no or only imprecise land use information is available, the uncertainties of the inversion results will increase. In forested and urban areas, soil moisture information can not be derived from the image data.

In a second step, the dielectric constant is converted to a volumetric soil moisture content m_v using a dielectric model (Hallikainen et al., 1985).
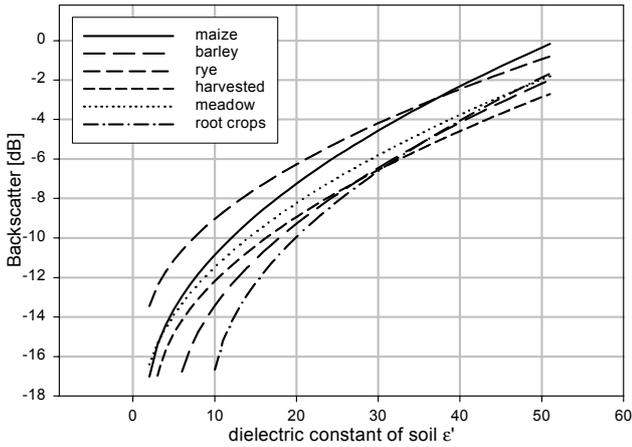
Fig. 3. Empirical relationship between dielectric constant and backscatter for various land use types.
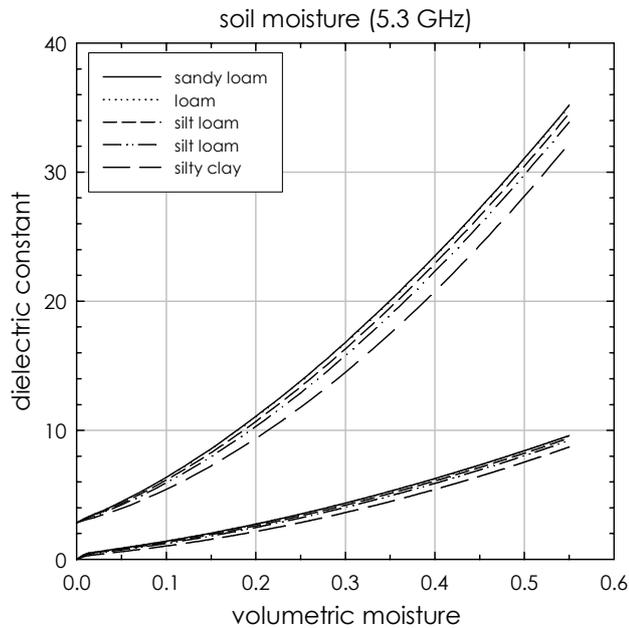

Fig. 4. Dielectric constant of soils as function of water content and soil texture.

As shown in Fig. 4 the relationship between the dielectric constant and m_v is dependant on the soil texture. Thus additional information about soil texture is required.

3.4 Model validation

To quantify the accuracy of the proposed soil moisture inversion scheme, comparisons with ground measurements are made at local and regional scale. The inverted soil moisture values from the image data (30 m, 150 m) are validated against in situ measured TDR probes. Figure 5 shows measured and retrieved soil moisture values, as derived from different ASAR images with various imaging geometries. It can be seen, that the retrieved soil moisture values are almost within a range of ±5 vol.% which is a promising result.
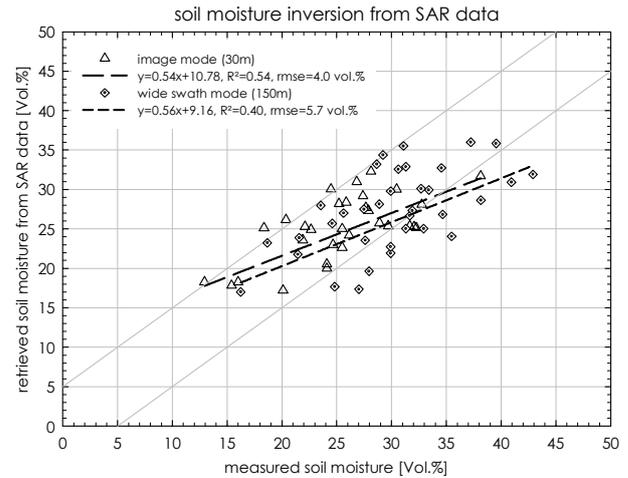

Fig. 5. Comparison between measured and retrieved soil moisture values at 30 m and 150 m resolution.

