MICROWAVE RADIOMETRY FOR SOIL MOISTURE MONITORING: PRELIMINARY RESULTS FROM THE EUROSTARRS-2001 CAMPAIGN

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RESUMEN

El uso de microondas pasivas en banda L (1.4 GHz) permite obtener la humedad del suelo cerca de la superficie desde satélite a escala global. La humedad del suelo afecta fuertemente a las propiedades dieléctricas del suelo en esta banda del espectro y por tanto a la temperatura de brillo de la superficie. Los estudios actuales se hallan en fase de perfeccionamiento de los modelos de simulación de la temperatura de brillo de la superficie considerando condiciones específicas de rugosidad, tipo de vegetación y geometría de la observación. La campaña aerotransportada EuroSTARRS de la Agencia Espacial Europea tiene como objetivo aportar datos experimentales para el desarrollo y mejora de estos modelos. En esta comunicación se ofrece una introducción teórica al fundamento de la medida y algunos resultados preliminares de la campaña EuroSTARRS-2001.

Palabras clave: humedad del suelo, radiometría de microondas pasivas, SMOS.

ABSTRACT

Passive microwaves at L-band (1.4 GHz) can be used to estimate near surface soil moisture from satellites at a global scale. Soil moisture affects very strongly surface dielectric properties at this frequency and thus surface brightness temperature. Current studies are focused on the improvement of surface emissivity models for specific conditions regarding surface roughness, type of vegetation cover and geometry of observation. The airborne-based campaign EuroSTARRS from the European Space Agency will provide experimental data to support the development and improvement of these models. The basis of microwaves for surface soil moisture estimation is presented in this communication, together with some preliminary results of the EuroSTARRS-2001 campaign.

Key words*: soil moisture, passive microwave radiometry, SMOS.*

1. INTRODUCTION

Soil moisture is known to be a crucial parameter in climatology and meteorology, but up to date there is no way to obtain global and regular measurements of this property at a global scale. Atmospheric global circulation models (GCMs) describe land-surface interface processes by means of soil-vegetation-atmosphere transfer models (SVAT), where fluxes between the two systems are modelled. Terrestrial fluxes are highly dependent on soil moisture from a soil layer spreading from the surface to the roots. Should it be possible to obtain large series of soil moisture data, then surface- atmosphere parameterisations would be significantly improved, thus resulting in a better representation of mass and energy fluxes driving atmospheric dynamics. Moreover, soil moisture affects not only vertical fluxes, but also horizontal fluxes (run-off), so important for coupled ocean-atmosphere-land models, where fresh-water supply from continents to oceans is important to describe the oceanic thermohaline circulation.

Microwave radiometry contemplates many applications in remote sensing, usually low- resolution applications for global scale studies. Microwaves present some advantages for earth observation since they show very little attenuation by the atmosphere, clouds, rain, calima, etc., therefore being very useful for the observation of equatorial and mid- latitude regions. At this wavelength, it is also feasible to acquire information over densely vegetated areas, where microwaves can penetrate. Main applications of microwaves are related to hydrology, agriculture, and meteorology where water vapour, temperature and oxygen concentration can be measured from satellites operating at this band. Oceanographers do also make use of microwaves to monitor ice layers, streams and surface winds among others.

One of the main interests of current microwave radiometry focuses on the development of models and techniques to measure soil moisture from space using L-band microwave radiometry (0.390-1.550 GHz). A radiometer can register the radiation emitted by the surface at that wavelength and this information can be related to the surface brightness temperature, defined as the product between the surface physical temperature and its emissivity, that is variable for every surface, observation angle and frequency. Brightness temperature can be related to another important magnitude that characterises the surface: its dielectric constant. The dielectric constant of a material provides a description of the easiness with which molecules can be polarised within the material, that is, to what extent does molecules orientation change within the material when an electric field is applied. As regards water (polar molecule), molecules tend to exhibit a very strong response to electric fields at L-band, resulting in a rotation of water molecules in the direction of the electric field. The high potential of microwave radiometry to estimate soil moisture stands out from there. Dielectric constant at 1.4 GHz is very high for free water, ($\sim$80); a value of 3 or 4 is found for dry soils, whereas the dielectric constant can reach a value of about 20 for wet soils (SCHMUGGE, 1998). As a result, by measuring the dielectric constant we should be able to get a good indicator of near surface soil moisture.

