Mapping surface soil moisture over the Gourma mesoscale site (Mali) by using ENVISAT ASAR data.

Authors: F. Baup, E. Mougin, P. de Rosnay, P. Hiernaux, F. Frappart, P.L. Frison and M. Zribi, J. Viarre

Response to the reviewers'#2 comments

Major comments:

1) The aims of the present study are:
- to generalize a recently proposed method for surface soil moisture monitoring in sandy soils (Baup et al., 2007) of the Sahel to soil erosion (gravelly and rocky) surfaces, . Both surfaces account for more than 90% of the considered region. We use data collected at a second sandy site and a rocky site in the same region in Mali.
- to generate SSM maps at meso-scale (1 x 3°) by using a soil map.
- to evaluate the validity of the generated soil moisture maps at meso-scale with relevant and available SSM products (Zribi et al., 2008) and rainfall maps (Bergès and Chopin, 2004).

These objectives have been clarified in the proposed paper in the introduction and conclusion sections. Novelties since the last publication have also been highlighted since the last publication.

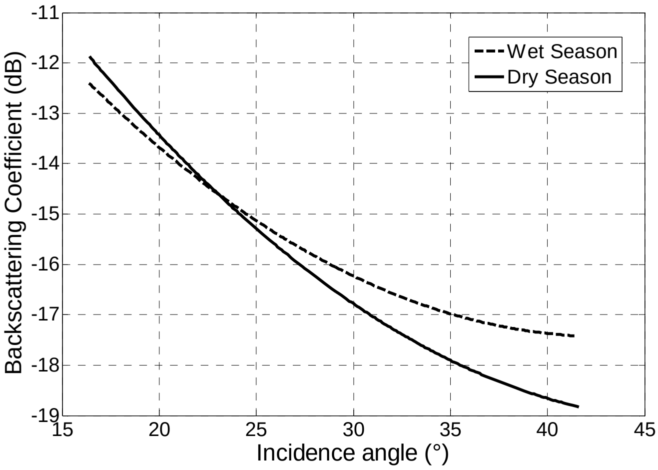
2) Using LAI instead of NDVI to account for the effect vegetation does not improve significantly the SSM estimates. So, we chose to keep the more robust method for this paper, to reduce uncertainties due to vegetation effects and to estimate the better soil moisture maps as possible. This method allows to take into account1) the strong spatial heterogeneities of the vegetation cover, 2) the inter-annual variations of the vegetation cover (correction of the vegetation effects will be more relevant for wet years).
For dry years, similar soil moisture maps would be obtained without taking into account the vegetation, with a 0.1% lower precision as mentioned in Baup et al., 2007 (RSE).

A sentence has been inserted in the section 2.4 to clarify this point:

"Despite a low vegetation cover in this semi-arid region, a vegetation correction is applied to better take into account 1) the strong spatial heterogeneities of the vegetation cover, 2) the inter-annual variations of the vegetation cover. Particularly, this correction is relevant for wet years for which the vegetation cover is well developed."

3)

a) This method allows taking into account the seasonal vegetation effect on the angular variation of the backscattered coefficient. In this case, two normalization functions depending on the season are used. For the dry season (from January to May and from October to December), which is when the green vegetation cover is small or absent. For the wet season, a simple normalization function is built by considering all of the ASAR data recorded at the date of maximum green vegetation cover. The following figure illustrates the angular dependency of the radar signal during the dry (no vegetation) and the wet seasons (maximum of vegetation). The wet regression is estimated from a radar image acquired in September (DoY 248), when soil surface is getting drier and green vegetation is closed to its maximum (DoY 232). The resulting angular functions show that the effect of the vegetation layer has to be taken into account in the normalization procedure.



Angular variations of the HH backscattering coefficient during the dry and wet seasons for the sand dune landscape estimated for the 2005 dry period and on DoY 248.

This angular normalisation function has been presented in previous papers (see Baup et al., 2007a and b). So, we simply add a short description of the normalisation method in the proposed paper.

b) The term "change detection" is not exact and leads to confusion. Accordingly, it has been removed from the text. The method consists of using an image acquired during the dry season as reference for soil roughness state. Then, we calculate the difference between the reference image and the image of interest (IOI) acquired during the wet season (figure 5). Radar changes are thus attributed to soil moisture change or vegetation cover since soil roughness is considered constant in time during the wet season (checked by in-situ measurements (see Table 3)).

c) Coefficients of the linear empirical functions are given in Table 4.

This point has been underlined in the text as follow:
"Finally, *SSM* maps are estimated at kilometric scale from the difference between dry images acquired respectively between the dry and the wet seasons over the mesoscale window by applying empirical inversion functions estimated for sandy and rocky soils. Coefficients of these linear functions are given in Table 4."

