JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. D14, 10.1029/2001JD000958, 2002

Modeling approaches to assimilating *L* band passive microwave observations over land surfaces

Jean-Pierre Wigneron,[1] André Chanzy,[2] Jean-Christophe Calvet,[3] Albert Olioso,[2] and Yann Kerr[4]

Received 19 June 2001; revised 16 November 2001; accepted 27 November 2001; published 31 July 2002.

[1] *L* band passive microwave remotely sensed data have great potential for providing estimates of soil moisture with high temporal sampling and on a regional scale. Several studies have shown the possibility of assessing the hydrological conditions deep down in soil (in the top 1 or 2 m) from these repetitive estimates of surface soil moisture. Water availability for plants, which is related to soil moisture in the root zone, is a key variable for estimating the evapotranspiration fluxes over land surfaces. This estimation is an important issue for meteorological and hydrological modeling, since it is a basic term of land surface forcing in mesoscale atmospheric circulations. However, at the present time the assimilation approach of remotely sensed brightness temperature data for operational use in the fields of meteorology and hydrology is poorly defined and important issues remain to be addressed in order to develop an operational assimilation approach. Two important issues are to identify (1) how vegetation variables describing vegetation development can be accounted for and (2) how the attenuation effects of *L* band microwave radiation within the canopy layer can be computed on large spatial scales. On the basis of an exhaustive data set including multiangular and dual-polarization passive microwave measurements acquired over a wheat crop during a 3-month period in 1993, two main modeling approaches are tested in this study. The principle of both approaches was based on the use of dual-polarization and multiangular observations to discriminate between the effects of soil and vegetation on the crop microwave signature. For the two approaches, both the initial soil water reservoir R_2 (at the beginning of the crop development) and parameterizations of the crop development could be retrieved simultaneously from the assimilation of the passive microwave measurements. From these results, promising assimilation strategies can be expected from the multiangular Soil Moisture and Ocean Salinity (SMOS) observations made over the land surface. ***INDEX TERMS:*** 1640 Global Change: Remote sensing; 1818 Hydrology: Evapotranspiration; 1866 Hydrology: Soil moisture; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; ***KEYWORDS:*** Microwave radiometry, soil moisture, vegetation biomass, global change, assimilation, coupling radiative transfer and soil-vegetation-atmosphere-transfer (SVAT) models

ELSEVIER

Agricultural and Forest Meteorology 80 (1996) 177–194

AGRICULTURAL AND FOREST METEOROLOGY

Monitoring water interception by crop fields from passive microwave observations

Jean-Pierre Wigneron [a,*], Jean-Christophe Calvet [b], Yann Kerr [c]

[a] INRA / Bioclimatologie, Agroparc, F-84914 Avignon Cedex 9, France
[b] METEO-FRANCE / CNRM, 42 av. Coriolis, F-31057 Toulouse Cedex, France
[c] CESBIO (CNES, CNRS, UPS), 18 av. E. Belin, F-31055 Toulouse Cedex, France

Received 23 February 1995; accepted 4 August 1995

Abstract

In the present work, the time variations of a wheat field microwave emission are analysed during irrigation phases. The aim of the study is to investigate the use of low-frequency microwave measurements to monitor hydrological variables over a wheat crop: surface soil moisture and water interception by the vegetation canopy. The irrigation phases were representative of rainfall or dew events. It appears that the radiometric measurements are strongly sensitive to the hydrological characteristics of the soil and of the vegetation canopy. The 1.4 GHz measurements are mainly sensitive to surface soil moisture m_v, whereas the 5 GHz measurements are sensitive to both m_v and to the vegetation water content W_v. A simple model approach is implemented to retrieve simultaneously these two surface parameters. The results of this procedure show the high potential of the microwave remote sensing measurements to monitor the time variations of soil moisture and of the total vegetation water content. The value of the wheat water storage capacity is derived from the microwave measurements and is in good agreement with experimental data.

1. Introduction

Water interception by vegetation is an important component of the water balance of vegetation canopies. Total interception is a combination of water storage in the canopy and evaporation during rain. Therefore, measurements of interception should include an

* Corresponding author.

