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Airborne soil moisture determination at regional level: a data fusion mission approach for Catalan territory

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Abstract

Water cycle is considered to be a key factor in the study of climate change and its associated effects on society. In turn, soil moisture holds an important share of the overall water cycle. Is for this reason that at present missions like ESA's SMOS, and future NASA's SMAP aim to estimate soil moisture at a global level, offering spatial resolutions of 40 km for SMOS, and 10 km for SMAP. Such resolutions do not adequately match at a regional/local levels. At this point the Supporting Centre of the Catalan Earth Observation Program (PCOT), within the structure of the Cartographic Institute of Catalonia (ICC) and with the collaboration of the Remote Sensing Laboratory of the Polytechnic University of Catalonia (RSLAB UPC), runs the HUMID program to retry the soil moisture at a regional level based on radiometry and data fusion with VNIR and thermal sensors on board ICC airborne platforms.

Key words: soil moisture, remote sensing, passive microwave, L band, data fusion, VNIR, thermal sensor.

Resumen

Estimación de la humedad del suelo con avión a nivel regional: una aproximación para una misión de fusión de datos en el territorio catalán

El ciclo del agua está considerado como uno de los factores claves en el estudio del cambio climático y sus repercusines en la sociedad. A su vez, la humedad del terreno juega un papel importante dentro del ciclo del agua. Es por ello que en la actualidad se están aplicando recursos en misiones como SMOS de la ESA y la futura SMAP de la NASA, las cuales están centradas en calcular la humedad del terreno a nivel global, ofreciendo una resolución espacial de 40 km para el caso de SMOS, y de 10 Km para el de SMAP. Dichas resoluciones no se ajustan suficientemente a escalas a nivel regional/local,. En esta situación el Centro de Soporte del Programa Catalán de Observación de la Tierra (PCOT), dentro de la estructura del Instituto Cartográfico de Cataluña (ICC), ha puesto en marcha con la colaboración de RSLAB UPC, el programa «HUMID» para la recuperación de la humedad del suelo a nivel regional/local, basado en la radiometría y el data fusión con sensores VNIR y térmicos, a bordo de los aviones del ICC.

Palabras clave: humedad del terreno, teledetección, microondas pasivas, banda L, data fusion, VNIR, sensor térmico.

Introduction

Changes in climate seem already evident. In the Occidental Mediterranean average temperatures have increased during the XX century.

During the second part of the XX century, especially in the middle of 70's, this trend has accelerated, being is some places higher than 1.6°C for the 1975-1998 period. In Spain temperatures have risen more than 0.4°C in winter and 0.7°C in summer. In Catalonia average temperatures during this period have suffered an increase of 0.88°C, whereas maxima have

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increased in 1°C and minima in 0.75°C (Brunet *et al.,* 2005).

What is more, previsions for the future are not very optimistic (severe scarcity of fresh water): it is estimated that during next century temperatures will continue to increase (between 1.4°C and 6°C). At the same time precipitations are expected to increase at the humid tropics and at high altitudes, whereas at middle and low altitudes they are expected to drop. This will result in extreme climatic events, such as droughts, floods, tornados, etc, to occur with higher frequency and intensity (Philipona *et al.,* A1.GR1 32:L19809;Sigro *et al.,* 2004;Ayala-Carcedo *et al.,* 2004).

An example of this could be the episode of drought suffered in southwest China, which caused economical loses of 952 millions of dollars. The lack of fresh water affects stockbreeding and in special for the agriculture where more than two million hectares of crops (81.7% of the total) were affected by drought producing a fall of more of the 40% in the production of crops.

A better understanding of the water cycle will improve forecasting these episodes. To do so soil moisture is a key parameter, also very useful to improve sensible management of a scarce resource such as water.

For this reason at present the scientific community is dedicating a lot of effort to this topic. Fruit of it are the recent SMOS mission launched by ESA, and the future SMAP mission which NASA plans to launch in 2013. Both are focused in the retrieval of soil moisture (SM) and ocean salinity.