A new figure was added showing the relationships between the backscattering coefficient and the surface soil moisture for the three sites under consideration, i.e. the two sandy sites and the rocky site. In addition, the general regression function used for sandy sites has also been added.

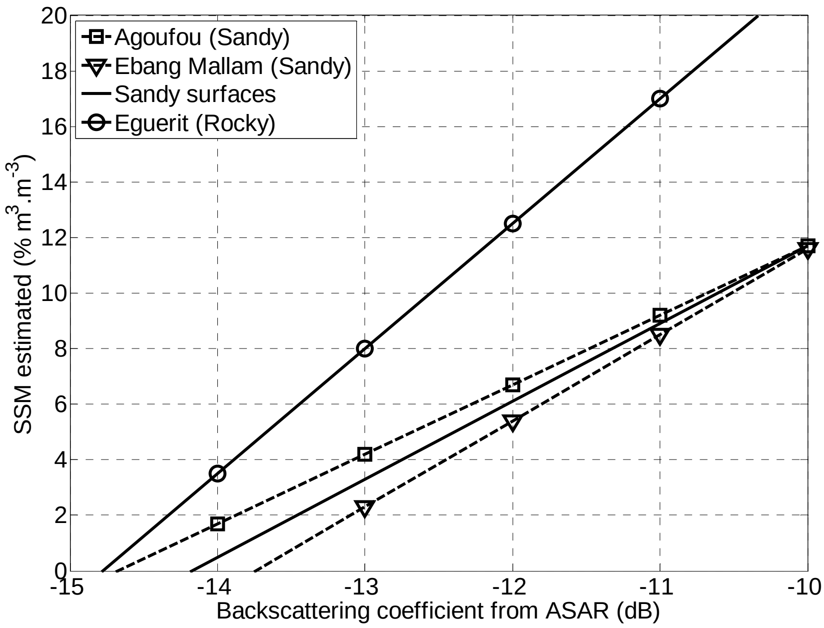


Fig 7: Backscattering coefficient– Surface Soil Moisture regression functions estimated over the two sandy sites and the rocky site. The final regression function used over sandy surfaces is also plotted.

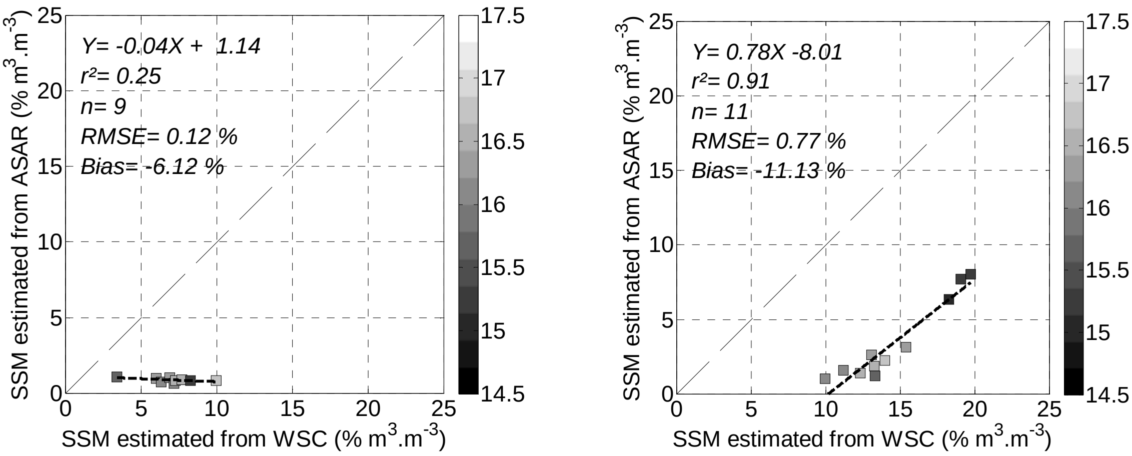
4) As mentioned by the reviewer, in Baup et al. (2007), already proposed a method to up-scale surface soil moisture at 1 km scale over sandy soils. The purpose of the present study is to generalize the approach over the 2 main types of soils present in the Malian mesoscale site (sandy and rocky surfaces accounting for more than 90% of the area). This is the reason why we use a texture map in opposition to the 2007 paper. The inverted SSM are then evaluated by using independent and relevant data (same antenna frequency and different satellite) that were not available in 2007 (Zribi et al., 2008). The paper also shows better potentialities to monitor fine SSM heterogeneity than browse modes like the global monitoring mode (more often used in global mapping of surface soil moisture: Wagner et al., 2008, Pathe et al., 2009, Mladenova et al., 2010…).

