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Benoît Duchemin, Olivier Hagolle, Bernard Mougenot, Iskander Benhadj, R. Hadria, Vincent Simonneaux, J. Ezzahar, Joost Hoedjes, S. Khabba, M. H. Kharrou, et al.

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Agrometerological study of semi-arid areas: an experiment for analysing the potential of time series of FORMOSAT-2 images (Tensift-Marrakech plain)

B. DUCHEMIN†, O. HAGOLLE†, B. MOUGENOT†, I. BENHADJ†, R. HADRIA‡, V. SIMONNEAUX†‡, J. EZZAHAR‡, J. HOEDJES†, S. KHABBA‡, M. H. KHARROU§, G. BOULET†, G. DEDIEU†, S. ER-RAKI‡, R. ESCADAFAL†, A. OLIOSO¶ and A. G. CHEHBOUNI†

†CESBIO (UMR 5126 CNES-CNRS-UPS-IRD), 18 Avenue Edouard Belin, bpi 2801, 31401 Toulouse cedex 9, France

‡Faculté des Sciences Semlalia, Université Cadi Ayyad, Marrakech, Morocco

§ORMVAH—Office Régional de Mise en Valeur Agricole du Haouz, Marrakech, Morocco

¶INRA—Unité Climat, Sol, Environnement, Avignon, France

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Earth Observing Systems designed to provide both high spatial resolution (10 m) and high capacity of time revisit (a few days) offer strong opportunities for the management of agricultural water resources. The FORMOSAT-2 satellite is the first and only satellite with the ability to provide daily high-resolution images over a particular area with constant viewing angles. As part of the SudMed project, one of the first time series of FORMOSAT-2 images has been acquired over the semi-arid Tensift-Marrakech plain. Along with these acquisitions, an experimental data set has been collected to monitor land-cover/land-use, soil characteristics, vegetation dynamics and surface fluxes. This paper presents a first analysis of the potential of these data for agrometerological study of semi-arid areas.

1. Introduction

Irrigated agriculture makes a major contribution to food security, producing nearly 40% of food and agricultural commodities on 17% of cultivated lands (FAO 2002). However, serious water shortages occur in semi-arid areas as existing resources reach full exploitation. The design of tools for providing with land-cover/land-use as well as regional estimates of water balance and crop yield is necessary to ensure a sustainable development of these areas. This is one of the objectives of the SudMed project which focus on the Tensift basin as a pilot region (Chehbouni *et al.* 2005).

Effective management and monitoring of environmental resources require spatial data in order to integrate land-cover features as well as hydrological and vegetation parameters. Remote sensing may be the only feasible means of providing such information on a consistent space and time basis. Data acquired in the solar spectral domain have been the most intensively investigated in this context (e.g. Scotford and Miller 2005). Until now, they have been acquired either by high-resolution systems or by large field-of-view sensors. The former (Landsat-TM, SPOT-HRV …) provides data at a fine spatial resolution (10 m) but with moderate revisit capacities

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(around 15 days), so the possibility of temporal monitoring is limited. The latter (SPOT-VEGETATION, TERRA-MODIS …) observes the Earth on a daily basis but under a large range of viewing conditions (up to $\pm 55°$ off-nadir angles) and at a much coarser spatial resolution (250 m to 1 km). The use of low-spatial-resolution images is not trivial, since pixels generally include a mixture of different land classes.

Presently, the FORMOSAT-2 Taiwanese satellite is the only one able to acquire daily high-resolution images with constant viewing angles. In the perspective of the launch of others systems with similar characteristics such as GMES-Sentinel, RapidEye or Venµs, one of the first time series of FORMOSAT-2 images has been acquired over the Tensift-Marrakech plain. In this context, the objective of this letter is twofold:

- to describe the main characteristics of FORMOSAT-2 images and of the ground data that have been acquired along with these acquisitions;
- to present a preliminary—mainly qualitative—analysis of the potential of these data for land-cover mapping and agricultural water management.