Soil moisture is responsible of water exchange and energy fluxes between Earth's surface and atmosphere. More specifically, evaporation, infiltration and runoff are driven by soil moisture, and in the vadose zone it is in charge of the water absorbed by vegetation. Thus, soil moisture is an important component in the hydrologic cycle.

SMOS and SMAP missions will offer continuous measurements of soil moisture and ocean salinity with a revisit time between 3 and 5 days, and a spatial resolution of some 40 km for SMOS (Kerr *et al.,* 2001) and 10 km for SMAP (Njoku *et al.,* 2009).

These performance parameters are useful to model global circulation, but cannot be used for local applications. For example, in scenarios such as Catalonia, where temperatures have increased and precipitation has remained constant, making the level of evapotranspiration to increase, and producing situations of high hydrological stress. In situations like this, making an optimal use of fresh water is crucial for different reasons. The first one is because fresh water is a scarce resource, and the second one is because a bad use of the fresh water implies negative repercussions in the harvests (currents and future) in terms of quality and quantity.

It is within this context that the Supporting Center for the Catalan Earth Observation Program (PCOT), considering the need of acquiring specific data for regional applications, has envisioned an airborne soil moisture mission program: HUMID, supported by the Spanish Ministry of Science and Innovation as the RADERO program (PTQ-09-01-00535).

PCOT is conscious that Spain is prone to suffer drought episodes. In 2009 they affected almost 40% of the country, where the major problems were found in Catalonia, Valencia, Murcia, and Andalucia (Mediterranean shore). In these territories water reservoirs stored less than 30% of their overall capacity. In Catalonia, for instance, water flowing through rivers decreased a 5%, and the impact on the GDP has been of 7.7%, according to information supplies by Environmental Department of Catalonia.

In order to develop HUMID, ICC/PCOT benefits from the more than 20 years of experience in aircraft missions of the Institut Cartogràfic de Catalunya (ICC, Official Mapping Agency of Catalonia), as well as of the availability of several remote sensing sensors, such as a «thermal sensor» or «hyperspectral sensor», along with a good scientific advisory aboard. All this shall allow obtaining soil moisture maps with improved spatial resolution and minimized vegetation and roughness impact.

To do so HUMID relies on a «data fusion» approach, combining L-band radiometric measurements (under development by an agreement between RSLAB-UPC and ICC) with two optical sensors, the «CASI» (0.75-1.4 μm) and «TASI» (8-11.5 μm), to improve spatial resolution and minimize vegetation and roughness-induced errors. Both sensors belong to and are operated by ICC onboard their airplanes. Fi-

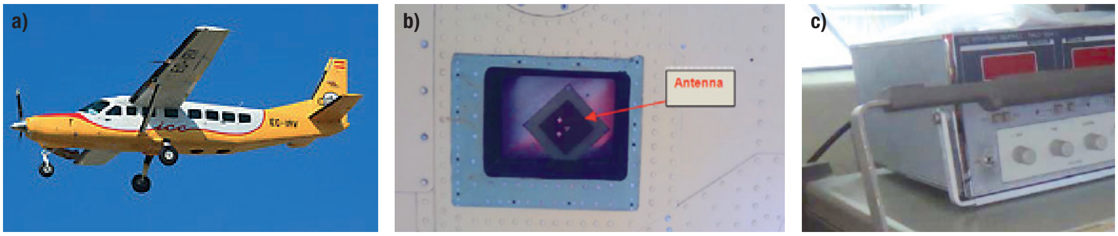

Figure 1. a) ICC aircraft, b)Radiometer mounted on ICC aircraft, and c) Spectrum of the radiometer measured.

gure 1 shows the aircraft that will be employed in the different campaigns as well the radiometer and it spectrum.

