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Evaluation of ERS Scatterometer soil moisture products over a half-degree region in Southwestern France

Thierry Pellarin¹, Jean-Christophe Calvet², Wolfgang Wagner³

***Abstract*— This paper investigates the ERS Scatterometer soil moisture products precision over a half-degree region in Southwestern France. Based on a high resolution soil moisture simulation (1km²) validated at the local scale, the ERS-scat product is assessed at its own resolution (about 50x50 km²). The study points out the suitable quality of the surface soil moisture product (root mean square error equal to 0.06 m³.m⁻³ for a 4-year period) and assesses the retrieved root-zone soil moisture accuracy provided by a semi-empirical methodology exclusively based on surface soil moisture products.**

1 Introduction

Surface soil moisture plays a key role in the water and energy exchanges between the land surface and the atmosphere. Several authors have shown that microwave frequencies (1-10 GHz) are relevant for soil moisture monitoring. Current sensors are used to provide soil moisture estimates such as the European Space Agency (ESA) sensors ERS-Scatterometer and ERS-SAR (since 1992), ENVISAT-SAR (since 2002), and the National

¹ Laboratoire d'Etude des Transferts en Hydrologie et Environnement, Université de Grenoble, Institut National des Sciences de l'Univers, CNRS, Grenoble, France

² Centre National de Recherche Météorologique, Météo-France, Toulouse, France

³ Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Vienna, Austria

Aeronautics and Space Administration (NASA) sensors such as the AMSR-E radiometer (since 2002). In near future, soil moisture measurements will also be provided by METOP-ASCAT (2006) and the first satellite specifically dedicated for improving the knowledge of soil water content in the upper surface layer on a global scale : the Soil Moisture and Ocean Salinity (SMOS) mission [Kerr *et al.*, 2001] scheduled for launch in 2007.

Derived soil moisture estimates from satellite sensors are mainly confronted to two main difficulties. First, the validation problem due to the coarse spatial resolution which is about 50x50 km² (ERS-Scat, AMRS-E, METOP-ASCAT, SMOS). Several studies were devoted to assess the retrieval error using indirect approaches over different environments, e.g. Wagner *et al.* [1999ab] who used meteorological observations or Drusch *et al.* [2004] who used operational products. A direct quantitative estimation of the retrieval error requires a large amount of in-situ soil moisture measurements over a 50x50 km² area such as in the study of Ceballos *et al.* [2005] in the Iberian Peninsula (20 in-situ soil moisture measurements). Presently, apart from a small number of regions worldwide, no extensive ground measurements of soil moisture exist to quantitatively assess the retrieval error. Second, active and passive microwaves measurements are only sensitive to the first centimetres of the surface layer whereas most applications use the root-zone soil moisture (0.5 m to a few meters depending on soil type and bioclimatic conditions).

In the present study, both difficulties related to the use of soil moisture satellite observations were discussed. A high resolution (1 km²) synthetic soil moisture data set over a 40x40 km² area in Southwestern (SW) France was used to assess the two ERS-scat

soil moisture products (surface soil moisture and root-zone soil moisture) of the Vienna University of Technology [Wagner *et al.*, 2003]. Section II is devoted to describe the study area and to validate soil moisture simulations as well as ERS-scat near-surface soil moisture observations. Section III presents the methodology to provide root-zone soil moisture from surface soil moisture time-series. Then, Section IV is devoted to compare the root-zone soil moisture ERS-scat products with high resolution soil moisture simulations.

2 Study area and data validation

2.1 A 40×40 km² region in SW France with soil moisture field observations

A 40×40 km² area was selected in SW France, close to the Les-Landes forest because ground soil moisture data were available for 1986 (Hapex-Mobilhy). The geographic coordinates of the centre of the pixel are: 0.045 E, 43.86 N. The most important fraction of the pixel is composed of annual crops (77 %), the rest is composed of vineyards (6.2 %), grasslands (7.2 %) and forests (9.6 %). A detailed description of soil and vegetation characteristics is available at 1 km resolution, based on ECOCLIMAP, a surface parameter database derived from land cover and climatic maps [Masson *et al.*, 2003]. This classification distinguishes 7 different land covers over the selected area.

The considered pixel is rather heterogeneous and displays strong East-West gradients of vegetation cover and precipitation (the Eastern part of the pixel is wetter). Also, large differences of soil texture are observed in this region.