0168-1923/96/$15.00
SSDI 0168-1923(95)02296-1

A Simple Algorithm to Retrieve Soil Moisture and Vegetation Biomass Using Passive Microwave Measurements over Crop Fields

*Jean-Pierre Wigneron,** *André Chanzy,*† *Jean-Christophe Calvet,*‡ *and Nadine Bruguier**

A simple algorithm to retrieve soil moisture and vegetation water content from passive microwave measurements is analyzed in this study. The approach is based on a zeroth-order solution of the radiative transfer equations in a vegetation layer. In this study, the single scattering albedo accounts for scattering effects and two parameters account for the dependence of the optical thickness on polarization, incidence angle, and frequency. The algorithm requires only ancillary information about crop type and surface temperature. Retrievals of the surface parameters from two radiometric data sets acquired over a soybean and a wheat crop have been attempted. The model parameters have been fitted in order to achieve best match between measured and retrieved surface data. The results of the inversion are analyzed for different configurations of the radiometric observations: one or several look angles, L-band, C-band or (L-band and C-band). Sensitivity of the retrievals to the best fit values of the model parameters has also been investigated. The best configurations, requiring simultaneous measurements at L- and C-band, produce retrievals of soil moisture and biomass with a 15% estimated precision (about 0.06 m^3/m^3 for soil moisture and 0.3 kg/m^2 for biomass) and exhibit a limited sensitivity to the best fit parameters.

*INRA / Bioclimatologie, Montfavet, France
†INRA / Science du Sol, Montfavet, France
‡Météo-France / CNRM, Toulouse, France

Address correspondence to Jean Pierre Wigneron, INRA / Bioclimatologie, 84914 Avignon Cedex 9, France.
Received 1 May 1994; revised 5 September 1994.

INTRODUCTION

Numerous studies have shown that passive microwave radiometers can be used to estimate surface soil moisture and vegetation biomass (Jackson and Schmugge, 1989; Choudhury et al., 1990; Paloscia and Pampaloni, 1992; Wegmüller, 1993; Wigneron et al., 1993a). Over bare fields, the measured microwave emissivity is almost linearly related to the moisture content of a soil layer whose thickness is dependent on the frequency of the observation [between 1 cm and 5 cm at 5 GHz and 1.4 GHz (Wang, 1987)]. The slope and intercept of this relationship is dependent on the configuration of the observation system (in terms of frequency, incidence angle, and polarization) and on the characteristics of soil (in terms of soil texture and surface roughness) and vegetation. The vegetation cover attenuates soil emission and adds its own contribution to the emitted radiation. In order to reduce the effect of vegetation when estimating soil moisture, low-frequency observations can be used (between 1 GHz and 5 GHz). Nevertheless, for crop fields with dense vegetation coverage the contribution of vegetation can be very important even for L- and C-band observations. The depolarization of the soil-vegetation emissivity increases as the vegetation density increases (depolarized vegetation emission increases whereas polarized soil emission is attenuated by the vegetation layer). The index PDI (polarization difference index) quantifies this effect and can be used to monitor vegetation biomass. Therefore, the low-frequency microwave emissivity of vegetation-covered surfaces contains information about both the vegetation canopy and the underlying soil layer.

Several approaches can be used to retrieve this information. Over a given area, a linear relationship between emissivity and soil moisture can be calibrated

REMOTE SENS. ENVIRON. 51:331–341 (1995)

655 Avenue of the Americas, New York, NY 10010

0034-4257 / 95 / $9.50
SSDI 0034-4257(94)00081-W

Microwave Emission of Vegetation: Sensitivity to Leaf Characteristics

Jean-Pierre Wigneron, Jean-Christophe Calvet, Yann Kerr, *Member, IEEE*, André Chanzy, and Armand Lopes