Data fusion approach

The HUMID approach has been planned in order to obtain the best results with the technology and sensors available to PCOT, disregarding solutions requiring non-available technology, models and taking into account user's needs. PCOT has committed significant efforts to address these latter issues.

Theorical background

HUMID relies on the capability of radiometry for estimating soil moisture. A radiometer is a passive microwave sensor, which is capable of measuring the radiation emitted by the surveyed surface. All matter emits energy in form of electromagnetic radiation. The amount of radiation emitted depends, among other aspects, on the dielectric properties, heavily determined by water content, since dielectric constant exhibits a large contrast between that of liquid water and that of a dry soil. So, whereas the real part of the dielectric constant of water is approximately 80, the real part of the dielectric constant of a dry soil is only around 3-5. A radiometer takes advantage of the fact that moisture, increasing the soil dielectric constant, decreases its overall emissivity.

The envisioned radiometer will measure at L-band for several reasons, the most important being that this band is the most sensitive to moisture content at the same time that is less affected by the presence of vegetation and roughness than higher bands (C or X bands, for instance) are. At the same time the penetration depth at this band is higher (Jackson *et al.,* 1983; Paloscia *et al.,* 1993).

But there are many aspects that must be improved. The fact that L-band is more robust to vegetation and roughness effects does not imply that the presence of these elements does not affect the measurements taken. What is more, under certain circumstances they can fully mask the soil moisture signature.

At the same time the coarse spatial resolution offered by the L-band radiometer is other issue that must be improved.

The model

The limitations mentioned previously point out that using only the L-band radiometer will not yield satisfactory enough results. In fact, emissivity (e_q) depends on both brightness temperature (TB) and surface temperature (Ts):

$$T_B(\theta_i,p) = e_q(\theta_i,p)T_s \qquad [1]$$

Therefore is it straightforward that in addition to TB it is necessary to retrieve TS. This can be done by means of a thermal sensor such as the TASI that ICC owns and operates. Such an instrument, with its finer spatial resolution, not only will obtain TS but also will improve the overall spatial resolution of the SM product.

As it has been mentioned before, surface roughness and more intensely vegetation disturb the measurements taken by the radiometer. Thus, it is necessary to take into account both effects in our model.

Soil roughness can be accounted modifying the Fresnel reflectivity coefficient as follows:

$$\Gamma_s(\theta,p) = \Gamma_s(\theta,p)*\exp(-h_s) \qquad [2]$$

where h_s is an adimensional parameter usually determined empirically, which determines the soil roughness (hs = 0 for smooth soils, hs = 0.2

for an intermediate case, and hs = 0.4 for rather rough ones).

The case of the vegetation-covered soil can be modeled by the so-called $\tau-\omega$ model, where expression [1] is reformulated taking into account the effect of the vegetation.

$$\begin{aligned} T_b(\theta,p) = & [1 - w(\theta,p)]\,[1 - \gamma(\theta,p)] \\ & [1 + \Gamma_s(\theta,p)\gamma(\theta,p)]T_V + \\ & + [1 + \Gamma_s(\theta,p)]\gamma(\theta,p)T_E + \\ & + T_b^{SKY\downarrow}(\theta)\Gamma_s(\theta,p)\gamma(\theta,p)^2 \end{aligned} \qquad [3]$$

where $w(\theta,p)$ is the albedo and describes the scattering of the soil emissivity by the vegetation (typical values vary between 0.04 and 0.13, and at L-band it can be neglected), $\Gamma_s(\theta,p)$ is the Fresnel reflectivity, T_V refers to the temperature of the vegetation, and T_E is the effective soil temperature (it can be assumed to be equal).

The downwards atmospheric and galactic brightness temperature $T_b^{SKY\downarrow}(\theta)$ is very small after the reflection on the ground and the attenuation through the vegetation layer (Pellarin *et al.,* 2003), and consequently will be neglected.