The Hapex-Mobilhy experiment [André *et al.*, 1986] goals were to measure and to simulate the energy and water budget over a 14500 km² region in SW France in order to

develop and validate the now operational land surface scheme of Météo-France known as Interaction between Soil Biosphere and Atmosphere (ISBA) [Noilhan and Planton, 1989]. During this experiment a ground network was implemented: 14 soil moisture measurement sites, 12 surface flux stations and 33 gauging stations, during 1986 and part of 1987 [Goutorbe *et al.*, 1989]. Four soil moisture Hapex-Mobilhy sites are within the 40x40 km² selected area: Caumont (43°41N, 0°06W), Courrensan (43°49N, 0°16E), Fusterouau (43°42N, 0°01W) and Lagrange (43°58N, 0°03W). Two of them (Caumont and Courrensan) are non-irrigated sites.

2.2 The ISBA-A-gs 10-year simulation

The ISBA surface scheme [Noilhan and Planton, 1989] is based on the equations of the force-restore method [Deardorff, 1978]. This scheme has been developed for both operational forecast and climate modelling requirements. The Hapex-Mobilhy experiment provided the initial database for ISBA development and led to successive improvements of the surface scheme [Mahfouf and Noilhan, 1996, Noilhan and Mahfouf, 1996, Boone *et al.*, 2000]. Since Hapex-Mobilhy, numerous experiments were undertaken over various ecosystems and ISBA surface scheme performed well in intercomparison projects such PILPS2c [Wood *et al.*, 1998] or PILPS2d [Slater *et al.*, 2001]. In order to improve the representation of the vegetation in ISBA, Calvet *et al.* [1998] proposed a CO₂-responsive version of ISBA, called ISBA-A-gs. In ISBA-A-gs the stomatal conductance is driven by photosynthesis, following the approach of [Jacobs 1994]. The accumulated net assimilation of CO₂, is used by the model to simulate the leaf biomass and the leaf area index (LAI). The parameters of ISBA-A-gs were adapted for the vegetation types observed in SW France.

The atmospheric forcing is a continuous, gridded data base derived from the observations provided by the surface network of Météo-France, for a 10 year period (1985-1995). The ISBA-A-gs model was run for each 1×1 km² grid-point of the 40×40 km² pixel. Therefore, 1600 simulation series of ten-year were performed. The simulated variables include LAI, surface and root-zone soil moisture.

2.3 ERS-scat data

The Scatterometer onboard the ERS-1 satellite, operated by the ESA, regularly acquired data between August 1991 and May 1996. The instrument operates at 5.3 GHz (C-band) vertical polarization, and has three antennas collecting backscatter measurements over incidence angles ranging between 18° and 59° at the surface. The spatial resolution is 50 km at approximately 10:30 and 23:00 local time for ascending and descending tracks, respectively.

The backscattering signal is principally influenced by surface soil moisture, vegetation and soil roughness effects. Several studies were devoted to retrieve vegetation parameter using ERS Scatterometer data [*Frison and Mougin 1996; Jarlan et al. 2003; Frison et al. 1998*]. Other studies have shown the sensitivity of the ERS Scatterometer to soil moisture over different regions [*Wagner and Scipal 2000, Woodhouse and Hoekman 2000, Ceballos et al. 2005*]. Finally, authors investigated the way to separate soil moisture from surface roughness and vegetation effects [*Magagi and Kerr, 2001*].

In this study, the methodology used to extract surface soil moisture from the backscattered coefficient is based on the change detection method, such as suggested by *Dobson and Ulaby [1986]*. The methodology is described in *Wagner et al. [1999ab]*, which exploits the information provided by the multiple incidence angle measurements acquired by the

ERS scatterometer. The change detection method allows discriminating between variable processes (soil moisture, vegetation) and invariant processes (surface roughness). Thus, considering a nine-year measurement period (1992 to 2000), it is assumed that the minimum and the maximum extracted backscattered values represent completely dry and saturated surface soil conditions, respectively, over the considered area. Therefore, the retrieved surface soil moisture status is represented by a saturation index which can take values between 0 and 1.