However, good retrieval of soil moisture from brightness temperature is difficult to achieve. On the one hand, it is necessary to evaluate the influence of variable topography on surface brightness temperature at the satellite scale, as non-smooth surfaces increase the microwave signal. Moreover, vegetation influences the signal from the soil in a different way, depending on the type of vegetation, density, polarisation and observation angle.

Although the scientific basis of L-band passive microwave radiometry has been proved for bare soils (WANG *et al.*, 1981, JACKSON, 1993) and certain types of crops (MO *et al.*, 1982), further development is required for other vegetation canopies and scenes, mainly forests and natural mixed vegetation.

The European Space Agency is carrying out a space mission based on L-band passive microwave technology for soil moisture monitoring from space (SMOS: *Soil Moisture and Ocean Salinity*). The satellite will be operational around year 2006. Current state of the mission includes algorithm development and field campaigns to provide data for testing and supporting the retrieval algorithms.

The EuroSTARRS-2001 campaign was conducted in November of 2001 in several sites around Europe. An L-band radiometer (STARRS, *Surface Temperature and Roughness Remote Scanner*, Naval Research Laboratory, U.S.A) was placed on board an aircraft to obtain measurements of surface emission at different altitudes. The main interest of the campaign was to obtain measurements over forests and natural vegetation where there is lack of data to get rid of the vegetation water content which is a perturbing effect when retrieving soil moisture. Aircraft measurements, accompanied by dense ground-data collection, were performed at Les Landes Forest (near Bordeaux, France), Agre Forest (near Toulouse) and Valencia Site (Utiel-Requena plateau, near Valencia, Spain) to fulfil this requirement. In order to assess the effect of topography in surface emission, the transit flight from France to Spain through the Pyrenees together with some sampling sites such as the Valencia Site (undulated terrain) were selected for the study. Other issues such as the influence of urban areas on the microwave signal (Toulouse urban area) and the effect of mixed vegetation on surface emission were also evaluated.

2. PHYSICAL BASIS FOR REMOTE SENSING OF SOIL MOISTURE

Microwave remote sensing refers to the region of the electromagnetic spectrum ranging from 500 GHz (15mm) to 500 MHz (1.5m). Within this region we can distinguish several bands historically labelled with letters as follows: L-band (0.390-1.550 GHz), S (1.550-4.20), C-band (4.20-5.75 GHz), X (5.75-10.90), etc.

Microwaves present some advantages for surface monitoring from space which other regions of the spectrum lack of. More precisely:

- microwaves show little attenuation by the atmosphere, being equally useful under cloudy and rainy conditions.
- illumination is not required, therefore allowing day and night observation.
- microwaves can penetrate vegetation in most cases reaching the surface.
- dielectric properties at microwave frequencies (especially below 6 GHz) are very sensitive to water content.
- L-band gathers optimal properties for soil moisture monitoring.

Emission from the surface can be approximated by the Rayleigh-Jeans function (Planck's law for low frequency), which can be expressed as follows:

$$B(\theta,\phi)_\nu = \frac{2\nu^2 K T_b(\theta,\phi)}{c^2} \tag{1}$$

where $B(\theta,\phi)$ represents radiometric temperature ($W{\cdot}m^{-2}{\cdot}sr^{-1}{\cdot}Hz^{-1}$), ν is frequency (Hz), K is the Boltzmann's constant and T_b refers to the brightness temperature of the surface. The brightness temperature T_b defines the temperature of a body whose emission corresponds to the emission of a black body at temperature T_b. Brightness temperature and physical temperature, T, are related through emissivity, $\varepsilon(\theta,\phi)$, as follows:

$$T_b = \varepsilon(\theta,\phi)T \tag{2}$$

Brightness temperature for vegetated surfaces can be expressed in terms of different contributions to the signal: surface emission, vegetation emission, and atmospheric emission. The approach followed in this study considers 3 basic layers, one corresponding to the atmosphere, another is a single vegetation layer and the last one is the soil layer; moreover, reflection at the vegetation-atmosphere interface is neglected, single scattering albedo for the vegetation is assumed (multiple reflections within the vegetation layer are not accounted for), as well as uniform vegetation temperature, and a simple atmospheric model based on latitude, season and water vapour content (WIGNERON *et al.*, 1995, 2000). A solution of the radiative transfer equations with these hypotheses produces the following equation describing the surface emission as seen from a sensor above the canopy:

$$T_b(\theta,p) = T_{atm}\uparrow + (1-\Gamma_{soil})T_{soil}\gamma + T_{veg}(1-\omega)(1-\gamma) + T_{veg}(1-\omega)(1-\gamma)\Gamma_{soil}\gamma + T_{sky}\Gamma_{soil}\gamma^2 \tag{3}$$

where $T_{atm}\uparrow$ accounts for direct atmospheric emission, T_{veg} corresponds to the vegetation canopy temperature, T_{soil} defines the soil effective temperature (dependent on soil moisture content, temperature and frequency), ω defines the vegetation single scattering albedo, Γ_{soil} corresponds to the soil reflectivity (dependent on soil moisture), γ refers to the transmisivity of the vegetation layer, and T_{sky} includes the atmospheric and space microwave signal. Dependence on polarisation, p, and angle, θ, is due to the vegetation geometry and observation angle.

Vegetation transmisivity can be related to vegetation optical depth, τ, also dependent on polarisation and angle. Although this relation has been studied for crops (WIGNERON *et al.*, 1996), few studies have been conducted to determine it for forests and scrubland.

The relationship between brightness temperature and soil moisture mainly holds on the soil reflectivity parameter in Eq. (3). Reflectivity within two media can be expressed in terms of their refractive indexes, or equivalently in terms of their dielectric constant. The dielectric constant provides a measurement of the polarisability of molecules in a material when an electric field is applied; the higher this value is, the easier molecules (dipoles) can be oriented in the direction of the electric field. The following table shows some examples of the dielectric constant, κ, for several materials at microwave frequencies.

As a result, an accurate model of surface brightness temperature can be used to obtain surface emissivity and retrieve the dielectric constant from it. The high difference amongst the dielectric constant values for dry and wet soils is the basis for soil moisture microwave remote sensing.

Models for the dielectric behaviour of soils vary according to surface characteristics –dry sand, ice, wet soil–. In this study, the Dobson dielectric mixing model (DOBSON *et al.*, 1985) is used.

Table 1: Dielectric constant, reflectivity and emissivity for several materials. (Modified from VAN DE GRIEND, 1995).

	Freq. (Hz)	κ real	κ imaginary	κ module	Reflectivity	Emissivity
Free water 20°C	1 GHz	80	4.5	80.1	0.64	0.36
Dry soil	1.4 GHz	2.8	¡?0	2.8	0.06	0.94
Wet soil	1.4 GHz	19.6	4.8	20.2	0.40	0.60
Ice	1 GHz	5	0.5	5.02	0.15	0.85
Granite	10 GHz	4.4	0.3	4.4	0.13	0.87
Limestone	14 GHz	8.4	0.03	8.4	0.24	0.76

The model considers different ’particles’ with different dielectric behaviour as to produce one soil dielectric constant value. These particles are free water, bounded water, air and soil particles. A characterisation of the soil type is therefore required to determine the soil dielectric constant. Other models are required for dry sandy soils (MÄTZLER, 1998) or ice (HALLIKAINEN, 1985).

3. CURRENT STATUS OF SOIL MOISTURE RETRIEVAL ALGORITHMS

A good parameterisation of all terms in equation (3) is required to obtain soil moisture with the required accuracy for the SMOS mission (0.04 cm^3/cm^3) (WIGNERON *et al.*, 2000, KERR *et al.*, 2001). Actually, it has been proved that having several configurations for the observation (angle, polarisation), it is possible to invert equation (3) and retrieve simultaneously soil moisture, surface temperature and biomass (WIGNERON *et al.* 1995, 2000). The latter variable is related to transmisivity as follows:

$$\gamma = e^{-\tau/\cos\theta} \qquad \text{and} \qquad \tau = bW_c \tag{4}$$

where W_c represents the vegetation water content and b is a parameter (also dependent on angle and polarisation) relating vegetation optical depth to water content.