***Abstract*—This paper presents an analysis of leaf-characteristics effects on the microwave emission of land surfaces. In order to simulate these effects, a radiative transfer model is presented. The medium consists of a vegetated layer containing randomly oriented leaves, modeled as elliptic-shaped scatterers, over the ground surface. Radiative transfer equations are solved with a discrete ordinate-eigenanalysis method. The calculation of the phase matrix of the elliptic scatterers is based on the generalized Rayleigh–Gans approximation which increases the frequency range of the modeling.**

The sensitivity of brightness temperature and polarization ratio to leaf characteristics, volume fraction, gravimetric moisture, size, shape, and inclination distribution is investigated at *L*-, *C*-, and *X*-bands. The behavior of the simulated emission of a soybean canopy versus frequency and incidence angle is studied for different soil moisture levels. These computations are consistent with measurements performed with a multifrequency radiometer. Up to 10 GHz the microwave emission appears to contain significant information on underlying soil moisture.

I. Introduction

MANY parameters influence the microwave emission of land surfaces, the most important being soil and vegetation water content, vegetation structure and biomass, surface temperature, and soil roughness. Theoretical models can be most useful to understand the effect of these different parameters on the microwave remotely sensed data. The microwave thermal emission of vegetation-covered soil can be divided into three main components: the upward canopy emission, downward and soil reflected canopy emission, upward soil emission [1]–[3]. The vegetation canopy attenuates and scatters these radiations. Therefore, theoretical models which have been developed to simulate the thermal emission of vegetation canopies have taken into account volume absorption and scattering by the discrete scatterers of the vegetation: leaves, branches and stalks.

Volume scattering can be modeled through two types of approaches: the wave approach and the radiative transfer approach. Even though the radiative transfer approach does not take into account diffraction effects in the computation of multiple scattering contributions and considers only far-field interactions, it is more appropriate for modeling strongly scattering media like vegetation canopies [4].

The vegetated canopy can also be modeled through two types of approaches: either as a continuous random medium [5], [6] (the so-called continuous approach) or as an homogeneous medium containing discrete scatterers (discrete approach). In the discrete approach every contribution to the microwave emission (from soil, leaves, branches) is precisely described. So this approach is useful to better understand and analyze the sensitivity of the canopy microwave thermal emission to soil and vegetation characteristics.

The numerous discrete models which have been developed describe more and more precisely the vegetation structure. In developing the discrete approach for passive microwave remote sensing, England [7] solved the radiative transfer equations for a half-space medium containing Rayleigh point scatterers. Tsang and Kong [8] solved the same equations for spherical scatterers using Mie scattering phase functions. Scattering from randomly oriented discs or circular cylinders with application to active remote sensing of vegetation was described by Karam and Fung [9]. Choe and Tsang [10] solved radiative transfer equations for a one-layer medium containing both circular-shaped discs (leaves) and cylinders (branches) and derived the thermal emission of crop canopies. Lang *et al.* [11] modeled passive emission of a soybean canopy using the Peake approach which relates the bistatic scattering coefficients of vegetation to its emissivity. Vegetation is modeled as a half-space medium containing lossy dielectric discs.

In this study the vegetation canopy is modeled as a one-layer medium containing randomly oriented leaves. The radiative transfer equations are solved using a discrete ordinate-eigenanalysis method [6], [12]. The leaf-scattering modeling used in this study is based on the model developed by Karam and Fung [13] for active microwaves. The modeling of leaf scattering is significantly improved with regards to other approaches since:

- The scattering amplitude of the leaves is computed with the generalized Rayleigh-Gans (GRG) approximation which is valid in the frequency region where leaf dimensions are of the order of the emitted wavelength.
- Scattering is accounted for in the extinction formulation since the optical theorem accounts only for absorption under low frequency approximations.
- Leaves are modeled as elliptic rather than circular-shaped scatterers.

The model presented in this paper is developed in order

Manuscript received April 17, 1992; revised August 24, 1992; rerevised November 25, 1992.

J.-P. Wigneron is with INRA, Bioclimatologie, BP91, 84143 Montfavet cedex, France.

J.-C. Calvet is with Meteo-France/CNRM, Toulouse, France.