2.4 Validation of ISBA root-zone soil moisture using field observations

The Soil Wetness Index (SWeI) is generally used to describe the relative plant extractable soil moisture, between the wilting point (SWeI=0) and the field capacity (SWeI=1). The formulation of the SWeI is given by :

$$SWeI = \frac{w_2 - w_{wilt}}{w_{fc} - w_{wilt}} \quad (1)$$

where w_2 is the modelled root-zone soil moisture, w_{wilt} is the wilting point and w_{fc} is the field capacity (in ISBA, both values depend on the fraction of clay).

Two SWeI comparisons were conducted on the Caumont and the Courrensan sites (the two others are irrigated sites and irrigation is not accounted for in this version of ISBA-A-gs). Soil moisture measurements were archived every 10 cm from 5 cm to 155 cm depth. The root zone soil moisture w_2 (eq.1) represents the mean value along the profile. The results are shown in Fig. 1. A good agreement is observed between simulated and

observed root-zone soil moisture over both sites. The efficiency score⁴ (or Nash criterion [Nash and Sutcliffe, 1970]) and the correlation coefficient are greater than 0.86 for both sites and the RMS errors are equal to 0.155 and 0.123 respectively. These results are consistent with a previous study where ISBA simulations were performed during the Hapex-Mobilhy experiment [Habets et al., 1999].

2.5 Validation of ERS Scatterometer surface soil moisture

In order to compare the ERS-scat derived surface soil moisture indices (ms^{01} ranging from 0 to 1) to our continuous simulations, the ERS-scat indices were converted to physical units of $m^3.m^{-3}$ by using the 90% confidence interval of the ISBA simulations. The following procedure was used:

$$ms^{scat} = ms^{01} [int^{+90\%}(ms^{isba}) - int^{-90\%}(ms^{isba})] + int^{-90\%}(ms^{isba}) \quad (2)$$

with

$$int^{+90\%}(ms^{isba}) = \mu(ms^{isba}) + 1.64 * \sigma(ms^{isba}) = 0.334 m^3.m^{-3}$$

$$int^{-90\%}(ms^{isba}) = \mu(ms^{isba}) - 1.64 * \sigma(ms^{isba}) = 0.111 m^3.m^{-3}$$

where $\mu(ms^{isba})$ and $\sigma(ms^{isba})$ are respectively the mean and the standard deviation of the ISBA surface soil moisture, and ms^{01} the ERS-scat degree of saturation (ranging from 0 to 1). For a Gaussian distribution, the 90% confidence interval is equal to $\mu \pm 1.64 * \sigma$. Figure 2 presents the comparison between simulated and observed normalized surface soil moisture during a 4-year period. The analysis of the two time-series leads to values of correlation coefficient (R^2), efficiency score, RMS error, and mean bias, equal to 0.34,

⁴ The efficiency score was developed to compare two time-series in hydrology. It takes values between 1 (perfect fit) and $-\infty$. An efficiency score equal to 0 means that the predicted time-series gives as much information as a constant average observed value.

0.24, $0.061 \text{ m}^3\text{m}^{-3}$ and $0.01 \text{ m}^3\text{m}^{-3}$, respectively. It can be noted that changing the confidence interval to 80% or 90% leads to a RMS error equal to 0.058 and $0.066 \text{ m}^3\text{m}^{-3}$ respectively instead of $0.061 \text{ m}^3\text{m}^{-3}$. As a comparison, the RMS error of SMOS surface soil moisture product over crop regions is expected to be close to $0.04 \text{ m}^3\text{m}^{-3}$ [Kerr *et al.*, 2001]. Despite the estimate of the ERS-scat error is higher than what is expected for SMOS, the rather low error we obtain shows that the ERS-scat products permit to monitor surface soil moisture.

3 Root-zone soil moisture derivation

Active and passive microwaves are sensitive to the first centimetres of the surface layer (depending on the wavelength and soil moisture), only. However, most applications use the root-zone soil moisture. Several approaches have been developed in order to obtain profile soil moisture estimates based on surface soil moisture information. These approaches are based on regression equations [Ragab, 1995; Biswas and Dasgupta, 1995; Arya *et al.*, 1983; Jackson *et al.*, 1987; Srivastava *et al.*, 1997], inversion approaches [Njoku and Kong, 1977; Entekhabi *et al.*, 1993, 1994], or assimilation methods using surface schemes [Calvet and Noilhan, 2000; Wigneron *et al.*, 1999; Crow and Wood, 2002].