On the other hand $\gamma(\theta,p)$ is referred to as the transmissivity of the vegetation and can be expressed as:

$$\gamma(\theta,p) = \exp[-\tau(\theta,p) \,/\, cos\theta] \qquad [4]$$

where $\tau(\theta,p)$ is the optical depth, and can be expressed as (Jackson and Schmugge *et al.,* 1991):

$$\tau = b * VWC \qquad [5]$$

In [5] VWC stands for Vegetation Water Content, and it can be computed by means of the NDVI (Normalized Differential Vegetation Index), based on the NIR and RED bands. It can be measured by means of a hyperspectral sensor such as the CASI, also owned and operated by ICC, as:

$$NDVI = NIR - RED / NIR + RED \qquad [6]$$

The model explained so far still has a weak point: the NDVI parameters are not suitable to account for all scenarios. More specifically, in presence of dense vegetation the NDVI tends to saturate and its estimation will not be useful. An alternative to the NDVI is the NDWI (Normalize Difference Water Index), which is more sensitive to VWC, in special in situations of dense vegetation. It is based on the NIR and SWIR bands, instead of the RED and NIR bands used by the NDVI, as:

$$NDWI = NIR - SWIR / NIR + SWIR \qquad [7]$$

In order to improve soil information without the availability of SWIR bands a complementary approach is needed.

It seems clear that the solution consists in modifying the design of the radiometer. Equations [2], [3] and [4] are strongly dependent on the incidence angle and polarization. Thus, increasing the incidence angle means that losses increase, and thus vegetation effects are more critical for higher angles than for lower ones.

Figure 2 show the influence of incidence angle and polarization (Piles *et al.,* 2010).

Combining equations [2], [3], [4], [5], and taking into account the empirical relationship between Fresnel reflectivity coefficient and soil moisture (Saleh *et al.,* 2006):

$$\log[\Gamma_s(\theta,p)^*] = A(\theta,p)\,\log(w_s) + B(\theta,p) \qquad [8]$$

where $\Gamma_s(\theta,p)^*$ is the soil reflectivity, ws is the

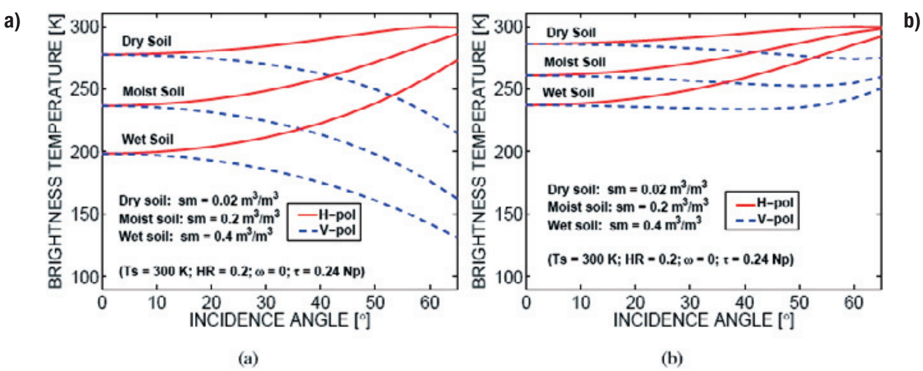

Figure 2. Brightness temperature dependence with incidence angle and polarization for (a) bare soil and (b) vegetation-covered soil.

soil moisture and $A(\theta,p)$ and $B(\theta,p)$ are coefficients in function of the soil type, soil temperature, and the configuration of the observation.

And making different assumptions, soil moisture could be expressed as a function of incidence angle or polarization (Saleh *et al.,* 2006; Wigneron *et al.,* 2004; Wigneron *et al.,* 2004),

$$w_s = exp\{a \log[1 - e(\theta_1,p)] + \\ + b \log[1 - e(\theta_2,p)] + c\} \quad [9]$$

$$w_s = exp\{a \log \log[1 - e(\theta,p)] + \\ + b \log \log[1 - e(\theta,p)] + c\} \quad [10]$$

If using equation [9] it would be a good choice a difference of 30° between both angles according to a vegetation coverage, where 15° and 45° respectively as for example will be work pretty well (Wigneron *et al.,* 2004). Considering equation (10), an incidence angle of 50° would be optimal (Wigneron *et al.,* 2004).