The objectives of the present paper have been thus rewritten in accordance with the reviewer's comment to clarify the aims of the present paper (see answer 1).

5) We add the following sentences at the beginning of the section 2.2.
"The ground data section 2.2 is divided in 3 sub-sections:
- 2.2.1: Surface soil moisture measurements
- 2.2.2: Rainfall measurements
- 2.2.3: Soil map

To improve the clarity of the manuscript, the following sentence has been inserted at the beginning of this section:
"This section presents the available ground data collected in 2005 for the processing and the evaluation of the SSM maps. Three different datasets are described: Surface Soil Moisture (SSM), rainfall and soil types"

6) In accordance with the reviewer's comments, the Bamba site has been removed from the analyses due to an insufficiently number of data .
In addition, we add the rms error and the bias in figure 11 for best analyses.



The section 4 has been modified, and comments on figure 11 have been completely rewritten as follow:

"Dry and wet periods are separated in the analysis to better discriminate between noise and changes related to SSM. During the dry season characterised by no rainfall event, WSC-derived *SSM*, ranging between 3% and 10%, is obviously overestimated, as already mentioned by Gruhier et al. (2010) (Fig. 11a). The observed bias of 6% between ASAR SSM and WSC SSM also confirms this overestimation. The highest *SSM* values are located in the Northern part of the site where the WSC signal is mainly affected by the Niger River and its vegetation. The initial offset of 3% is explained by the inversion method initially developed over slightly wetter surfaces (see Zribi et al., 2008). In contrast, ASAR-derived *SSM* show a higher stability with only 2% of dynamic range and an offset of about 1%.

Results obtained for the rainy season indicate a high correlation ($r^2=0.91$) between the two datasets with a low rms error (0.77%) despite the small number of considered samples ($n = 11$) which results from both the small number of available ASAR images and the small size of the Gourma site compared to the WSC product (at the resolution of 25km). The 11% bias observed during the wet season is consistent with results shown in Gruhier et al. (2010 confirming the general overestimation trend of ERS/WSC *SSM* products."

For example, the 3 following figures, taken from Gruhier et al. (2010), represent the comparison between ERS/CETP *SSM* products (similar products are used in our study but not the same data) and ground soil moisture measured over three local tests sites.

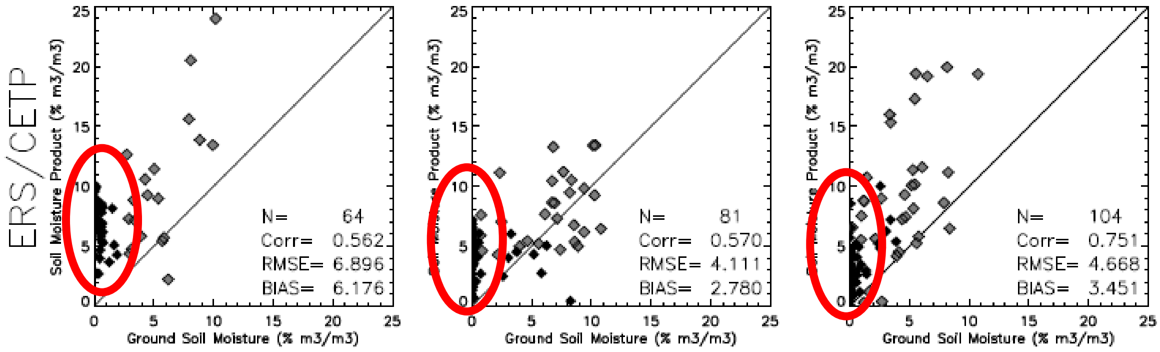


Fig. 11. Soil moisture from products versus from ground measurements. Black points correspond to dry seasons (October to June) and grey points to monsoon seasons (July-August-September). Statistical results shown are calculated during two years period.

Red circles underline the high variability of estimated SSM for dry surfaces (as observed in the present study). The overestimation

Gruhier C., de Rosnay P., Hasenauer S., Holmes T., de Jeu R., Kerr Y., Mougin E., Njoku E., Timouk F.,Wagner W., and Zribi M. Soil moisture active and passive microwave products: intercomparison and evaluation over a Sahelian site, Hydrology and Earth System Science, 14, 141-156,2010.