However, some issues still need to be studied to achieve satisfactory results in the inversion process. On one hand, the influence of vegetation on soil moisture retrieval needs further study. Dependency of the vegetation optical depth with observation configuration is not known for all canopy types and this is a key parameterisation required for the inversion process. Once the SMOS satellite mission is operational, a surface area will be observed with different angles and polarisation; therefore, it will be necessary to include the dependence of vegetation optical depth on the observation configuration to use multi-angular bi-polarisation brightness temperature to retrieve soil moisture.

Other factors that are under investigation are related to the effect of topography on the microwave signal (NJOKU y ENTEKHABI, 1996; KERR *et al.*, 2001). Roughness increases emissivity as compared to smooth surfaces (WANG *et al.*, 1981), but this effect is not fully known at satellite scale. Moreover, how mixed covers within the same footprint will influence the emissivity needs still to be evaluated.

4. THE EUROSTARRS CAMPAIGN TO PROVIDE DATA FOR ALGORITHM DEVELOPMENT

In order to provide data to address the issues stated above, the European Space Agency funded an experimental airborne campaign in support of the SMOS Mission and focussing on the following scientific requirements:

- Analysis of L-band emissivity models over forests.
- Analysis of the effects of mixed vegetation covers on the microwave signal.
- Analysis of the effects of topography on the signal.
- Urban and RFI impact effects on the signal.

EuroSTARRS-2001 involved airborne-based acquisitions of the surface brightness temperature over several sites covering the requirements just mentioned. A summary of the main interest and type of activity in every region is outlined in table 2.

5. PRELIMINARY RESULTS OF THE EUROSTARRS-2001 CAMPAIGN

Initial processing of the EuroSTARRS-2001 data acquired over all sites shows satisfactory results of the campaign performance.

The sensitivity of brightness temperature to soil moisture content can be observed in Fig. 1-4. showing the transects over all the study areas. Figure 5 shows the multi-angular emissivity of bare soil obtained by STARRS at Les Landes forest and the simulated emissivity for the same conditions. Although the STARRS radiometer is expected to be recalibrated after reporting possible maladjustments in two antennas -mainly on the near-nadir one (5^{o})-, minor modifications are expected for the rest of them. Experimental data correspond to the emissivity of several plots of bare soil; dispersion in data is mainly due to the variability of texture and surface roughness in different patches. This effect is larger as the observation angle increases, since the radiometer integrates information over larger areas. A preliminary simulation of emissivity seems to fit rather satisfactorily to experimental data.

Over natural vegetation (Valencia Site), a similar plot provides acceptable values assuming uniform vegetation optical depth and using best-fitting values of the vegetation single scattering albedo and optical depth (Fig. 6). These results, however, need to be normalised to reduce the effect of surface temperature on brightness temperature. Surface roughness for the simulation was obtained from STARRS data over an adjacent bare soil field. Another example can be seen in Fig. 7, where results over orchard (olive trees) fields are shown. Firstly, brightness temperature values are slightly higher in this case. On the one hand, surface roughness is larger than in Fig. 6, soils are drier and the percentage of vegetation cover is smaller, thus resulting in higher values of

Table 2: Description of sites involved in the EuroSTARRS-2001 campaign from ESA.