Y. Kerr is with LERTS, CNES–CNRS, 31055 Toulouse cedex, France.

A. Chanzy is with INRA, Science du sol, BP91, 84143 Montfavet cedex, France.

A. Lopes is with CESR, UMR-CNRS BP4346, 31029 Toulouse cedex, France.

IEEE Log Number 9207390.

Soil Moisture Retrieval from Space: The Soil Moisture and Ocean Salinity (SMOS) Mission

Yann H. Kerr, Philippe Waldteufel, Jean-Pierre Wigneron, Jean-Michel Martinuzzi, Jordi Font, and Michael Berger

***Abstract*—Microwave radiometry at low frequencies (L-band: 1.4 GHz, 21 cm) is an established technique for estimating surface soil moisture and sea surface salinity with a suitable sensitivity. However, from space, large antennas (several meters) are required to achieve an adequate spatial resolution at L-band. So as to reduce the problem of putting into orbit a large filled antenna, the possibility of using antenna synthesis methods has been investigated. Such a system, relying on a deployable structure, has now proved to be feasible and has led to the Soil Moisture and Ocean Salinity (SMOS) mission, which is described in this paper. The main objective of the SMOS mission is to deliver key variables of the land surfaces (soil moisture fields), and of ocean surfaces (sea surface salinity fields). The SMOS mission is based on a dual polarized L-band radiometer using aperture synthesis (two-dimensional [2-D] interferometer) so as to achieve a ground resolution of 50 km at the swath edges coupled with multiangular acquisitions. The radiometer will enable frequent and global coverage of the globe and deliver surface soil moisture fields over land and sea surface salinity over the oceans. The SMOS mission was proposed to the European Space Agency (ESA) in the framework of the Earth Explorer Opportunity Missions. It was selected for a tentative launch in 2005. The goal of this paper is to present the main aspects of the baseline mission[1] and describe how soil moisture will be retrieved from SMOS data.**

***Index Terms*—2-D interferometry, passive microwaves, soil moisture retrievals.**

I. Introduction: Mission Rationale

WATER and energy fluxes at the surface/atmosphere interface are strongly dependent upon soil moisture. Evaporation, infiltration and runoff are driven by surface soil moisture (SSM), while soil moisture in the vadose zone governs the rate of water uptake by vegetation. Soil moisture is thus a key variable in the hydrologic cycle. The spatio-temporal evolution of soil moisture fields is an important factor for numerical weather and climate models, and should be accounted for in hydrology and vegetation monitoring [1], [2].

For the oceans, sea surface salinity (SSS) plays an important role in the Northern Atlantic subpolar area, where flow intrusions with low salinity influence the deep thermohaline circulation and the meridional heat transport. Variations in salinity also influence the near-surface dynamics of tropical oceans, where rainfall modifies the buoyancy of the surface layer and the tropical ocean-atmosphere heat fluxes. SSS fields and their seasonal and interannual variabilities are thus tracers and constraints on the water cycle and on the coupled ocean–atmosphere models [3].

Even though both SM and SSS are used in predictive atmospheric, oceanographic, and hydrologic models, no capability exists to date to measure them directly and globally. The SMOS mission is aimed at filling this gap through the implementation of a satellite that has the potential to provide globally and routinely this information [4]. Over land it is also expected that the SMOS mission will provide significant information on vegetation water content, and root zone soil moisture, which will be very useful for regional estimates of crop production. Finally, significant research progresses are expected over the cryosphere, by improving the assessment of snow packs, and multilayered ice structures. These quantities are of significant importance to the global change issue.

A direct way to monitor SSM and SSS is through the use of L-band (21 cm, 1.4 GHz) microwave radiometer systems. Other means (higher frequency radiometry, optical sensing, active microwaves remote sensing) suffer strong deficiencies due to vulnerability to cloud cover and/or various perturbing factors (such as soil surface roughness or vegetation cover). They have inferior sensitivity to SSM and SSS.