Minor comments:

1) As indicated by the reviewer, the Global Monitoring mode, not described in the present paper, offers a significantly better temporal resolution at a moderate spatial resolution (about 1km). Nevertheless, high noise levels present in the 1 km data are associated with the use of the considered mode (Pathe et al., 2009, Mladenova et al., 2010). Table I shows a summary of performances of the ENVISAT ASAR antenna. The radiometric accuracy and stability are lower in GM mode than in WS mode (Table I) and the effective number of looks is also lower (7 instead of 13). Moreover, spatial analyses can not be performed at the pixel size like with optical data (due to speckle effects).

As demonstrated by Baup et al., 2007b, the GM mode is more appropriate for global analyses of continental areas than for studying local variation of SSM at kilometric scale.

Parameter	Unit	IM Mode	WS Mode	GM Mode	ERS-1/2
Polarization		VV or HH	VV or HH	VV or HH	VV
Spatial resolution	m	27.5x28.1	149x145	949x977	27.5x28.1
Radiometric resolution	dB	1.54	1.45 to 1.72	1.35 to 1.44	2.07
Radiometric Accuracy (1 σ)	dB	0.39 to 0.46	0.40 to 0.48	0.51 to 0.58	n/a
Radiometric stability (1 σ)	dB	0.32 to 0.40	0.32 to 0.42	0.46 to 0.53	0.24/0.27
Noise equivalent σ_n^0	dB	-19.6 to -22.1	-20.9 to -26.2	-31.5 to -35.0	-26.2 to -25.2
Effective number of looks		~4	~13	~7	~3

Table I: Summary of ASAR and ERS performances (taken from Baup et al., 2007)

Baup, F., Mougin, E., Hiernaux, P., Lopes, A., De Rosnay, P., Chênerie, I.: Radar signatures of Sahelian surfaces in Mali using ENVISAT-ASAR data. IEEE Transaction on Geoscience and Remote Sensing 45, 2354-2363, 2007b.

Pathe, C., Wagner, W., Sabel, D., Doubkova, M., & Basara, J.B.: Using ENVISAT ASAR Global Mode for surface soil moisture retrieval over Oklahoma, USA. IEEE Transaction on geoscience and remote sensing, 47, 468-480, 2009.

Mladenova, I., Lakshmi, V., Walker, J.P., Panciera, R., Wagner, W., & Doubkova, M.. Validation of the ASAR Global Monitoring Mode Soil Moisture Product Using the NAFE'O5 Data Set. IEEE Transaction on geoscience and remote sensing, 48, 2498-2508, 2010.

To improve the clarity of the manuscript, a sentence has been added in the Introduction section:
"The "Global Monitoring" mode is more suitable for analyses at a lower spatial resolution than the kilometric scale (e.g. Baup et al., 2007b; Pathe et al., 2009, Mladenova et al., 2010)."

2) The sentence has been rephrased as follows:
"Indeed, the influence of the green vegetation can be either neglected or simply taken into account at low incidence angles and for low vegetation density (Leaf Area Index –LAI- $<2m^2.m^{-2}$) as proposed in Tansey et al., 1999 and Moran et al., 2000."

3) The sentence has been rephrased as follows: "At such the 1km scale and for this coverage (1° by 3°), the evaluation of *SSM* maps is a difficult exercise since no direct comparison is possible with *SSM* ground data. Here, the ASAR *SSM* maps are thus interpreted with the help of…"

4) The bias in the Mehrez et al's products originate from the method used to derive soil moisture. This method is based on the largest difference between maximum and minimum bascattering values that are observed in the temporal series. As minimum values in WSC data are not observed during the dry season but at the beginning of the rainy season (see e.g. Frison et al., 1996; Jarlan et al., 2002; Zine et al., 2005), SSM derived values are overestimated during the dry period.

Frison, P.L. and Mougin, E., 1996. Use of the ERS-1 Wind scatterometer data over land surfaces. IEEE Transaction on geoscience and remote sensing, No 2, 34: 550-560.

Jarlan, L., Mougin, E., Frison, P.L., Mazzega, P. and Hiernaux, P., 2002. Analysis of ERS wind scatterometter time series over Sahel (Mali). Remote Sensing of Environment, 81: 404-415.

Zine, S., Jarlan, L., Frison, P.L., Hiernaux, P. and Rudant, J.P., 2005. Land surface parameter monitoring with ERS scatterometer data over the Sahel: A comparison between agro-pastoral and pastoral areas. Remote Sensing of Environment, 96: 438-452.

5) A comment has been added in the conclusion section on the future SENTINEL mission, underlying the interest of the high temporal sampling:

"In the near future, with the launch of the Sentinel satellites, the temporal resolution of SAR images will significantly increase (<6 days, depending on the latitude) and become more suitable for monitoring the high dynamics of the *SSM*, especially over arid or semi-arid areas.”