Bare soil moisture retrieval from multi-temporal X-band TerraSAR-X SAR images

A. Gorrab, M. Zribi, N. Baghdadi, Z. Lili-Chabaane

BARE SOIL MOISTURE RETRIEVAL FROM MULTI-TEMPORAL X-BAND TERRASAR-X SAR IMAGES

Azza Gorrab[1-2], Mehrez Zribi[1], Nicolas Baghdadi[3] and Zohra Lili Chabaane[2]

1- CESBIO (CNRS/UPS/IRD/CNES), 18 av. Edouard Belin, bpi 2801, 31401 Toulouse cedex 9, France
2- University of Carthage/INAT, 43 av. Charles Nicolle 1082, Tunis, Mahrajène Tunisie
3-IRSTEA, UMR TETIS, 500 rue François Breton, 34093 Montpellier cedex 5, France

ABSTRACT

The aim of the present study is to analyze the sensitivity of X-band SAR (TerraSAR-X) signals as a function of different physical bare soil parameters (soil moisture, soil roughness), and to evaluate the accuracy of change detection approach proposed for soil moisture estimation. Firstly, we presented a brief description of our ground and satellite database. Secondly, we considered the main results of our statistical analysis of the relationships between radar and soil parameters: soil moisture and different roughness parameters (the rms height, Zs parameter, and a new roughness parameter Zg. Finally, we proposed an algorithm combing multi-temporal X-band SAR images (TerraSAR-X) with different continuous thetaprobe measurements for the retrieval of surface soil moisture at a high spatial resolution.

Index Terms— Soil moisture mapping, change detection, TerraSAR-X, Roughness

1. INTRODUCTION

Surface soil parameters retrieval with meter-scale spatial resolution is essential for multi- domains particularly hydrology and agronomy. It allows water resources and irrigation management decisions and validation of multi-hydrological water balance models. Soil properties are characterized by a very high spatial and temporal variability. Conventional soil moisture and roughness measurement methods, as gravimetric, time-domain reflectometry (TDR), and pine profiler, are not sufficient to describe their variability. Besides, these methods consume generally much time and may disturb the soil structure. In the last years, several researches based on imaging active microwave data have demonstrated the potential of synthetic-aperture radar (SAR) sensors, mainly from C frequency band, to measure and monitor effectively soil surface characteristics with meter-scale resolution [1,2]. Over bare agricultural areas, backscattered radar signal is very sensitive to physical soil characteristics particularly roughness and soil water content [3]. However, the accuracy of the soil moisture estimation is affected by the influence of surface roughness parameter on backscattered radar signals [4]. Consequently, different empirical, semi empirical and physical approaches are developed for bare soil conditions, to estimate accurately spatial soil moisture variability.

In this context, we propose a methodology using X-band SAR “TerraSAR-X” data for the estimation of surface soil moisture at a high spatial resolution. Our analysis is based on seven radar images acquired at a 36° incidence angle in the HH polarization, over a semi-arid site in Tunisia (North Africa). The soil moisture estimations are based on an empirical change detection approach using TerraSAR-X data and ground auxiliary thetaprobe network measurements. We considered two assumptions: (1) roughness variations during the three-month radar acquisition campaigns were not considered; (2) a simple correction for temporal variations in roughness was included. Our soil moisture retrieval algorithm was validated on the basis of comparisons between estimated and in situ soil moisture measurements over test fields.

2. DATABASE DESCRIPTION

2.1. Study site and ground database

Our study site is situated in the Kairouan plain (9°23′−10°17′E, 35°1′−35°55′N, in central Tunisia. The climate in this region is semi-arid, with an average annual rainfall of approximately 300 mm/year, characterized by a rainy season lasting from October to May, with the two rainiest months being October and March. As is generally the case in semi-arid areas, the rainfall patterns in this area are highly variable over time and space. The mean temperature in Kairouan City is 19.2 °C (minimum of 10.7 °C in January and maximum of 28.6 °C in August). The mean annual potential evapotranspiration (Penman) is close to 1600 mm. The landscape is mainly flat. Between November 2013 and January 2014, ground campaigns were carried out at the same time as the seven satellite acquisitions. Fifteen bare soil reference fields were considered for soil moisture ground measurements, with different types of roughness ranging from smooth to ploughed surfaces. The ground measurements made on the test fields involved the characterization of the following soil parameters: soil moisture using a theta-probe instrument, soil roughness using a pin profiler, soil bulk density and soil texture. For each test field, approximately 20 handheld thetaprobe measurements were made at a depth of 5 cm. Over the studied site, in addition to the moisture measurements carried out in test fields, a network of seven continuous thetaprobe stations, installed in bare soil locations, and provided moisture measurements every 3 hours. At each station, the measurements were made at depths of 5 and 40 cm. The surface geometry was characterized by means of a 1 m long pin profiler with a resolution of 2 cm. Ten roughness profiles, five parallel and five perpendicular to the tillage row direction, were established in all reference fields during three different ground campaigns. Two main surface roughness parameters, the root mean square surface height (Hrms) and the correlation length (l), were determined from the mean correlation function, which was computed from the digitized soil profiles.