2. FORMOSAT-2/Tensift experiment

2.1 *FORMOSAT-2/RSI Earth observing system*

FORMOSAT-2 has been launched by the National Space Organization of Taiwan (NSPO, http://www.nspo.org.tw/). It has been operational since May 2004 onto a Sun-synchronous orbit, with onboard the Remote Sensing Instrument (RSI). RSI provides high-spatial-resolution images (8 m in the multispectral mode for nadir viewing) in four narrow spectral bands ranging from 0.45 µm to 0.90 µm (blue, green, red, and near-infrared). Unlike other systems operating at high spatial resolution, FORMOSAT-2/RSI observes a particular area every day with the same viewing angle. However, it only surveys a part—about the half—of the Earth.

2.2 *Space–time characteristics and processing of Formosat-2 images acquired over the Tensift/Marrakech Plain*

The FORMOSAT-2/RSI images presented in this study have been collected from November 2005 to May 2006. The size of the scenes is 24 km along-track and 27 km cross-track, centred around 7°35′ W × 31°40′ N (figure 1). All images were acquired with an off-nadir angle of $18 \pm 1°$, viewing to the west across track. Given this viewing angle, the original pixel size is about 9 m in the cross-track direction and 8 m in the along-track direction. SPOT-Image has provided us with level 1A images. Images registration was performed using a three-step procedure: (1) absolute geolocation of the cloud-free image acquired December 2005 the 16th against a set of ground control points collected with GPS; (2) registration of this and other images using an autocorrelation algorithm; (3) resampling of data using Lambert North Morocco projection, with a sampling interval of 8 m.

The images were acquired with a nominal time step of 4 days, and about 50 images were collected during the 7-month period of interest (November to May). Twenty-six images were eliminated, most of them because they were contaminated by clouds, some others because ancillary data were unavailable for atmospheric correction. In this study, we kept only the images that were totally cloud-free, and the atmospheric correction was performed using the SMAC code (Rahman and Dedieu 1994). Atmospheric water vapour content and aerosol optical depth were collected using two CIMEL Sun photometers: the first was operational until June

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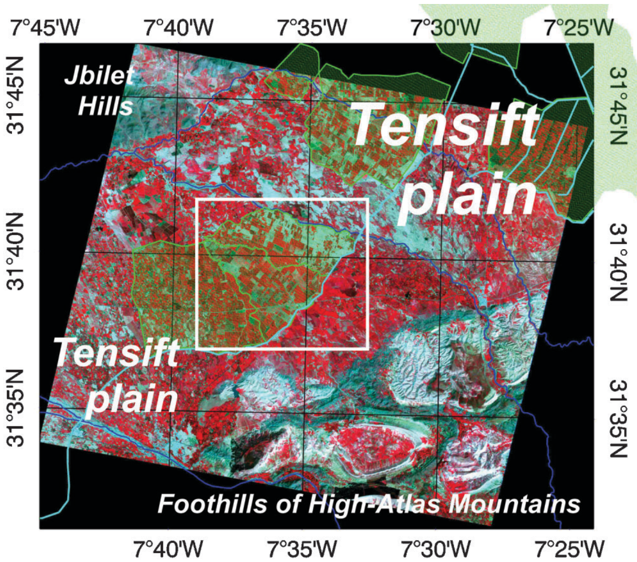

Figure 1. FORMOSAT image acquired 22 March 2006 (R ← near infrared; G ← green; B ← red). ORMVAH irrigated areas are depicted in green, with the main area of interest delimited by a white square. Most important irrigation channels and rivers are highlighted in cyan and blue, respectively.

2006 but located 50 km east from the region of interest, while the second was installed at the centre of the FORMOSAT-2 scene but only operational at the beginning of March. Some images could not be corrected for atmospheric effects (and thus rejected in this study) when there were clouds above the Sun photometers or in case of device failure. Finally, it should also be mentioned that some failures or conflicts in the programming occurred at the end of January, the beginning of February, and the beginning and end of April (see details in Duchemin *et al.* 2006a). Due to the programming conflicts and high cloudiness, no data are available between mid-January and the beginning of March.