SITE	DESCRIPTION	MAIN INTEREST	TYPE OF ACTIVITIES	EXPECTED OUTCOME
Les Landes Forest (South-West France)	Coniferous forest, distribution of plots with different ages, flat region	Study of forest emissivity, information retrieval of forest characteristics	Low altitude flights (300m above surface), multi- angular observations over same patches + ground sampling	Assessment of the influence of dense vegetation on soil moisture retrieval algorithms, parameterisation of vegetation optical depth with observation configuration for coniferous trees.
Agre Forest (near Toulouse, France)	Deciduous forest, flat region	Study of forest emissivity, information retrieval of forest characteristics	Low altitude flights (300m above surface), multi- angular observations over same patches + ground sampling	Assessment of the influence of dense vegetation on soil moisture retrieval algorithms, parameterisation of vegetation optical depth with observation angles over a mixed area of deciduous vegetation (mainly oak trees) and some coniferous trees
Valencia Site (near Valencia, Spain)	Mediterranean shrubs, pine trees, olive trees. Undulated terrain	Study of the emissivity of orchards and Mediterranean natural vegetation, mixed vegetation, and undulated terrain	Low altitude (600 m above surface) and high altitude (1800 m above surface) flights, multi-angular observations over same patches + ground sampling	Parameterisation of vegetation optical depth with observation angle over Mediterranean vegetation, impact of heterogeneous cover on simulated brightness temperature and retrieved soil moisture, impact of surface roughness on soil moisture retrieval algorithms
Pyrenees (transit flight France to Spain)	Abrupt topography; different surface cover	Study of the emissivity of surface over very irregular topography areas	Variable altitude flight over the chain of mountains	Effect of irregular topography on retrieved soil moisture
Toulouse urban area	Urban environment	Study of L-band emissivity over urban areas	Low altitude single flight over the city of Toulouse	Impact of urban nuclei on the frequency used for the soil moisture study

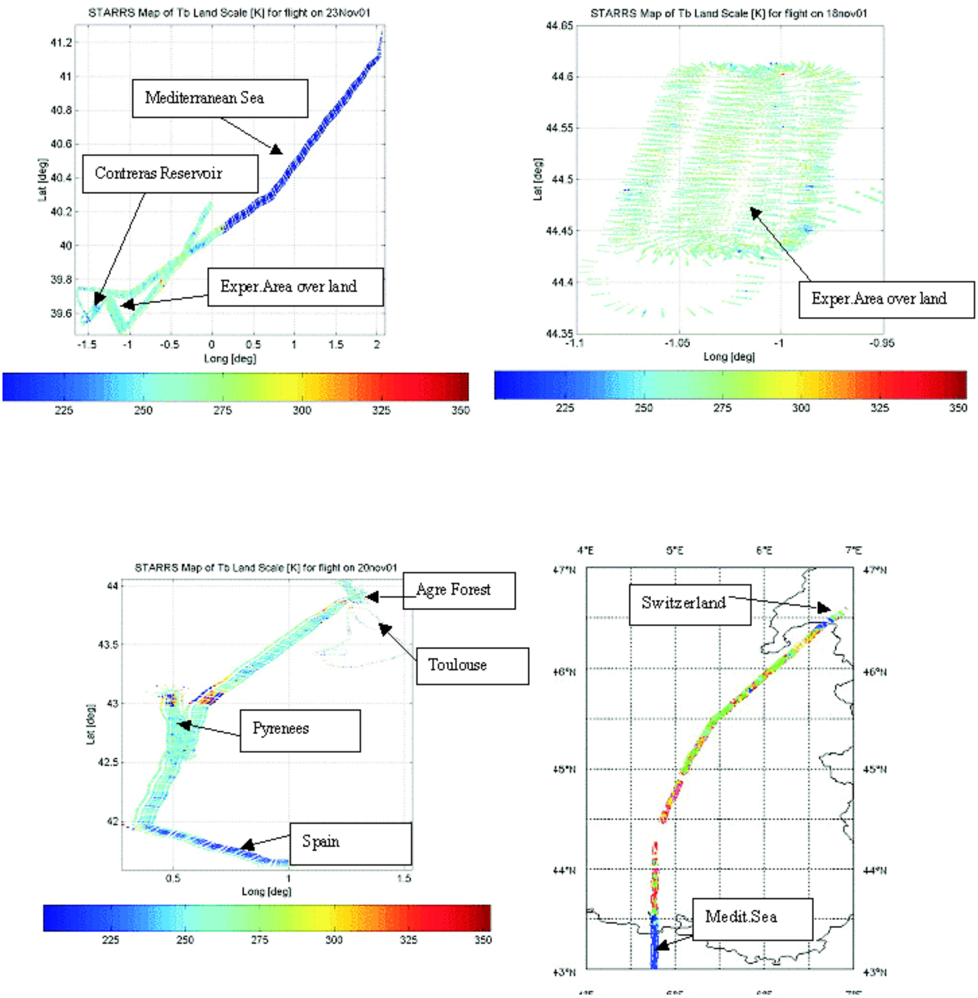
brightness temperature. Simulated brightness temperature, however, differs more in this particular case. Actually, this might be due to a stronger effect of topographic effects, and to a stronger influence of the vegetation geometry –less homogeneous than in Fig. 6– on the microwave signal.