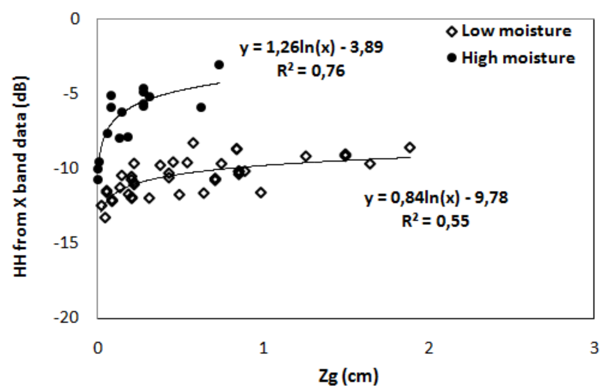
2.2. Satellite database

Seven TerraSAR-X images (X-Band ~ 9.65 GHz) were acquired (HH polarization, incidence angle of 36°). All of the images were acquired in the form of "Single Look Complex" products, with the TSX images produced in the Single Look Slant Range Complex (SSC) representation, having a ground pixel spacing of approximately 2 m. The SAR images were firstly multi-looked to reduce speckle using the NEST software (available at: https://earth.esa.int/web/nest/home/). For all images, five looks were used in the azimuth and range directions (resulting pixel size ~ 9 × 9 m^2). The images were then radiometrically calibrated to derive the backscattering coefficients σ0, and then geo-referenced using the SRTM 3Sec as a DEM (Auto download in NEST software). The mean radar signals were computed for each test field.

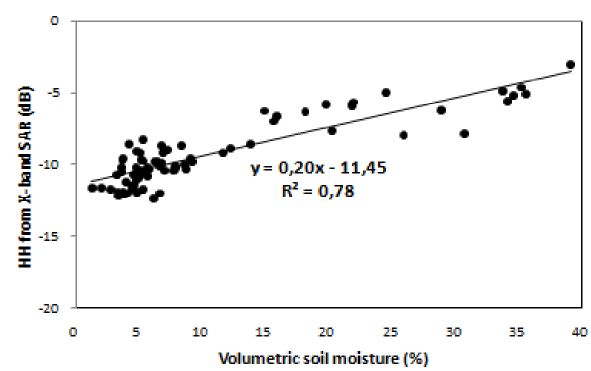
3. RESULTS AND DISCUSSIONS

3.1. Sensitivity of X-band TerraSAR-X signals to physical soil parameters

In this section, we presented the main results of our statistical analysis of the backscattering coefficient behavior as a function of volumetric soil moisture and various roughness parameters. Firstly, we analyzed the sensitivity of TerraSAR-X backscattering coefficients to three different roughness parameters: i) the root mean surface height Hrms, ii) the parameter $Zs = \mathrm{Hrms}^2 / l$ developed by [5] and iii) the parameter $Z_g = \mathrm{Hrms}\left(\mathrm{Hrms}/l\right)^{\alpha}$ introduced by [6] at different radar configuration (incidence angle and polarization). Results show a high sensitivity of the TerraSAR-X signal to all roughness parameters (Hrms, Zs and Zg). These relationships can be represented by a logarithmic function in which backscattering coefficient σ° increases clearly with increasing values of roughness parameters. The strongest correlation (R2=0.76) is obtained with the parameter Zg (figure 1.a). Then, we analyzed the sensitivity of TerraSAR-X signals as a function of volumetric soil moisture. A linear relationship is observed between radar backscattering coefficients and the in situ volumetric soil moisture. Several studies obtained this linear correlation [7,8]. Our results have revealed that the strongest correlation is obtained with gravimetric measurements with a coefficient of determination R^2 about 0.78 (figure 1.b).



a)



b)

Figure1. Relationships between TerraSAR-X signals and measured soil parameters in HH polarization: a) Zg roughness parameter and b) volumetric soil moisture.

Finally, we established a simple empirical expression relating the radar signal to the two surface soil characteristics: soil moisture (Mv) and surface roughness parameter (Zg):

$$\sigma^\circ = \alpha\ Mv + \beta \log(Zg) + \gamma \qquad (1)$$

By validating the proposed model, results have demonstrated an agreement between experimental radar dataset and simulated values using the proposed expressions with an RMSE about 1 dB and 0.94 dB in the HH and VV polarizations respectively (figure 2).