It has to be emphasized that these comparisons are made on the resolution cell size of the image data (30 m, 150 m). The in situ soil moisture measurements are only a representative for a small area and not for the entire resolution cell size of the SAR image. Due to the spatial variability of the soil moisture it is difficult to compare the point measurements with the image data. A systematic analysis of the variability of the soil moisture within agricultural fields revealed standard deviations of the soil moisture values between 2 vol.% and 8 vol.%. This scale gap introduces additional uncertainty to the validation of the model results. Thus the variability of the retrieved soil moisture, compared to the in situ measurements is partly a result of the scale gap between the point measurements and the image resolution cell size, as well as uncertainties resulting from land use information and imprecise soil texture maps.

Figure 6 shows examples of derived surface soil moisture maps and their temporal development. It can be seen, that the soil moisture patterns are consistent with the observed precipitation evolution within the same area.

4 Uncertainty analysis

Each modelling process is associated with uncertainties which are the result of simplified assumptions being made in the model and imprecise input datasets provided to the model. The total model uncertainty is the result of the interference of different contributing sources. For the presented soil moisture inversion model these sources of uncertainty are (Fig. 1).

1. *image calibration errors*: the radiometric calibration error of ASAR image products is within 0.5–1.0 dB (Rosich et al., 2003)

2. *incidence angle correction*: the empirical correction of the incidence angle effect on the signal, as shown in
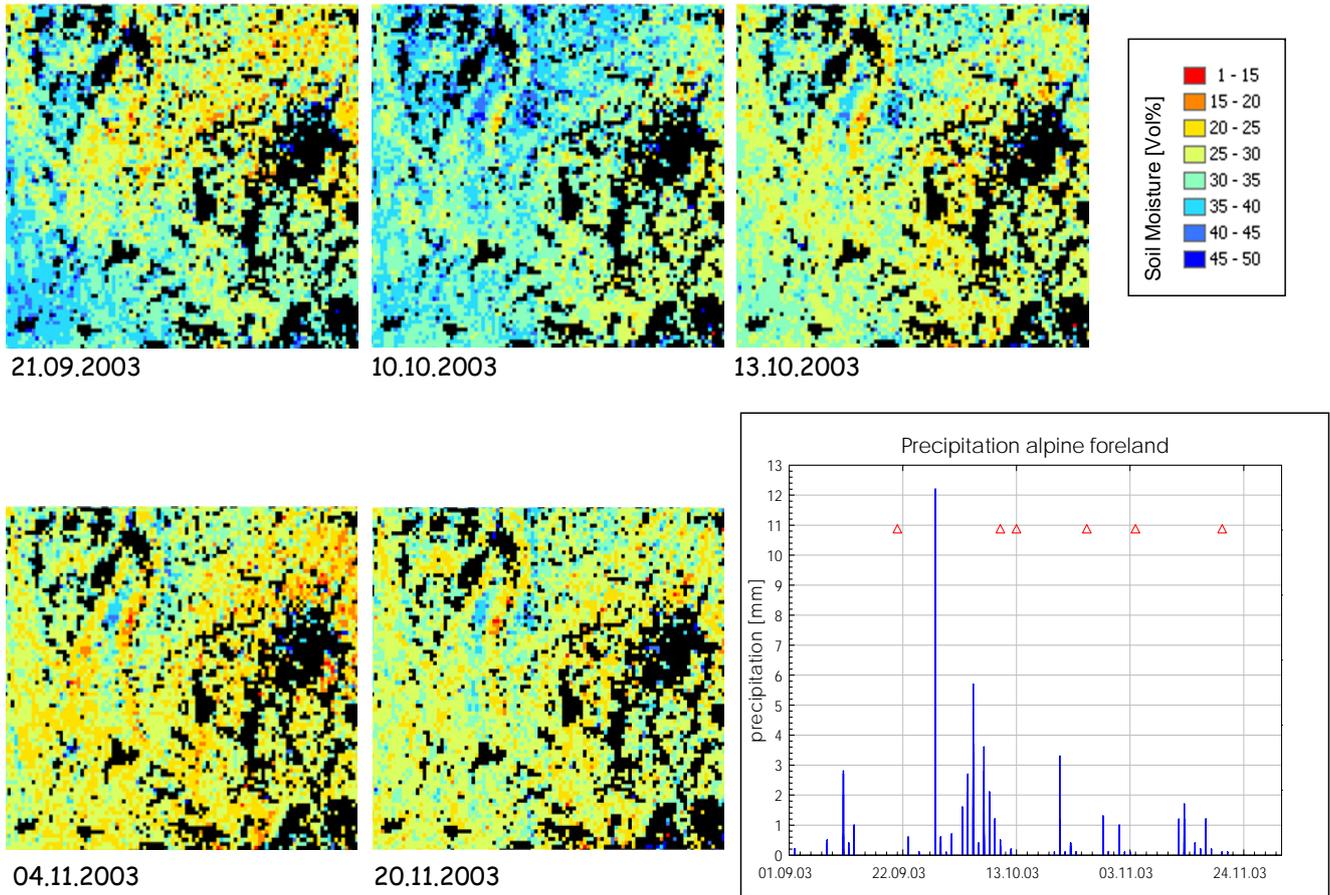
Fig. 6. Multitemporal soil moisture patterns around Munich (Germany) as a function of precipitation distribution.