Two perspectives have to be mentioned for improving the processing of FORMOSAT-2 images. First, cloud detection and temporal compositing algorithms will be tested, so the remaining partially cloud-free images will allow the number of useful observations to be increased. Second, the high repetition of observations with constant viewing angles offers perspectives to enhance radiometric correction. Indeed, illumination conditions (Sun location) slowly and continuously vary over short periods (e.g. 10–15 days), during which the consistency of land surface may generally be supposed. We can thus expect a temporal stability of the top-of-atmosphere radiance collected by the sensor, except in case of variation of atmospheric components. This assumption is at the basis of the method we developed for estimating the aerosol content and performing the atmospheric correction. This method has been successfully tested on several FORMOSAT-2/RSI data sets including this one (Hagolle *et al.* 2006).

2.3 *Region of interest and experimental data*

FORMOSAT-2/RSI images include the eastern part of the Tensift plain and the surrounding '*Jbilet*' hills and foothills of High-Atlas mountains (figure 1). This region is located in Central-Morocco, 40 km east of Marrakech. The climate in the plain is of semi-arid continental type with low and irregular rainfall around 240 mm year^{-1} in contrast to a high evaporative demand around 1500 mm year^{-1} (Duchemin *et al.* 2006b). To the south, High-Atlas mountains have considerable precipitation up to 600 mm year^{-1}, which supplies several large irrigated areas in the plain.

Dominant crops are cereals (mostly wheat), fallows, and orchards (mainly olive trees); additional land classes include forages (mainly alfalfa) and vegetable crops (Simonneaux *et al.* in press). The main irrigated areas are managed by a regional public agency (ORMVAH) in charge of the distribution of dam water that is transported into regular irrigation units through concrete channels (figures 1 and 2). This network crosses over the traditional system, directly connected to High-Atlas oadis, which operates during flood events. Ground water is also used for irrigation by the mean of pumping stations. This organization results in a complex agricultural landscape with a high heterogeneity in field sizes and patterns, rather uniform within ORMVAH irrigated areas and more irregular on other areas (figure 1).

During the 2005/2006 agricultural season, an important experiment has been set up in the area observed by FORMOSAT-2/RSI. Two types of information were collected on numerous plots spread over the entire scene: surface reflectances, for testing the quality of atmospheric correction; and information on crop type, for evaluating land-cover mapping algorithm. As detailed in figure 2, additional data were collected on an ORMVAH irrigated area named R3 (white square in figure 1). This site was documented in Duchemin *et al.* (2006b), Hadria *et al.* (in press), and Er-Raki *et al.* (2007) after the design of previous experiments during the 2002/2003 and the 2003/2004 agricultural seasons. The 2005/2006 experimental data set includes information on agricultural practices (ploughing, sowing, irrigation, fertilization, and weed and pest controls), estimates of soil and vegetation biophysical variables (soil moisture and texture, leaf area index, wheat biomass, and yield), and continuous measurements of surface fluxes using both eddy correlation and large-aperture scintillometer systems.

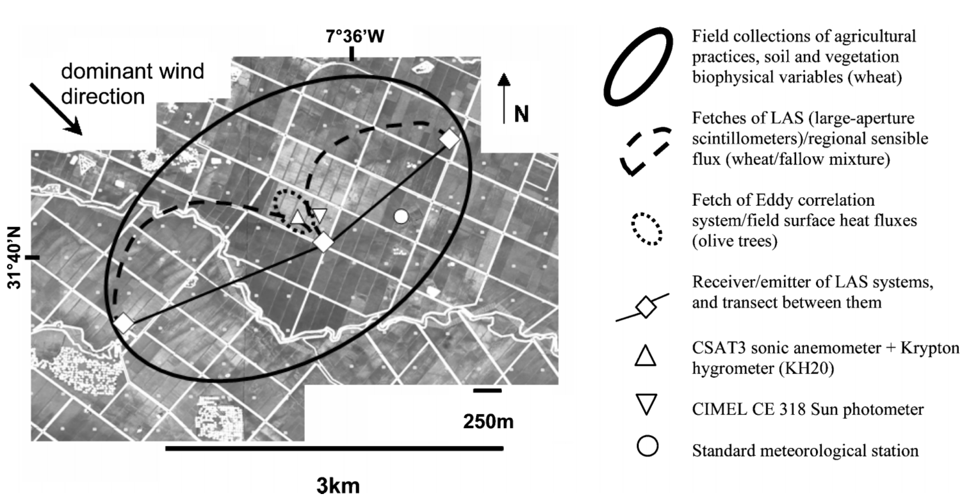

Figure 2. Details of the experimental set-up (type and/or spatial scale, land-cover type) collected at the centre of the R3 irrigated area. White lines highlight the irrigation network.