User's needs

HUMID program, as maintained in the introduction, is focused at regional/local scales, with the purpose of covering user's needs at this scale at the same time that it can be complement to the current satellite missions.

In this sense the products offered by HUMID have clearly three main objectives: The first one is be a tool to improve manage of fresh water. Efficient use of fresh water is indispensable for agriculture, since an inadequate mater supply affects both quantity and quality of harvest. Crops consume 70% (80% in semiarid regions) of total fresh water resources. In this scenario two issues are fundamental for the generated soil maps: The first one is related to the spatial resolution, since it is necessary to improve the current spatial resolutions, due to the high variability that can present soil moisture. At the same time it is necessary to ensure a robust model, which guarantees the most reliable results, particularly in presence of vegetation.

HUMID data fusion approach provides a high spatial resolution at the same time that the robustness of the data is ensured. In a first approximation the information provided by the thermal sensor among with the VNIR sensor allows to obtain a first soil moisture product, by means the tau omega model. This first product is recovered at the radiometer resolution, which is around of 250 m, insufficient for the goal here established. Then soil moisture can be downscaled to the resolution offered by the optical sensors (around few meters), helping the radiometer data to improve the radiometric resolution. So soil moisture maps at few meters in a first approach are expected. At the same time HUMID allows a product that can adapted to the requirements of the end user, where he can select the data in which the flight campaigns takes part or the extension of the area. In this sense HUMID, flying at 1,000 meters and at constant speed of approximately 200 km/h it can be cover extended crop areas.

HUMID also proposes other products, such as hydrological maps, where spatial resolution becomes less restrictive than for water management in agriculture. In this case flights at high altitude are proposed for cover more extended areas, and making 4/5 flights per year can be enough to study the hydrological profile of Catalonia.

In sum, products proposed by HUMID shall improve fresh water management, help in hydrological studies and be an useful tool for forest fire risk assessment

Current status

At present a simulator is under definition to validate the performance of the different models as well the behavior of our sensor. Next a flow chart of the implemented simulator is shown:

Where first is simulated an arbitrary surface with an initial boundary conditions, and then is simulated the behavior of this surface in terms of emissivity. Finally is analyzed the trend of our radiometer and the soil moisture recovered, as well the improvement in the spatial resolution achieved by means the data fusion

For an initial case is working assuming thermal equilibrium and not vegetation conditions. Several simulations show the trend of the radiometer as well as the effects of the roughness on the measures.

As follows is showed a preliminary example of the running of the simulator commented previously. It is characterized for simulate an area of 1,200*1,200, with a soil texture of 2% Sand, 66% Silt and 32% Clay. The simulation showed here, were realized for an altitude of the flight of 750 m. Figure 3 show the spatial distribution of the soil moisture from the surface generated.

Figure 4 shows the soil moisture that in the condition previously defined our radiometer will be capable of retry. It can be appreciated the coarse spatial resolution obtained in this