Fig. 3 only accounts for a part of the variance while a certain amount remains unexplained by the linear regression model.

3. *land use specific derivation of the dielectric constant* (ε_r): To convert the backscattering coefficient to dielectric constant values, the actual land use has to be known. Uncertainties result from non existing or imprecise land use information as well as from the inversion model itself which is calibrated empirically

4. *unknown soil texture information*: the dielectric constant is converted to volumetric soil moisture with a high degree of accuracy using a dielectric mixture model. Due to a lack of spatially distributed precise soil texture information for the upper soil layer, the volumetric soil moisture content (m_v) can only be converted from dielectric measurements with uncertainties.

In the following, the impact of the different sources of uncertainties on the soil moisture retrieval is assessed using a Monte Carlo based approach (Fig. 7). Soil moisture is inverted for backscatter values in the range of −18 to −3 dB using the presented approach with a resolution of 0.05 dB.

For each backscatter value a number of 10 000 model realizations is inverted to soil moisture values. The different model realizations are achieved by adding random gaussian noise according to Table 1 for the different terms of uncertainty mentioned above. These values are estimated from known SAR image calibration uncertainties (Rosich et al., 2003) as well as from assumptions being made for the error that could be induced by the different model terms. The incidence angle normalization uncertainty is derived from the residues of the linear regression line in Fig. 2 while the uncertainties of the estimates of the dielectric constant and volumetric soil moisture can be derived from the variability of the parameters which is shown in Fig. 3 and Fig. 4.

The frequency distribution and the first and second order moment of the obtained soil moisture values is calculated.

To assess the impact of the various uncertainty sources on the total model accuracy, simulations are also conducted where random noise is added only for a single variable. This gives a measure for the sensitivity of the model on the different uncertainty terms.