In order to provide global root-zone soil moisture estimates using ERS-scat measurements, Wagner *et al.* [1999b] proposed a semi-empirical modelling approach which relates a series of surface soil moisture (ms^{0t}) values to the Soil Water Index (SWI) using the following expression:

$$SWI(t) = \frac{\sum_i ms^{01}(t_i) e^{-\frac{t-t_i}{T}}}{\sum_i e^{-\frac{t-t_i}{T}}} \quad (3)$$

At time t , all measurements taken within a period $[t, t-3T]$ are considered if at least 4 measurements have been recorded within the most recent time period $[t, t-T]$. The parameter T , called the characteristic time length, represents the time scale of soil moisture variations in units of time. Based on ERS-scat measurements, global SWI estimation using the Wagner's methodology can be viewed on the website: <http://www.ipf.tuwien.ac.at/radar> [Scipal *et al.*, 2002].

It can be noted that the Soil Water Index (SWI) formulation (Eq.3) is slightly different from the Soil Wetness Index (SWeI) formulation (Eq.1) since SWI may take on values between 0 (representing dry conditions) and 1 (representing wet conditions) whereas SWeI may take on values lower than 0 (i.e. below wilting point values) and greater than 1 (i.e. above field capacity values). Wagner *et al.* [1999b] indicated that $SWI = 1$ is representative of an intermediate soil moisture value, between field capacity and total water capacity. In order to compare the ISBA-A-g_s root-zone soil moisture simulations (SWeI) with the SWI derived from ERS-scat measurements, a normalization between 0 and 1 of the SWeI was performed.

4 Statistical analysis

Figure 3a illustrates the SWI comparison between the continuous ISBA-A-g_s simulation and the semi-empirical methodology of Wagner during the four-year period (1991-1995). The T parameter of (Eq.3) was optimized in order to fit the reference SWI curve in terms

of efficiency score over a 1-year period (dash-dotted line in Fig. 3a from September 1993 to September 1994). The best T value was found to be 32 days (d). The efficiency score is equal to 0.27 and the RMS error is equal to 0.198. Although the general behaviour of the two SWI is similar, some strong differences can be observed. In 1992, the Springtime values are clearly underestimated (SWI = 0.4 instead of 0.7) whereas the Summertime values are highly overestimated (SWI = 0.6 instead of 0.2). A similar behaviour can be observed in Spring 1993.

A sensitivity study was performed in order to quantify the respective effect of the noise level and the sampling time on the error on the retrieved SWI. For the rest of the study, we applied a Gaussian noise to the reference ISBA-A-gs surface soil moisture (ms^{isba}) and used the result as input of (Eq.3) for different sampling times. For example, a sampling time of 1 measurement every 3 days (at 10h30 am) and a Gaussian noise level of 0.04 m^3m^{-3} (similar to the SMOS expected configuration) is applied to ms^{isba} . The retrieved SWI is plotted in Fig. 3b. The efficiency score is equal to 0.65 and the RMS error is equal to 0.17. The best T parameter, in this case, is 20 d. Similar to Fig. 3a, a large mismatch can be observed during Springs 1992 and 1993 where the retrieved SWI is slightly underestimated. Frozen soil periods were found to be responsible for the Springtime underestimations of the root-zone soil moisture by the Wagner's methodology. A short soil freezing event appears like a sudden dry value of the surface soil moisture which is wrongly exploited in the root-zone calculation of Eq. 3. This constitutes a limitation of the methodology because just based on the scatterometer data alone it is not possible to identify frozen soil conditions. Figure 3b indicates frozen soil periods (vertical grey lines) which are often followed by a sudden unrealistic decrease of the root-zone soil moisture

retrieval. A verification of this assumption is proposed in Fig. 3c where the addition of both the liquid and the solid (iced) part of the surface soil moisture was used as input of Eq. 3. The retrieved SWI is clearly improved particularly during frozen soil periods (efficiency score equal to 0.73 instead of 0.65).