3. Potential of FORMOSAT-2/RSI imagery for agrometerological studies

3.1 *Land cover*

The knowledge of land cover is a prerequisite for land surface monitoring and modelling studies. In this objective, remote sensing has been intensively investigated (Rogan and DongMei 2004). However, approaches based on a few images generally have limitations, since usually the spectral response of different classes may overlap, and the intra-class variability may be large. In this regard, the Haouz plain offers an interesting case study. Despite the land cover being rather simple, considerable disparity may exist for the same crop type. The characteristics of orchards can be very different depending on the age of trees and the spacing between stems. Furthermore, trees are sometimes cultivated together with another short crop. For cereals, the farmers do not go along the same technical itinerary, and there is considerable heterogeneity in the crop calendar as well as irrigation and fertilization schedules. The example of the fields monitored from 2002 to 2004 as part of the SudMed project showed that the sowing period ranged from mid-November to mid-January and that the quantity of Nitrogen fertiliser varied from 0 to 100 $\mathrm{kg\,ha^{-1}}$ (Hadria *et al.* in press). Finally, alfalfa is also a particular case: it is cultivated in small fields, and the harvest is rarely carried out for the entire field at the same time. For these reasons, it is difficult to use ordinary classification methods based on statistical consistency between a set of spectral signatures and a thematic class (e.g. maximum likelihood).

In this context, the analysis of temporal patterns of simple surface characteristics, such as the greenness from vegetation indices, is probably more effective to map land cover in the Tensift-Marrakech area. A previous analysis of a set of eight Landsat-TM images acquired during the 2002–2003 agricultural season has shown the potential of this approach (Simonneaux *et al.* in press). From this time series, an NDVI profile was generated for each pixel, and the NDVI profiles were used to identify the main crop types of the Tensift-Marrakech region using a decision-tree algorithm. The resulting land-cover map was evaluated using ground data, and the confusion matrix computed gave a global accuracy up to 84%. However, the images used in this previous study were acquired on a monthly basis, and this work has allowed the distinction of only four broad land classes: bare soils, annual crops, trees, and annual crops mixed with trees. Thanks to the higher spatial and temporal resolution of FORMOSAT-2/RSI images, it is possible to gain both accuracy and refinement in the description of land cover; in particular we expect to discriminate additional sub-classes within annual crops by analysing the seasonality of growing and senescence of canopies.

A first example of NDVI time series derived from FORMOSAT-2/RSI on different crop types is given in figure 3. For each crop type, NDVI values were averaged over a group of two to eight plots juxtaposed and owned by the same farmer, ensuring the homogeneity of the agricultural practices; the average includes 1300–3500 pixels depending on the crop type, except for alfalfa for which only a small single plot of about 100 pixels was targeted. Figure 3 presents the NDVI seasonal courses for groups of plots representative of seven land classes split into two categories. The difference in NDVI levels between the three 'stable' targets (figure 3(*a*)) is consistent with surface features: the NDVI is always low (around 0.15) for bare soil and high (around 0.7) for alfalfa, which most of time totally covers the soil, while it displays intermediate values (around 0.4) for the young olive

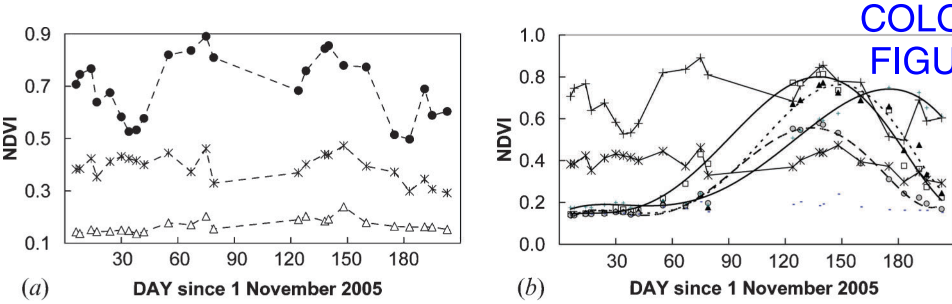

Figure 3. NDVI time courses derived from FORMOSAT-2/RSI images. (*a*) Three cases of 'stable' surfaces: alfalfa (•), young olive trees (∗) and bare soil (△). (*b*) Four cases of annual plants: early (◇) and late (▲) sown wheat, sugar beet (□), fallow (×).