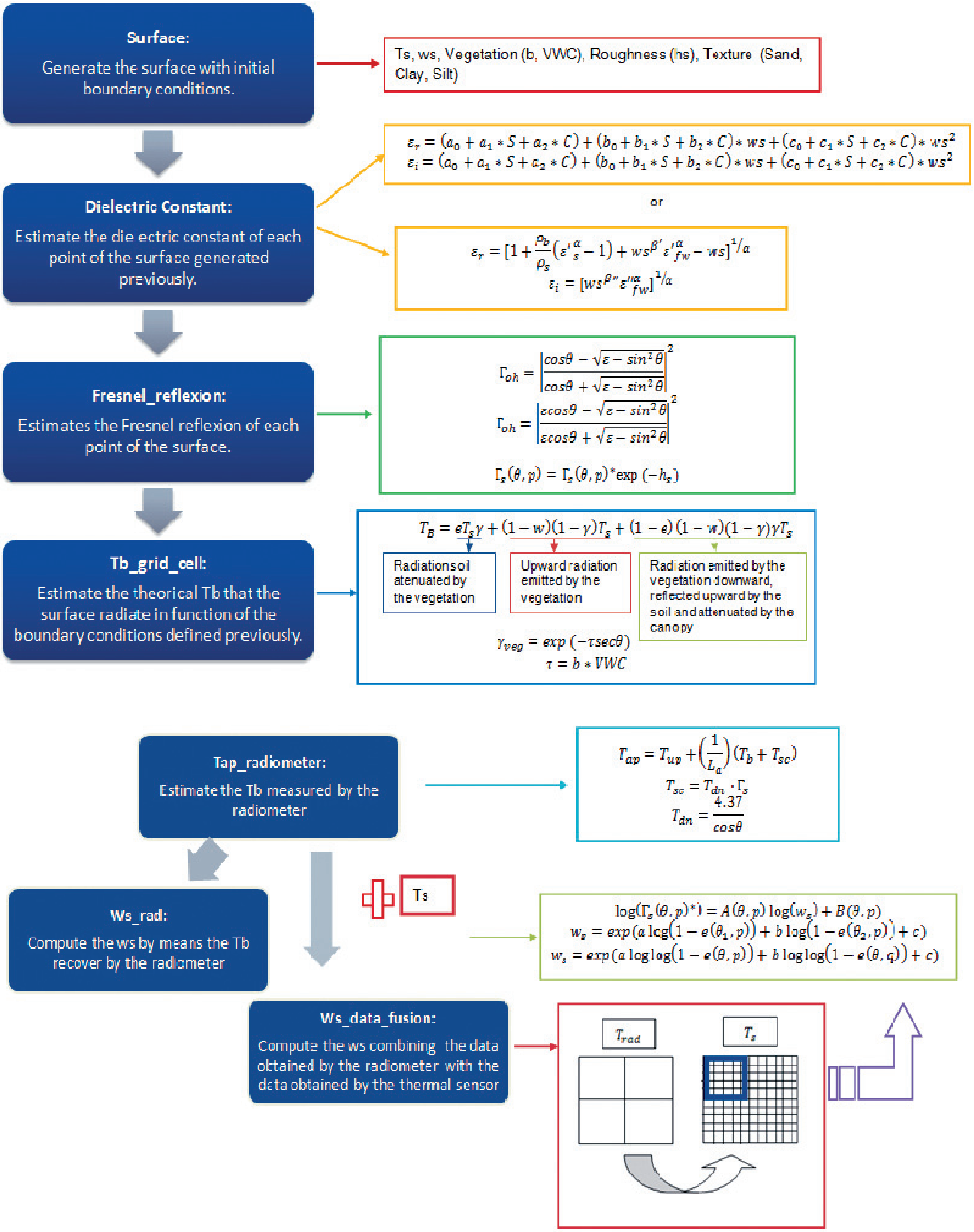

Figure 3. Flow Chart of HUMID simulator.