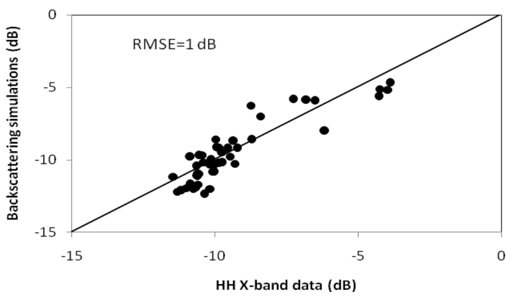


Figure 2. Validation of the empirical model used to simulate radar signal strength at 36° incidence, as a function of soil moisture and soil roughness for HH polarization.

3.2. Soil moisture estimation

In this section, we propose an approach based on the change detection method for the retrieval of surface soil moisture at a high spatial resolution. Our proposed algorithm combines multi-temporal X-band TerraSAR-X images (36°) with different continuous thetaprobe measurements. This approach takes advantage of the approximately linear dependence of radar backscattering signals (in decibels) on soil moisture [2, 7].

For each pair of successive images, we estimate the difference between the mean radar signals calculated for each of the entire radar images, over a bare soil mask. Our approaches are applied over bare soil class identified from an optical image SPOT / HRV image acquired in the same period of measurements. Results have shown linear relationship for the change in mean radar signals $\Delta\sigma^\circ$ (dB) as a function of the change in mean volumetric soil moisture Δmv(%) at image scale, with high sensitivity about 0.21 dB/vol% (figure 3).

It has been shown that the accuracy with which soil moisture can be retrieved by inverse backscattering models is affected by the influence of the surface roughness parameter on backscattered radar signals [4, 9]. When only one radar configuration is used (HH, 36° incidence angle), it is not possible to extract both soil moisture and roughness, without making additional assumptions.

Consequently, we considered, for estimation of change in soil moisture, two options: (1) On the first one, we applied the change detection approach between successive radar images ($\Delta\sigma^\circ$) assuming unchanged soil roughness effects; (2) on the second one, we considered a simple correction for temporal variations in roughness was included.

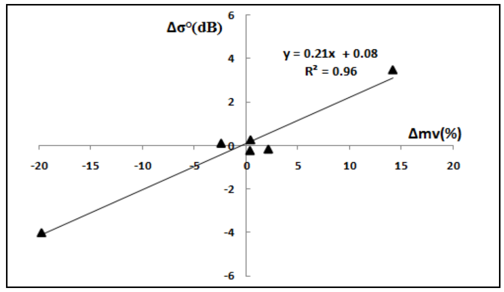
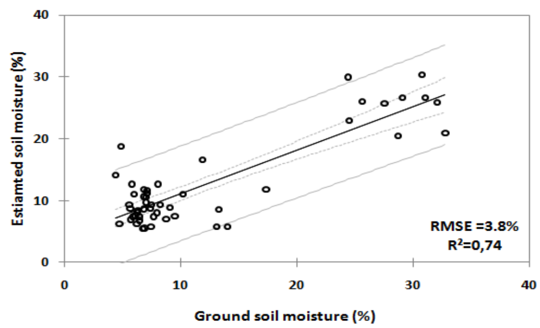
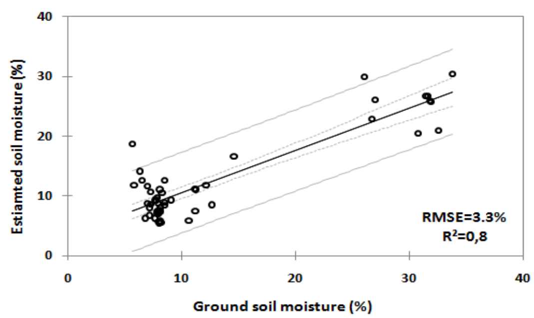


Figure3. Mean radar signal difference between two successive radar images (over bare soil) $\Delta\sigma^\circ$ (dB) as a function of moisture variations Δmv(%), applied for 7 successive radar images.

Our soil moisture retrieval algorithms were validated on the basis of comparisons between estimated and in situ soil moisture measurements over test fields. A very good agreement is found between the radar signal estimations and the ground measurements for both cases, with the RMSE equal to 3.8% and 3.3%, and the bias equal to 0.5% and 0.3%, respectively (figure 4). A small improvement in the accuracy of the soil moisture estimations is observed when roughness variations are taken into account.



a)



b)

Figure 4. Validation of the two proposed change detection approaches over 15 test fields (each point corresponds to one moisture condition in one test field): a) assuming no change in roughness, b) taking roughness changes into account.