trees for which the vegetation fraction cover was estimated to about 30%; for alfalfa, one can see rather large NDVI variations of ±0.2 around the average value, which result from the succession of cutting and regrowth periods. The differences in NDVI seasonal courses between annual plants (figure 3(*b*)) also appear coherent with the vegetation dynamics. First, the seasonal amplitude is maximal for wheat crops (about 0.65), on which the surface changes from bare soils to an almost totally covering canopy; the amplitude is minimal on the fallow, though it is rather high (about 0.45), indicating the presence of 'natural' vegetation (wild oat and colza). Second, NDVI seasonal patterns agree with ground observations and climatic features: the growing period was delayed for early wheat (sown 1 December) compared with late wheat (sown 2 January); for the fallow, the vegetation grows after the first significant rainfalls (end of December/beginning of January), and the senescence starts at the beginning of April after the drought observed in March (no rain this month), much earlier than for irrigated crops. Finally, it can be noticed that the senescence occurs nearly at the same time for the two wheat fields despite the differences between their sowing dates. The explanation for this is likely twofold: (1) plant emergence is delayed for the early sown wheat due to soil dryness, since there is only light rainfall and no irrigation before 24 December; (2) phenological stages are shortened at the end of the season, since temperatures know an important increase (maximal air temperatures of up to 40°C were recorded at the end of March compared with 15–20°C at the beginning of January). From the analysis of the example displayed in figure 3, it appears realistic to separate at least seven land classes using a decision-tree approach with simple criteria applied on NDVI time series (min./max. values, amplitude and phases …). This is an improvement compared with the previous analysis by Simonneaux *et al.* (in press) based on the 2002–2003 Landsat-TM data set. This information will serve to benchmark different land-cover mapping algorithms applied at various spatial, temporal, or categorical scales, i.e. for various types and groups of land-cover categories (Ju *et al.* 2005). In particular, it will be used as a reference to validate regional applications based on coarse spatial resolution data (Benhadj *et al.* 2006).

3.2 *Agricultural practices and water management*

Agricultural water management and planning is a key issue for sustainable development of arid and semi-arid areas. There is a crucial need to develop tools for quantitative monitoring of water and vegetation resources at regional scale. The scientific community has shown increasing interest in methodologies based on agro-ecological process modelling and remote sensing (Olioso *et al.* 2005). In this context, a daily survey with FORMOSAT-2/RSI would allow the description of the seasonality of soil–plant systems to be improved, therefore strengthening the results based on the assimilation of remote sensing observations into coupled crop/water balance models.

A more original opportunity is offered by FORMOSAT-2/RSI for a direct characterization of some aspects related to land-use. This is first illustrated from a time composite of three images acquired from 4 to 12 December (figure 4). Looking at the whole area in this figure, it can be seen that most pixels display grey tones. In these pixels, the land status is still nearly constant, with a more or less bright surface, over the 8-day period of interest. Indeed, this period corresponds to sowing of cereals, which are dominant in the area of interest, and the grey areas mainly include bare soils with no change in their status from 4 to 12 December. Some other fields display colours which indicate a steep variation of reflectances: decrease from 4 December to 8 December in red, decrease from 8 December to 12 December in yellow, increase from 4 December to 12 December in cyan to dark blue, or a peak around 8 December in green. These changes result from phenomena that induce a rapid change in surface status, among which we have identified ploughing, irrigation, topsoil drying, soil recovering by greenhouses, or harvest. Figure 5 details some of these effects from a time series of reflectances averaged for wheat fields on which technical itineraries have been recorded. There was only light rainfall at the end of November and no developed plant during this period. The reflectances displayed in figure 5 were normalized against those observed on bare soils (fallow area in figure 3). Furthermore, a steep variation of reflectance cannot be due to directional effects since: (1) viewing angles are constant throughout all the time series, (2) the viewing direction is far from the hot spot direction, and (3) Sun angles vary slowly with time. Given this, we believe that the temporal variations of reflectances are caused by local changes in the topsoil status. It can be seen from figure 5 that ploughing can be detected, since it results in a large decrease in reflectances due to the increase in soil roughness and shadowing. Thus, at the very beginning of the season, the level of reflectances appears as an indicator of the fact