A systematic sensitivity study was performed for a range of noise levels (from 0 to $0.08 \text{ m}^3\text{m}^{-3}$) and a range of sampling times (1 measurement every 1 to 19 d). The results of the sensitivity study are presented in Fig. 4. The effect of both the noise level and the sampling time can be observed in this graph in terms of efficiency score⁵. As expected, it can be noted that the accuracy of the retrieved SWI is decreasing as the noise level and the sampling time increase. Considering that an efficiency score equal to 0.6 is suitable, the sampling time should be of 1 measurement every day for a noise level of $0.06 \text{ m}^3\text{m}^{-3}$ whereas 1 measurement every 3 day is sufficient for a noise level of $0.04 \text{ m}^3\text{m}^{-3}$. The ERS-scat mean time sampling was considered to be 6 days given that 240 measurements were obtained during the 4-year period. The low value of the efficiency score (0.27) may be due to the irregular time sampling of ERS-scat which leads to lower SWI retrieval accuracy than a regular 6-days time sampling.

5 Conclusions

A 10-year simulation was performed over 1600 square-kilometre pixels, representing a $40 \times 40 \text{ km}^2$ area in SW France. Results were compared with the $50 \times 50 \text{ km}^2$ ERS-scat surface soil moisture and root-zone soil moisture products. A good agreement was found

⁵ Each efficiency score value is a mean value of 50 runs using the same noise level and time sampling but with a different random noise

between the ERS-scat surface soil moisture product and the averaged surface soil moisture values obtained with the ISBA-A-gs model over the 1600 pixels. The RMS error was found to be equal to $0.061 \text{ m}^3 \text{ m}^{-3}$, which is larger than the expected SMOS accuracy over crop fields ($0.04 \text{ m}^3 \text{ m}^{-3}$) but can be considered as an acceptable accuracy. The root-zone soil moisture product based on a semi-empirical modelling approach proposed by Wagner *et al.* [1999b] was analysed. The accuracy of the methodology was found to be dependant on the time sampling mode, the error on the surface soil moisture estimates and the presence of frozen soil conditions. First, it was shown that an irregular time sampling mode may leads to lower SWI retrieval accuracy than a regular time sampling mode (considering an identical number of surface soil moisture measurements during a 4-year period). Second, a sensitivity study described quantitatively the effect of the surface soil moisture noise level on the root-zone soil moisture estimates. Third, the effect of frozen soil was shown to be a potential source of erroneous root-zone soil moisture retrievals. The Wagner's methodology should be used together with a soil freezing detection procedure in order to not take into account frozen surface soil moisture estimates in the retrieval algorithm.

This study pointed out the potential of scatterometer measurements for soil moisture monitoring as well as Wagner's methodology for root-zone soil moisture estimates. In the near future, the regular 2-day time sampling of the METOP-ASCAT Mission (ESA, launch in July, 2006) and the 2-day time sampling of the SMOS Mission (ESA, launch in September 2007) should provide better root-zone soil moisture products (efficiency score equal to 0.65 for a RMS error equal to $0.04 \text{ m}^3 \cdot \text{m}^{-3}$ in our simulations).

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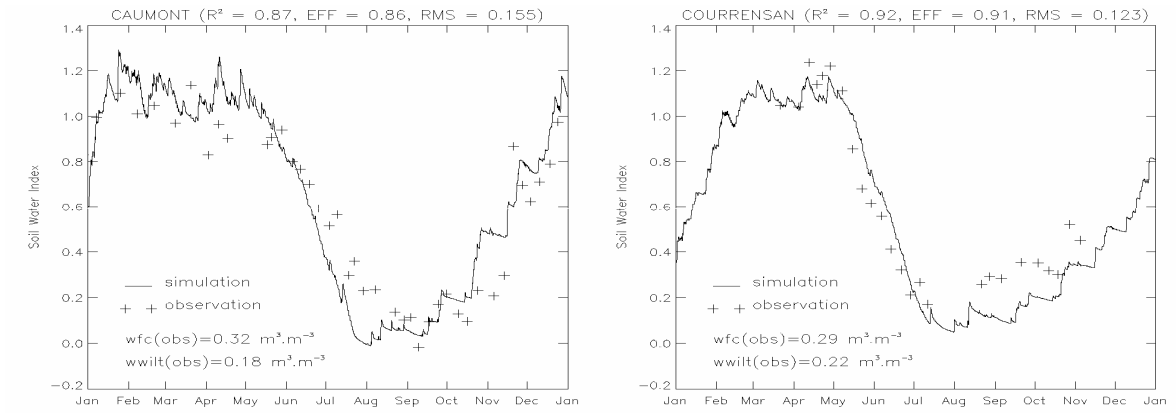


Figure 1: Soil Wetness Index (SWeI) observed by neutron soundings (+) and simulated over the corresponding grid-cell of Caumont and Courrensan (-) during 1986.