Figure 8 shows an example of uncertainty analysis results for arable land and an incidence angle of 30°. The results obtained when only a single noise term is added, as well
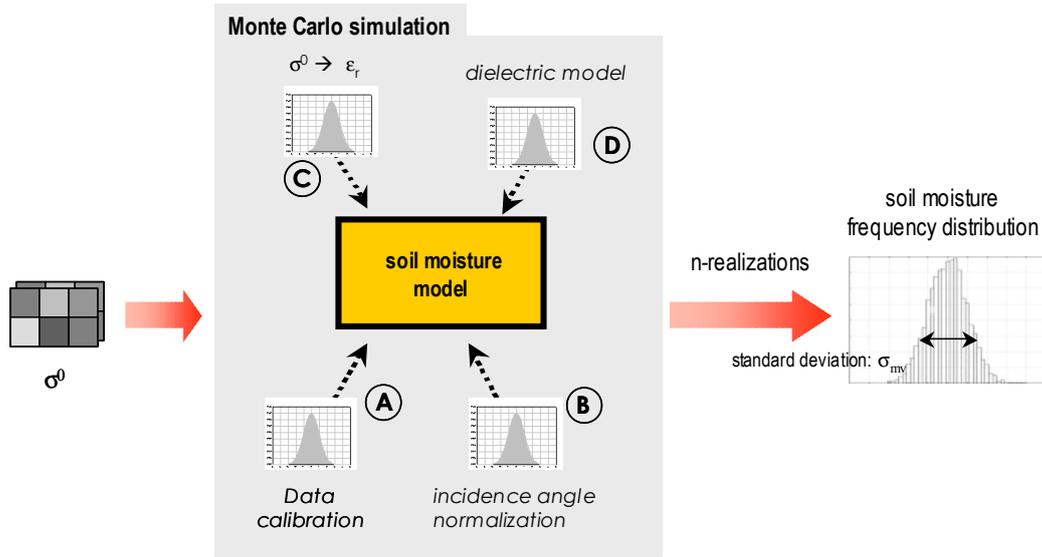
Fig. 7. Assessment of uncertainties in soil moisture inversion by means of Monte Carlo simulations.

Table 1. Gaussian noise standard deviation (s) for Monte Carlo based analysis of different terms of uncertainty.

	Uncertainty source	Unit	σ
A	Image calibration	dB	0.5
B	Incidence angle compensation	m^2/m^2	485
C	Backscatter to dielectric constant	–	2.5
D	Dielectric model	vol.%	3.0

as the result of the interference of the different noise terms are shown. The interference result corresponds to a worst case scenario where no detailed information about the actual land use and soil texture is available. For this worst case, the standard deviation of the inverted soil moisture values is approximately 7 vol.% for low backscattering coefficients and decreases to 4.5 vol.% for higher backscattering coefficients.

The different contributions of the various uncertainty terms can be summarized as follows:

1. the image calibration has a small effect on the soil moisture retrievals. With increasing backscattering coefficient, the influence of the calibration quality increases due to a reduced sensitivity of the backscattering coefficient to soil moisture changes.

2. The influence of the incidence angle normalization procedure to the model accuracy is affected by the magnitude of the backscattering coefficient. For low backscattering coefficients, corresponding to low soil moisture content, uncertainties are higher than for those of higher backscatter values. This is obviously caused by the better signal to noise ratio for the higher backscattering values due to the fact, that a constant gaussian noise is used for the simulations for the entire backscatter range.

3. If no detailed information about land cover is available, only a mean relationship between the dielectric constant and the backscattering coefficient can be assumed. This results in a standard deviations of 2.5 to 4.5 vol.% for the inverted soil moisture values.

4. The conversion of the dielectric constant to volumetric soil moisture content is dependant on the available soil texture information. The uncertainties in the soil moisture retrieval results, which are caused by a lack of soil texture information, contribute a systematic bias of 3 vol.% to the inversion results.

Typically, the different sources of uncertainties interfere and the resulting model uncertainty is higher than that of the singular error sources which is shown by the worst case scenario. Additional information can be provided to the inversion process by means of spatially distributed land cover and soil texture information which increases the accuracy of the soil moisture inversions. Figure 8 shows also the simulation results of such a more realistic scenario where the noise for the conversion of the backscattering coefficient to dielectric constant (C) as well as for the conversion from ε_r to m_v (D) was assigned a more realistic value of 1.0 due to prior land use and soil texture knowledge. It can be seen, that the uncertainties of the soil moisture retrievals decrease with higher backscattering coefficients. A significant reduction of the standard deviation over the entire backscatter range can be observed, compared to the worst case scenario. For low backscatter values, the inversion results have a standard deviation of approximately 5.5 vol.% which depletes below 3 vol.% for higher backscatter values.