Even though the L-band radiometry concept was demonstrated early by a space experiment (SKYLAB) back in the 1970s, no dedicated space mission followed because achieving a suitable ground resolution ($\leq$50–60 km) required a prohibitive antenna size ($\geq$4 m). All the research work was consequently performed using either ground (PAMIR, PORTOS, etc.) or airborne radiometers (e.g., PBMR, PORTOS, ESTAR) with significant achievements (see, for instance, [5]).

Recent development of the interferometry design inspired from the very large baseline antenna concept (radio astronomy) makes such a venture now possible. The idea consists of deploying small receivers in space (located on a deployable structure), then reconstructing a brightness temperature (T_B) field with a resolution corresponding to the spacing between the outmost receivers. The idea was put forward by LeVine *et al.* in the 1980s (the ESTAR project) and validated with an

Manuscript received October 1, 2000; revised February 5, 2001.

Y. H. Kerr is with the Centre d'Etudes Spatiales de la Biosphère (CESBIO), Toulouse Cedex 4, France (e-mail: Yann.Kerr@cesbio.cnes.fr).

P. Waldteufel is with the Institut Pierre Simon Laplace (IPSL), 78140 Vélizy, France.

J.-P. Wigneron is with the Institut National de Recherche Agronomique (INRA), Avignon Cedex 9, France.

J.-M. Martinuzzi is with the Centre National d'Etudes Spatiales (CNES), 31401 Toulouse cedex 04, France.

J. Font is with the Institut de Ciencies del Mar (CSIC), 08039 Barcelona, Spain.

M. Berger is with the Eropean Space Agency, European Space Research and Technology Centre, AG Noordwijk, The Netherlands.

Publisher Item Identifier S 0196-2892(01)06673-6.

[1]This paper describes the baseline mission. The project is currently undergoing phase A studies, which may result in changes of some of the instrument parameters.

A Simple Parameterization of the L-Band Microwave Emission from Rough Agricultural Soils

Jean-Pierre Wigneron, Laurent Laguerre, and Yann H. Kerr

***Abstract*—A simple model for simulating the L-band microwave emission from bare soils is developed. The model is calibrated on a large set of measurements obtained during a three-month period over seven plots covering a wide range of surface roughness (representing the total range which can be expected on agricultural fields), soil moisture, and temperature conditions. The approach is based on the parameterization of an effective roughness parameter as a function of surface characteristics: surface roughness (standard deviation of height and correlation length) and the surface soil moisture. The parameterizations that are developed are independent of incidence angle and polarization and are valid over a large range in surface roughness conditions, representative of most of typical agricultural bare fields, from very smooth (rolled field after sowing) to very rough surfaces (deeply plowed soil). This approach will enable the use of microwave radiometric observations for soil moisture retrieval over agricultural areas.**

I. INTRODUCTION

PREVIOUS research has shown that L-band passive microwave remote sensing sensors can be used to monitor soil moisture over land surfaces [1]–[4]. However, the effects of vegetation cover [5]–[9] and soil surface roughness [10]–[14] also play a significant role in the microwave emission from the surface. Therefore, a good parameterization of these two effects is a prerequisite for retrieving surface soil moisture information. The development of an efficient parameterization of the soil roughness effects could be very useful for large scale simulation studies. For instance, simulation studies could be implemented for evaluating the time changes in emissivity due to seasonal agricultural practices and how these changes may affect soil moisture retrievals over large scale agricultural sites.

Several physically-based models have been developed to account for the effect of surface roughness on the observed brightness temperature T_B [15]. These models are generally driven by surface characteristics derived from measurements of surface height profiles: the standard deviation in surface height (σ_S), the autocorrelation function, and the associated correlation length (L_C). These models can be very useful to develop the understanding of the microwave scattering effects by the soil surface.

However, there are some limitations in the use of these approaches. Ranges of validity frequently limit the use of a single modeling approach over a large range of surface roughness [13] and the validity of scattering models for high incidence angles may be often critical for an accurate simulation of bare soil passive microwave emission. Also, an accurate estimation of the surface characteristics requires a large number of height observations, both in terms of sampling intervals and profile length [16], [17]. These requirements cannot be met easily over a large number of field plots.