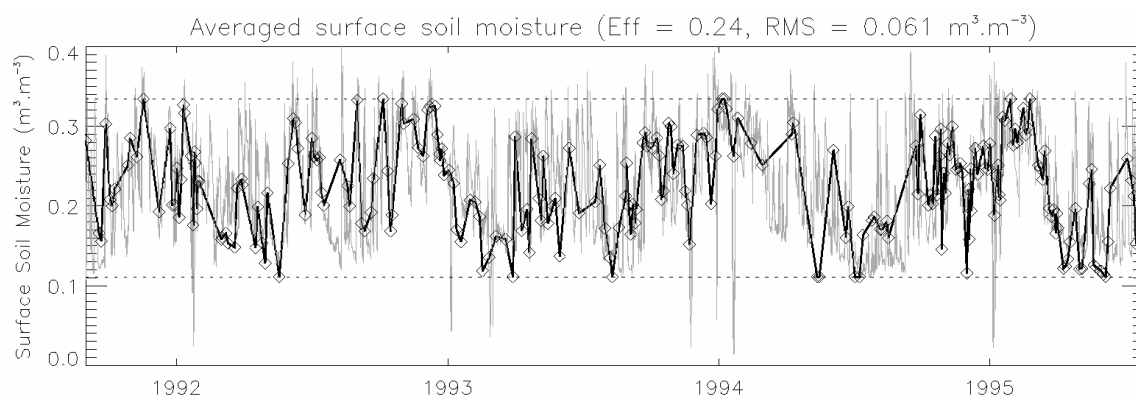


Figure 2: ISBA simulated surface soil moisture time-series averaged over the 1600 pixels (grey curve) and ERS scatterometer-derived surface soil moisture from August 1991 to July 1995 (diamonds and black curve). The variation range of ERS-scat surface soil moisture measurements has been delimited using 90% confidence interval values (dotted line) of ISBA-A-gs simulation.

