Inversion of Surface Soil Moisture from Radar Altimetry Backscattering in Semi-Arid Environments

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INVERSION OF SURFACE SOIL MOISTURE FROM RADAR ALTIMETRY BACKSCATTERING IN SEMI-ARID ENVIRONMENTS

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ABSTRACT

Surface Soil Moisture (SSM) is a key parameter of water and energy balances in semi-arid areas. SSM is linearly related to the radar backscattering coefficients (σ_0) over sand. Linear relationships are commonly used for inverting SSM in semi-arid areas from SAR and scatterometer data. Recent studies demonstrated that SSM can also be inversed from radar altimetry backscattering. An inversion method combining radar altimetry σ_0 and land surface model (LSM) outputs is proposed here.

Index Terms— Soil moisture, backscattering, radar altimetry

1. INTRODUCTION

Data from radar sensors on-board satellites, mostly SAR and scatterometers, are commonly used to monitor changes in land cover, vegetation density, SSM or flood extent (e.g., [1]–[4] over West and Central Africa). Recently, σ_0 from radar altimetry demonstrated a strong potential for the monitoring of land surface properties.

Radar altimetry backscattering coefficients acquired over West Africa (between 0° and 25°N and 5°W - 25°E) at S, C, Ku and Ka bands using nadir-looking altimeters were analyzed over the major bioclimatic zones, soil and vegetation types encountered in this region was performed [5], [6]. The analysis of the backscattering coefficients acquired by Topex/Poseidon at Ku-band showed their decrease as vegetation in Sahel increases [7]. SSM in a semi-arid area was first retrieved using ENVISAT RA-2 backscattering coefficients over Sahelian savannahs in the Gourma region of Mali [8]. High correlations between σ_0 acquired at Ka-band by SARAL were also observed in West Africa [6]. The impact of soil moisture on radar altimetry waveforms at Ku and Ka bands was estimated through an electro-magnetic modeling study [9]. An inversion method of SSM using σ_0 from radar altimetry was implemented and tested over several semi-arid sites in Australia [10].

In this study, an inversion approach of SSM from radar altimetry backscattering coefficients is proposed using SSM from ORCHIDEE LSM. Comparisons against in situ measurements from several sites in West Africa (Mali and Senegal are performed).

2. DATASETS

2.1. Altimetry data

The radar altimetry data used in this study were acquired by ERS-2, ENVISAT, Jason-1 and 2 and SARAL. Altimetry data used in this study consist of high frequency measurements, sampled at 18 to 40 Hz depending on the mission, of the acquisition time and geographical location (longitude and latitude) as well as the backscattering coefficient at Ku-band for all the missions except SARAL and at Ka-band for SARAL. Backscattering coefficients are derived from the Offset Center of Gravity (OCOG) or Ice-1 retracking algorithm following earlier studies [5], [6], [8], [10] present in the Geophysical Data Records from the space agencies for all the missions except ERS-2 and from the reatrcking performed by Centre de Topographie des Océans et de l'Hydrosphère (CTOH) for ERS-2 [11]. They were made available by CTOH: http://ctoh.legos.obs-mip.fr.

2.2. ORCHIDEE model outputs

The Organizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) is a LSM that describes soil temperature and vertical water transport dynamics and that also includes a a river routing scheme including floodplains coupled to simulated grid-cell runoff as well as a carbon cycle model [12]. In this study, soil moisture (SM) outputs were used in the inversion method presented in 3. Methods. These outputs are available from 2000 to 2010 at a spatial resolution of 0.5° and a temporal resolution of one day.

2.3. Global surface water data

The Global Surface Water dataset information on surface water extent over all land surfaces at a spatial resolution of 30 m based on Landsat images acquired since 1985 [13]. It is made available by the Joint Research Center (JRC - https://global-surface-water.appspot.com/download).

2.3. Soil map

The Harmonized World Soil Database v 1.2 provides the composition in terms of soil units and the characterization of selected soil parameters (organic Carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry) at a spatial resolution of 30'' [14]. It result of a collaboration between the FAO with IIASA, ISRIC-World Soil Information, Institute of Soil Science, Chinese Academy of Sciences (ISSCAS), and the Joint Research Centre of the European Commission (JRC).

2.5. In situ soil moisture data

In situ soil moisture data, acquired in the framework of the African Monsoon Multi-scale Analysis (AMMA – CATCH – http://www.amma-catch.org)) in Mali [15], were used for the validation of the altimetry-based SSM product.

3. STUDY AREA AND METHODS

Over semi-arid sandy areas, SSM is linearly related to the radar backscattering coefficient [2]:

$$SSM(\lambda,\varphi,t) = a\,(\sigma_0(\lambda,\varphi,t) - \sigma_0^{dry}(\lambda,\varphi)) + b \qquad (1)$$

where σ_0^{dry} is the backscattering coefficient for dry soil surface conditions, λ, φ, t are respectively the longitude, latitude and time of measurement, a and b are two constant terms.

3.1. Study area

The study area where the approach is tested is the Gourma region in Mali. The Gourma region (14.5–17.5°N and 1–2°W), is a vast peneplain at between 250 and 330 m altitude [15]. In this region, the mean annual rainfall varies between 150 and 400 mm from north to south with interannual variations ranging between 15 and 30% of the annual rainfall. Rainfall occurs during the northern hemisphere summer, starting between May and July until September or October with a maximum in August [16].