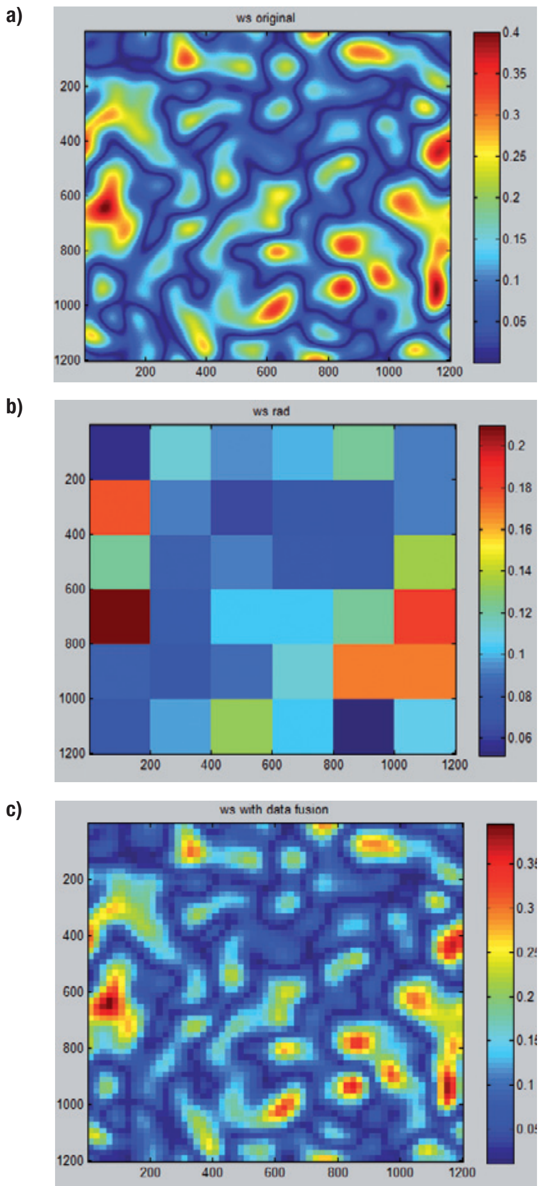

Figure 4. a) Initial soil moisture conditions for an arbitrary surface simulated, b) Soil moisture retrieved with the radiometer, c) Soil moisture by data fusion approach.

case (200 m), which implies that the level of accuracy obtained will not very high. The average error is around 6% which in general terms is not a bad value.

Figure 5 shows the soil moisture retrieved then of apply the data fusion approach. In this case the spatial resolution is of 20 m, improving thus the spatial resolution in a factor of 10. At the same time the accuracy obtained is higher that in the last case obtaining an average error less than 2%, being very positive.

Is important to stretch that the results here showed are realized for the simples case, is to said for a bare and smooth surfaces (if its is true that surfaces with roughness are tested and the results obtained has been similar), where thermal equilibrium were assumed too. The idea is enlarge these simulators to conditions of vegetated surfaces to analyze the influence that has, and the behavior of our models.

Future tasks

First aircraft campaigns are scheduled for fall 2010. They will serve to validate the results simulated previously. With this purpose three test sites are suggested as a candidate for realize the flights: Banyoles, Mollerusa and Delta de l'Ebre.

Banyoles is a good candidate since ICC has already undertaken flight campaigns in this area with the CASI sensor, and at the same time satellite imagery is available, so that additional information can be used to perform the SM retrieval.

Mollerusa and Delta de l'Ebre are interesting because both house experimental sites of IRTA (Institut de Recerca i Tecnologia Agroalimentaria), and thus are instrumented. Moreover, UPC (Universitat Politécnica de Catalunya) has conducted several aircraft campaigns flying an L-band radiometer onboard an UAV over Delta de l'Ebre. Therefore, previous SM data are available.

Conclusions

The present paper has introduced the HUMID program, conceived to address SM issues associated to Catalonia such as fresh water management improvement.

HUMID has been designed in terms of feasibility. To do so, it first detected user's requirements, and then dealt with existing limitations such as vegetation, roughness, coarse resolution... The solution proposed tries to offer the best results taking into account these limiting aspects, but also by considering feasible sensors run at own airborne platform to be operational.

HUMID products will benefit society by improving fresh water distribution, optimizing crop production, helping weather forecasters, allowing detection of extreme events such as droughts or floods, or assessing forest fire risks.

At present the algorithm and model definition phase is almost completed, including the data fusion algorithm, and the first test flights are scheduled for September 2010, once the test sites are chosen.

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