Commonly, remote sensing derived surface parameters are validated against in situ measurements as it has also been done for the present model (Fig. 5). Typically the in situ measurements are treated to represent the expected true value,
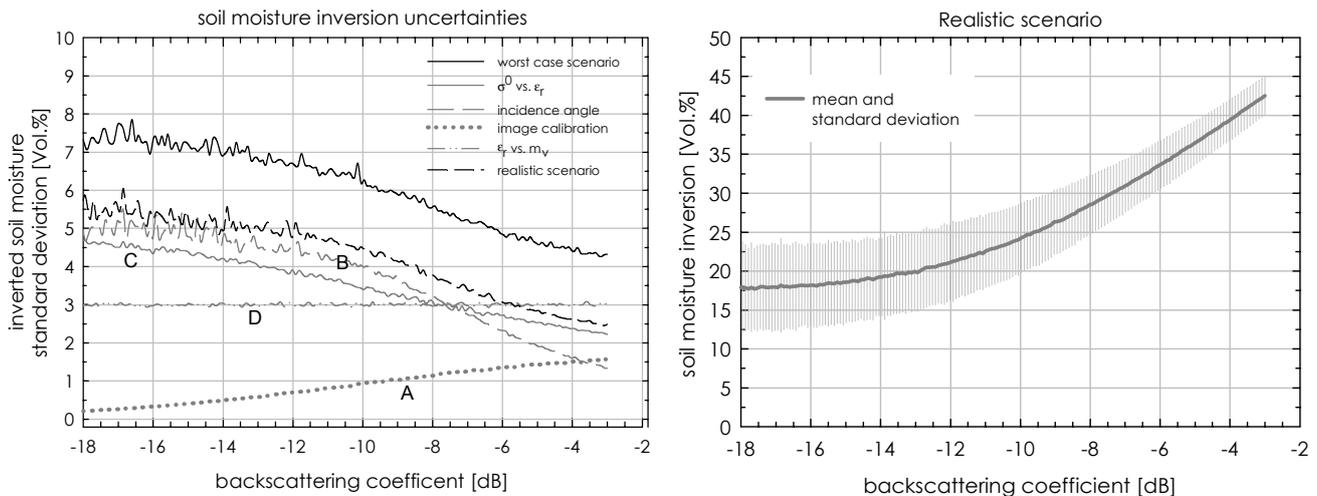
Fig. 8. Soil moisture inversion uncertainties based on Monte Carlo simulations assuming singular and combinations of different sources of uncertainty at an incidence angle of 30°: standard deviations of inverted soil moisture values (left) and relationship between backscattering coefficient and soil moisture, including uncertainties (right).

but they are as well associated with uncertainties. If ground based soil moisture measurements are made on a spatial resolution being comparable to the SAR sensor resolution cell size (>30 m), the in situ measurements show soil moisture standard deviations between 1 vol.% up to 10 vol.% (Löw, 2004; Huisman, 2002). Based on an analysis of a large database of soil moisture measurements on multiple sites and agricultural crops, typical inner field soil moisture standard deviations were found to range from 2 vol.% to 5 vol.%. Thus, the variability of the in situ soil moisture measurements is within the same order than those resulting from uncertainties in the realistic soil moisture inversion scenario.

5 Conclusions

The proposed soil moisture inversion model has shown promising results at the local as well as at the regional scale. It enables the homogeneous derivation of surface soil moisture for mesoscale watersheds. To obtain best inversion results, appropriate land use and soil texture information is required. The uncertainty analysis revealed that inversion uncertainties decrease with increasing soil moisture content. This is of particular interest for applications in flood forecasting and surface runoff prediction. The uncertainties at higher soil moisture values are comparable to those resulting from in situ measurements. Thus, ENVISAT ASAR data has the potential to provide spatially distributed soil moisture information at a high level of accuracy if the necessary input datasets are available with sufficient precision. A constraint remains in the fact that the soil moisture content of the root zone is typically required for hydrological applications. Adaptive data assimilation techniques are therefore required to use remote sensing derived soil moisture to update hydrological model state variables.

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