3.2. Selection of the valid altimetry data

SSM and radar altimetry are linearly related over sandy areas. Altimetry data are considered valid when the soil type in the altimeter footprint (in a disk of 5 km of radius) is composed of more than 90% of sand. The presence of open water in the altimetry footprint strongly dominates the surface response [9]. As already observed in [8], the altimetry backscattering coefficients cannot be used for SSM retrieving when open waters are present in the altimetry footprint. Backscattering coefficients are filtered out when open water from [13] are found in the altimeter footprint (in a disk of 5 km of radius).

3.3. Inversion of the valid altimetry data

The inversion approach to retrieve SSM from σ_0 is based on generalized least squares criteria [17]. The solution is a linear combination of the radar altimetry backscattering coefficients, of the a priori information from ORCHIDEE SSM estimates and optimal coefficients fitting.

$$SSM = SSM_0 + CG(C_D + C_M + GCG^T)(\sigma_0 - GSSM_0) \qquad (2)$$

where SSM_0 is the initial solution from ORCHIDEE, C is the covariance obtained minimizing the prediction error, C_D and C_M are the are the a priori covariances from the altimeter observations and from the model and G is the kernel linking parameters to data.

The a posteriori covariance matrix C^P obtained after solving the linear system is defined as:

$$C^P = C - CG^T(GCG^T + C_D + C_M)^{-1}GC \qquad (3)$$

The a posteriori uncertainties associated to the fitted SSM are given by the root-mean square of the diagonal elements of C^P:

$$\sigma^P = (diag(C^P))^{-1/2} \qquad (4)$$

The inversion will be performed using all the valid altimetry data present in a model cell at time t. The spatial resolution of the altimetry data is a couple of hundred meters along the track whereas the model cell is 0.5°. Valid altimetry data corresponds to data acquired over sand surfaces with no inland water present in the altimeter footprint based on the open water mask defined using the Global Water Data product.

4. RESULTS

In the Gourma region (14.5 – 17.5° N), once the different selection criteria were applied (sandy soils and no open water in the altimeter footprint), the following altimetry data along ERS-2/ENVISAT/SARAL ground-track 0302 were considered (Fig. 1).

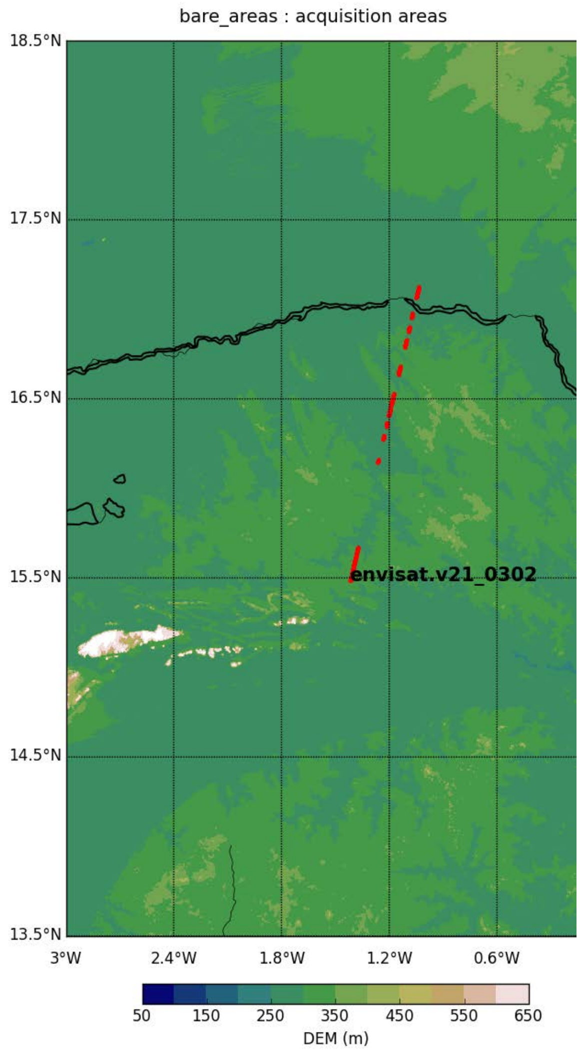

Fig. 1. Locations of the selected altimetry data along ERS-2/ENVISAT/SARAL ground-track 0302 in the Gourma region of Mali.

Backscattering coefficients exhibit annual variations between 10 and 32 dB whereas SSM values range from 5 to 25%. Maxima are observed during the rainy season, from June to September. Using these measurements, a linear regression was applied between ENVISAT altimetry backscattering coefficients (Ice-1) and soil moisture outputs from ORCHIDEE LSM (Layer-2c) over the period 2002-2009. The results are presented in Fig. 2. They show an overall good agreement with a R^2 of 0.71. Due to the coarse spatial resolution of the LSM grid step, plateaus are cearly visible at 5% of SSM for backscattering values between 10 and 15 dB, at 8% for backscattering values between 15 and 25 dB, and at 9% for backscattering values between 15 and 20 dB.

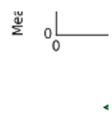

Fig. 2. Scatterplot between ENVISAT-RA-2 backscattering coefficients (Ice-1) and SSM from ORCHIDEE.

5. CONCLUSION

A good correlation was observed between radar altimetry coefficients and SSM from ORCHIDEE LSM over sandy areas without open water (temporary and permanent ponds) in the Gourma region of Mali (R^2=0.71) in spite of the difference of spatial resolution between the two datasets.

A method for inverting SSM from radar altimetry backscattering coefficients was developped. This method will be applied to backscattering coefficients from ERS-2 (1995-2003) and ENVISAT (2003-2010) ground-track 302 in the Sahelien Gourma region of Mali and from Jason-2 (2008-2016) ground-tracks 46 and 161 and SARAL (2013-2016) ground-tracks 1 and 846 in the Sahelian Ferlo region of Senegal.

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