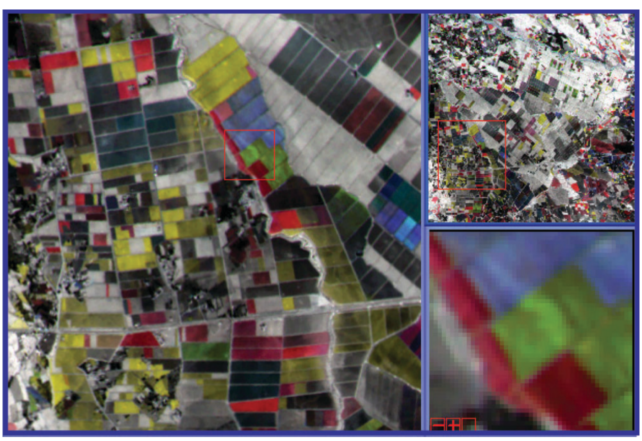

Figure 4. Time composite image of red reflectances acquired 4 December (red band), 8 December (green band), and 12 December (blue band). The top-right image displays the whole main area of interest (see figure 1), while the two other images correspond to successive zooms over the areas delimited with red squares.

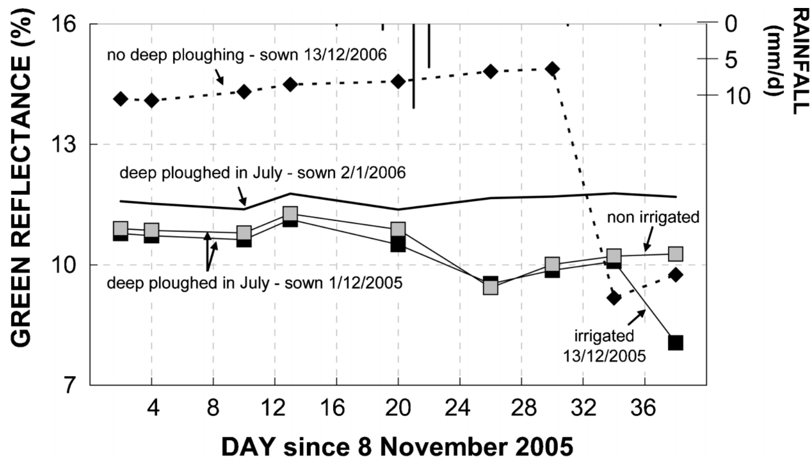

Figure 5. Time courses of green reflectances averaged on four wheat fields, with their various technical itineraries indicated by the labels. Rainfall is displayed with bars at top of the figure (secondary right axis). The reflectances were normalised against those observed on bare soils (fallow area in figure 3).

that fields have been ploughed at the end of the previous season to incorporate the residue in the soil (called deep ploughing in figure 5). Furthermore, a decrease in reflectances can be observed just before sowing, though it is less visible when deep ploughing has occurred. Additionally, a decrease in reflectance is also noticeable after an irrigation event due to the drastic increase in topsoil moisture. Indeed, water has a profound effect on soil spectral signature, decreasing the reflectance in all solar wavelengths. One way is therefore shown here to determine ploughing and irrigation dates at the beginning of the season, which is a critical input of evaporation and crop models.

This first investigation shows the potential of FORMOSAT-2/RSI images to directly derive characteristics about land use that are critical in crop modelling. This information may provide additional input in inversion scheme to better control crop and water-balance models. It will be particularly useful in a regional application, which generally suffers from the lack of spatially distributed data related to agricultural practices.

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