Finally, simple surface characteristics, as obtained from measurements of height profile, are inadequate to describe complex interactions between the soil medium and the microwave radiation. There are generally strong heterogeneities in the spatial variations of the soil characteristics (structure, moisture content, density, ...) within the soil volume over agricultural fields. For instance, for plowed soils, when dry and sunny conditions follow rainfall or irrigation events, large emerging clods are drying out more rapidly than hollows within the fields. These effects may lead to a large spatial variability in the soil moisture content at a spatial scale of about 1 m. There are also nonuniformities in the soil moisture in the soil clods, at a lower spatial scale of a few centimeters. These heterogeneities produce significant dielectric discontinuities at the soil surface and within the soil volume. At L-band, the thickness of the soil layer whose dielectric properties contribute to the soil microwave emission may exceed 10 cm [18], [19]. Therefore, both surface and volume effects are significant and should be considered by physically-based models at L-band. Studying these effects would require complex and time consuming electromagnetic approaches and an accurate three-dimensional (3-D) description of the soil volume that cannot be easily obtained.

Simplified semi-empirical approaches have also been developed. Most of these approaches are based on two roughness parameters: the roughness height h_S and a polarization mixing parameter Q_S that can be retrieved from brightness temperature measurements [10], [11]. These modeling approaches are generally found to be very useful in most soil moisture retrieval studies. However, the dependence of the model roughness parameters (h_S and Q_S) on the surface roughness characteristics $(\sigma_S, L_C, \ldots)$ is not well known. Several studies provided values for h_S and Q_S obtained from microwave observations over bare fields [11], [12]. However, the experimental data sets that were used in these studies were usually not large enough to allow the development of parameterizations with a large range of validity. Mo *et al.* [20] developed a simple parameterization to compute h_S as a function of σ_S, L_C and w_S. However, this parameterization was not validated over the whole range of soil roughness conditions encountered in agricultural fields, being only based

Manuscript received October 4, 2000; revised April 20, 2001.

J.-P. Wigneron is with the Institut National de Recherches Agronomiques (INRA), Climat Sol Environnement (CSE), Avignon Cedex 9, France (e-mail: wigneron@avignon.inra.fr).

L. Laguerre is with the Laboratoire Central des Ponts et Chausées (LCPC), Nantes, France.

Y. H. Kerr is with the Centre National d'Etudes Spatiales (CNES)/CESBIO, Toulouse Cedex 4, France.

Publisher Item Identifier S 0196-2892(01)06674-8.

Communications

Two-Dimensional Synthetic Aperture Images Over a Land Surface Scene

Franck Bayle, Jean-Pierre Wigneron, Yann H. Kerr, Philippe Waldteufel, Eric Anterrieu, Jean-Claude Orlhac, André Chanzy, Olivier Marloie, Marc Bernardini, Sten Sobjaerg, Jean-Christophe Calvet, Jean-Marc Goutoule, and Niels Skou

***Abstract*—The Soil Moisture and Ocean Salinity (SMOS) space mission is currently undergoing phase-B studies at the European Space Agency. The SMOS payload is an L-band interferometric radiometer based on a two-dimensional aperture synthesis concept. This paper presents the first images obtained by a demonstrator of the SMOS instrument over land surfaces at the Avignon test site in 1999.**

***Index Terms*—L-Band radiometry, passive microwave remote sensing, soil moisture, 2-D interferometer.**

I. Introduction

A number of experiments using both ground-based and airborne sensors have shown the high potential of L-band microwave radiometry for monitoring surface soil moisture w_S (m^3/m^3) over large areas [1]–[4]. However, from space, large antennas (several meters) are required to achieve a suitable spatial resolution at the L band. To overcome the problem of putting into orbit a large filled antenna, the possibility of using antenna synthesis methods has been investigated.