Moreover, brightness temperature appears to be more sensitive to angle variations for shrubs than it is for orchards. The reflectivity parameter Γ_{soil} in eq. (3) includes a roughness correction with respect to specular reflectivity (Γ_s^*) and can be written as follows (CHOUDHURY *et al.*, 1979, WIGNERON *et al.*, 2001):

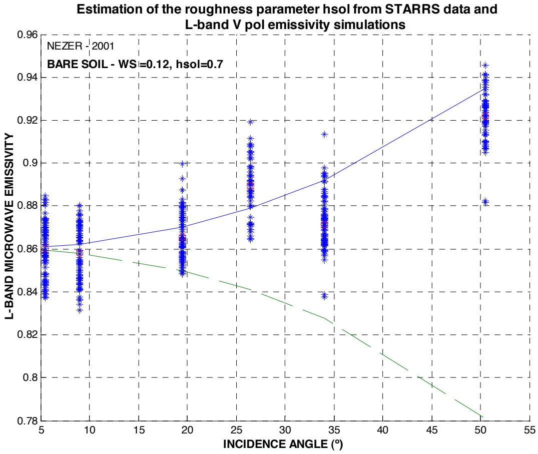
$$\Gamma_s(\theta, p) = \Gamma_s^*(\theta, p)e{-}h_s\cos^2\theta \tag{5}$$

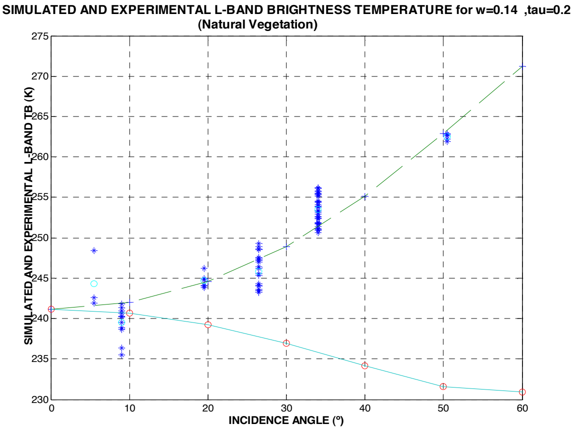
As a result, for higher values of the roughness parameter h_s, brightness temperature is less sensitive to angle variations, as it occurs in the orchards field.

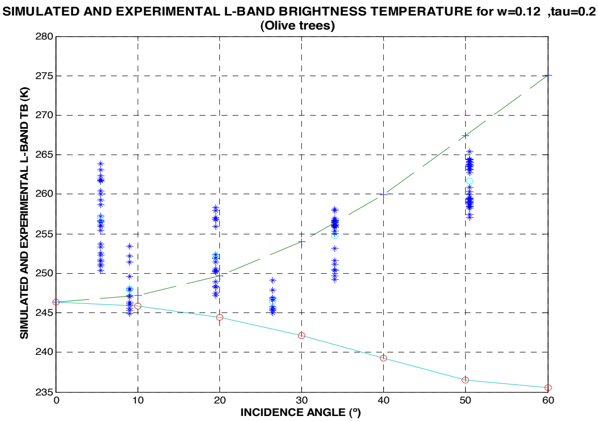
Finally, over forests, large differences between simulated and experimental brightness temperature are found (Fig. 8). It is over dense vegetation where optical depth is more likely to be angle dependent and parameterisations of that dependence are needed.



Figures 1-4: Sensitivity of brightness temperature to soil moisture content. (Transects over all the study areas).







Figures 5-7: Simulated and experimental L-band brightness temperature over bare soil, natural vegetation and olive tree orchard.