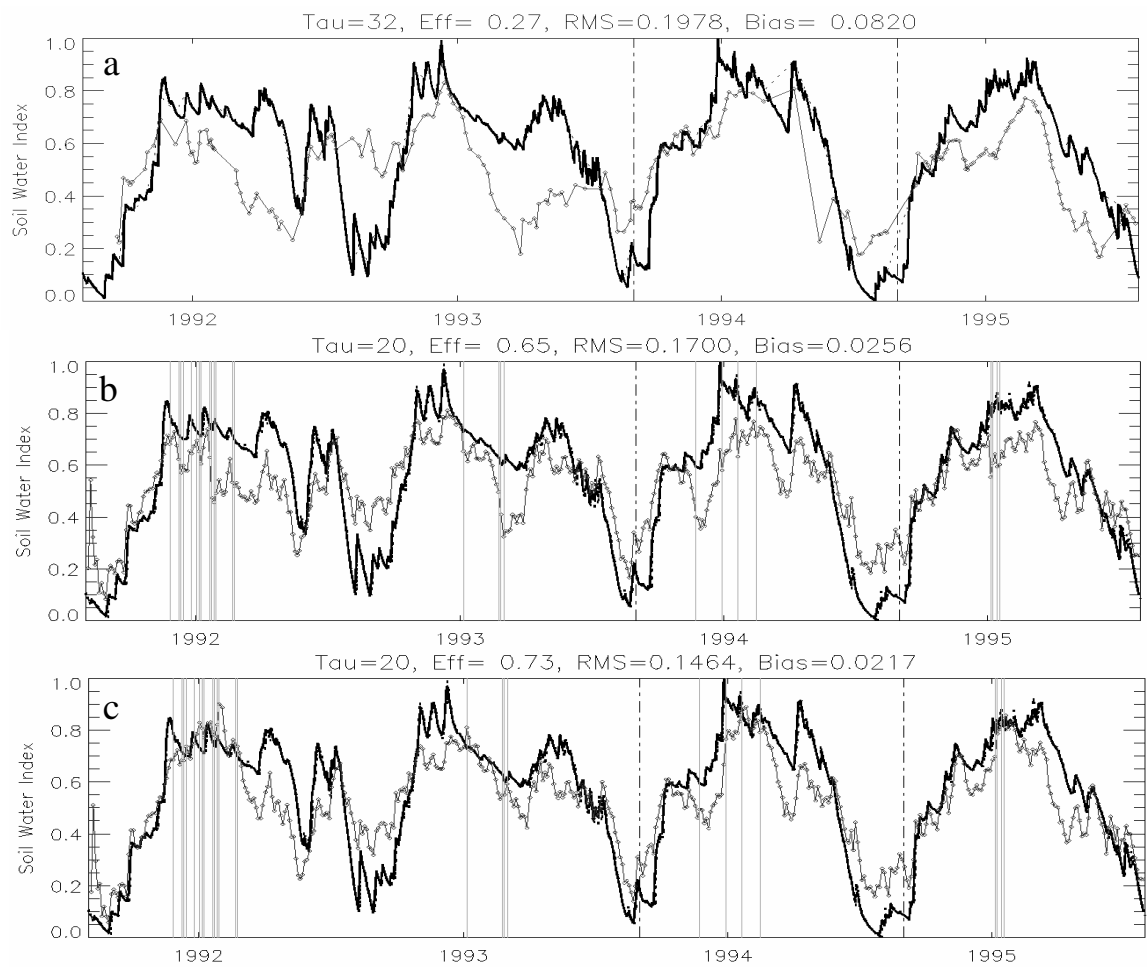


Figure 3: (a) Reference Soil Water Index (black curve) and SWI estimate (diamonds grey curve) based on ERS-scat surface soil moisture measurements and (Eq.3). The T parameter of (Eq.3) was optimized ($T = 32$ d). (b) SWI estimate (diamonds curve) obtained by using the ISBA-A-gs' simulated surface soil moisture noised with a Gaussian noise level of $0.04 \text{ m}^3 \text{ m}^{-3}$ and one value every 3 day (10h30 am). The T parameter of (Eq.3) was optimized ($T = 20$ d). Vertical grey solid lines correspond to soil freezing days. (c) Same as (b) but using the addition of iced and liquid part of surface soil moisture provided by ISBA-A-gs as input of Eq. 3.

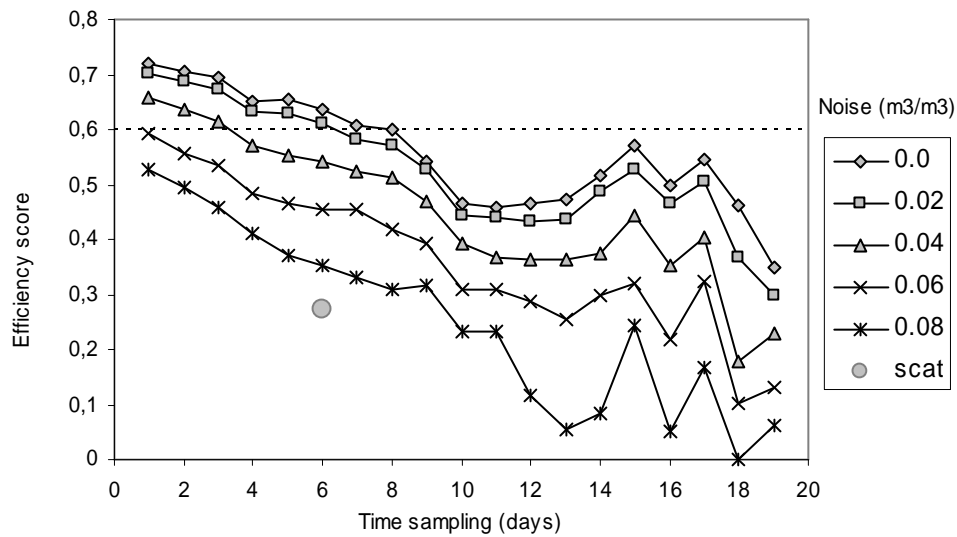


Figure 4: Time sampling and noise level effect on the retrieved root-zone soil moisture in terms of efficiency. The root-zone soil moisture retrieval using ERS-scat measurements is plotted with a closed circle (efficiency=0.27) and assumed to be a 6-day time sampling (240 measurements during 4 years corresponds to 1 measurement every 6 days in average).