4. CONCLUSIONS

In conclusion, logarithmic functions are observed between backscattering coefficients extracted from the TerraSAR-X sensor data and the surface roughness parameters: *Hrms* (root mean square height), *Zs* and *Zg*. roughness parameters: the rms height (Hrms), the Zs and the Zg parameters. The highest correlation (R^2=0.8) is obtained with Zg at 36° because its expression takes into account all the other roughness parameters (*Hrms*, correlation length and correlation function shape). A linear correlation is observed between the radar signals and the measured values of volumetric soil moisture. An empirical model is proposed to simulate radar signals as a function of soil moisture and the surface roughness parameter *Zg*. Validation of the proposed expressions with a second dataset reveals an excellent agreement between measurements and simulations, with an RMS error equal to 1 dB and 0.94 dB for the *HH* and *VV* polarizations, respectively.

For estimating soil moisture from TerraSAR-X data, we proposed a simple algorithm based on a change detection approach at the spatial resolution of the TerraSAR-X radar sensor, with auxiliary low-resolution estimates of soil moisture provided by a thetaprobe station network (7 points) installed on the studied site. We analyzed statistically the sensitivity between radar measurements and ground soil moisture derived from permanent thetaprobe stations. Our analyses are applied over bare soil class identified from an optical image SPOT / HRV acquired in the same period of the measurements. Results have shown linear relationship for the radar signals as a function of volumetric soil moisture with high sensitivity about 0.21 dB/vol%. A change detection methodology is proposed, by making two assumptions. The first of these considers only moisture variations during the studied period, and the second adds the influence of temporal changes in roughness on the variability of the soil moisture. In this case, it is assumed that variations in roughness make a linearly variable contribution to soil moisture over time. For the two considered approaches, the soil moisture estimations were validated using ground measurements acquired over fifteen test fields, under different moisture conditions. These comparisons lead to a volumetric moisture RMSE equal to 3.8% and 3.3%, and a bias equal to 0.5% and 0.3%, respectively. A small improvement in estimation accuracy is achieved with the approach using roughness corrections.

Acknowledgments

This study was funded by MISTRALS/SICMED, the ANR AMETHYST *(ANR-12 TMED-0006-01*) and TOSCA/CNES ASCAS project. We also wish to thank all of the technical teams of the IRD and INAT (Institut National Agronomique de Tunisie) for their strong collaboration and support in implementing the ground-truth measurements.

5. REFERENCES

[1] S. M. Moran, D.C. Hymer, J. Qi, E.E. Sano, Soil moisture evaluation using multi-temporal synthetic aperture radar (SAR) in semiarid rangeland. Agric. For. Meteorol. 105, 69–80, 2000. doi:10.1016/S0168-1923(00)00189-1

[2] A. Le Morvan, M. Zribi, N. Baghdadi, and A. Chanzy, “Soil moisture profile effect on radar signal measurement,” Sensors, vol. 8, pp. 256-270, 2008.

[3] N. Baghdadi, M. Zribi , C. Loumagne, P. Ansart, T.P. Anguela, “Analysis of TerraSAR-X data and their sensitivity to soil surface parameters over bare agricultural fields,”Remote Sens. Environ, vol. 112, pp. 4370-4379, 2008.

[4] H. Lievens, N.E.C. Verhoest, E. De Keyser, H. Vernieuwe, P. Matgen, J. Álvarez-Mozos, B. De Baets, “Effective roughness modelling as a tool for soil moisture retrieval from C- and L-band SAR,” Hydrology and Earth System Sciences. vol. 15, pp.151-162.2011.

[5] M. Zribi and M. Dechambre, “A new empirical model to retrieve soil moisture and roughness from Radar Data,”Remote Sens. Environ, vol. 84, pp. 42-52, 2003.

[6] M. Zribi, A. Gorrab, N. Baghdadi, “A new soil roughness parameter for the modelling of radar backscattering over bare soil,” Remote Sensing of Environment, vol.152, pp.62-73, 2014.

[7] S. Le Hégarat-mascle, M. Zribi, F. Alem, A. Weisse, C. Loumagne. Soil Moisture Estimation From ERS / SAR Data : Toward an Operational Methodology. East 40, 2647–2658, 2002.

[8] A. Gorrab, M. Zribi, N. Baghdadi, B. Mougenot, Z. Lili Chabaane. Potential of X-Band TerraSAR-X and COSMO-SkyMed SAR Data for the Assessment of Physical Soil Parameters. Remote Sens 7, 747–766, 2015.

[9] N.E.C. Verhoest, H. Lievens, W. Wagner, J. Álvarez-Mozos, M.S. Moran, F. Mattia, “On the soil roughness parameterization problem in soil moisture retrieval of bare surfaces from synthetic aperture radar”, Sensors. vol. 8, 4213–4248, 2008. doi:10.3390/s8074213