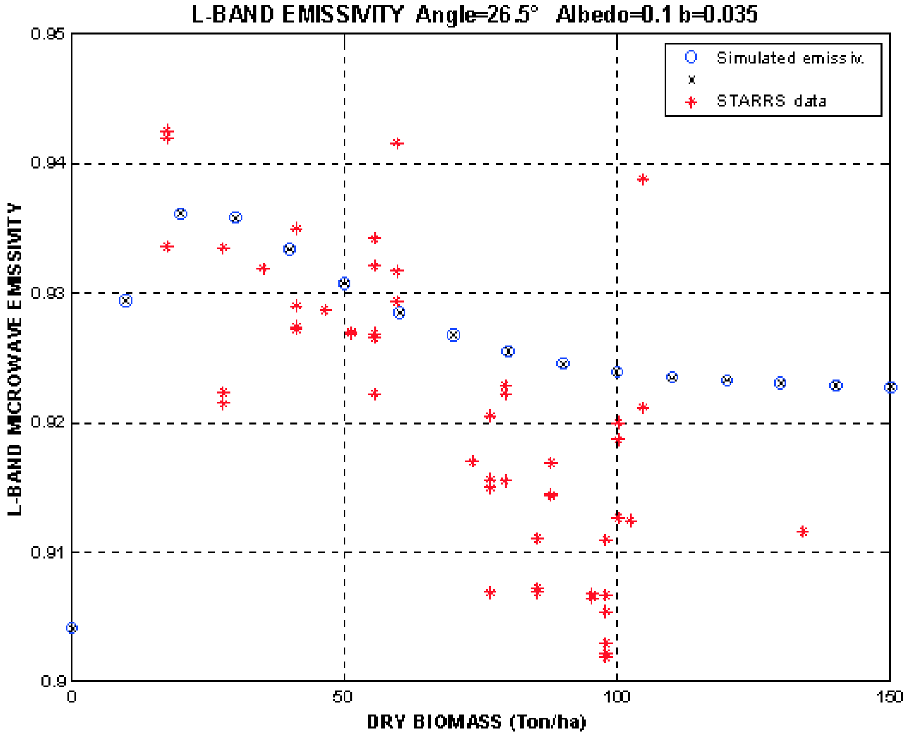


Figure 8: Simulated and experimental L-band brightness temperature over forest.

6. CONCLUSION

The sensitivity of soil dielectric properties to microwaves at L-band, together with the advantages of microwaves for earth observation -low atmospheric attenuation, penetration in vegetated areas- are the basis of soil moisture microwave remote sensing. Measurement and modelling of surface brightness temperature allow estimations of surface soil moisture though the determination of surface emissivity -related to the soil dielectric constant- and the use of dielectric mixing models to derive soil water content from it. Actually, multi-configuration observations of surface brightness temperature can be used to retrieve simultaneously soil moisture and vegetation optical depth. However, it is required to parameterise the dependence of vegetation optical depth on the observation parameters (polarisation and incidence angle) and to account for other factors such as the effect of topography on the microwave signal. An airborne and ground-based campaign, EuroSTARRS-2001, was conducted in France and Spain to address these issues. Preliminary results show good simulations of brightness temperature over bare soils, but indicate that some modelling work is still needed over forests and other types of irregular vegetation covers such as orchards fields and mixed covers of relatively dense vegetation. Further analysis of EuroSTARRS-

2001 data will focus on improving model parameterisations also for topography, dense vegetation and mixed vegetation covers, as well as urban emission.

7. ACKNOWLEDGMENTS

This work has been carried out in the framework of the respective ESTEC-ESA Contracts with Universitat de Valencia (Spain), INRA (Bordeaux, France) and CNRM (Toulouse, France). The Valencia group also acknowledges the MIDAS (*Medidas radiométricas en microondas y desarrollo de algoritmos para la misión SMOS*) project from the Spanish National Space Programme Project (ESP2001-4525-PE). This paper specifically addresses the remote sensing work and preliminary modelling analysis. But the authors sincerely recognise the intense ground sampling work carried out in the three sites.

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