Such a system, relying on a deployable structure, has led to the Soil Moisture and Ocean Salinity (SMOS) mission [5], [6]. The SMOS mission was proposed to the European Space Agency (ESA) in the framework of the Earth Explorer Opportunity Missions and was selected for a tentative launch in 2006. The main objective of this mission is to deliver key variables of land surfaces (soil moisture fields) and of ocean surfaces (sea surface salinity fields). The SMOS mission is based on a dual-polarized L-band radiometer using aperture synthesis (two-dimensional (2-D) interferometer) so as to achieve a ground resolution of 50 km at the swath edges coupled with multi-angular observations. The radiometer will enable a frequent (3-day revisit) and global coverage. The payload of SMOS is an L-band interferometer based on an innovative, 2-D aperture synthesis concept. Recent developments of the so-called interferometry design were inspired from the very large baseline antenna concept used in radio astronomy. The idea consists of deploying small receivers in space (located on a deployable structure), then reconstructing a brightness temperature (T_B) field with a resolution corresponding to the spacing between the outmost receivers. An aircraft prototype (ESTAR, Electronically Scanned Thinned Array Radiometer) based on this concept was built by NASA. It was designed as an L-band hybrid real and one-dimensional (1-D) synthetic aperture radiometer [7]. This instrument showed the validity of the hybrid instrument concept in several soil moisture mapping experimental campaigns [3], [4].

As an alternative, a concept based on 2-D aperture synthesis has been proposed [8]. This concept, the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS) became the core of the ESA Earth Explorer SMOS mission. The 2-D interferometer allows measuring brightness temperature (T_B) at several incidence angles, for two polarizations. The instrument instantaneously records a whole scene. Consequently, as the satellite moves, a given point within the 2-D field of view is observed with different view angles. The series of independent measurements allows retrieving surface parameters with much improved accuracy [9], [10]. An airborne demonstrator of MIRAS was developed to validate the concept. The MIRAS antenna consists of equally spaced antenna elements distributed along three equispaced coplanar arms (Y-shaped antenna). In 1999, the first experimental campaign was carried out at the Institut National de la Recherche Agronomique (INRA) Avignon experimental test site with MIRAS. The objective of the experiment was to demonstrate the 2-D synthetic aperture radiometry concept over a natural land surface scene. MIRAS was mounted on a crane boom and observations were carried out at different view angles over a large bare soil field. A specific scene with large contrasts in the soil surface emissivity was designed. The first images obtained by the 2-D synthetic aperture radiometer over this land surface scene are presented in this paper. Due to some technical problems, the full capabilities of the 2-D interferometry concept could not be totally exploited. However, in spite of these problems, the images could reveal the main 2-D emissivity patterns of the observed scene.

II. Experimental Setup

The experiment was carried out on a bare plot located on the INRA Avignon remote sensing test site. The soil is silty clay loam (48.7% silt, 14.8% sand and 36.5% clay). The demonstrator was mounted on a 20-m crane boom. The crane can be moved along a rail track, parallel to the site's main field. During the experiment, this field was without any vegetation and the surface was rough. To obtain large contrasts in soil surface emissivity over the plot, the field was artificially modified (Figs. 1 and 2). The scene thus consisted of a rough bare field, in which two 10-m-large smooth strips were made with a roadroller. In the middle of the plot, a 5 m $\times$ 5 m rectangular water pool (about 20-cm depth) was included. The length (L) of the crane displacement along the rail track was of 85 m. To increase the contrast in emissivity between the rough and the smooth strips, garden hoses were used to manually irrigate (saturation) both strips at the time of the radiometric observations. Thus, the wet smooth strips had a low microwave emission (estimated brightness temperature $T_B \approx 220$ K at incidence angle $\theta = 0°$), while the dry rough field had a high microwave emission (estimated $T_B \approx 280$ K at $\theta = 0°$).

The axis of the radiometer (boresight) was kept within a plane parallel to the railtrack, which is also almost parallel to the directions of the rows due to tillage (Fig. 1). The angular resolution for MIRAS is 14° leading to approximately 5-m spatial instantaneous resolution in

Manuscript received May 18, 2001; revised October 24, 2001.

F. Bayle, J.-C. Orlhac, and J.-M. Goutoule are with ASTRIUM, 31402 Toulouse Cedex 4, France.

J.-P. Wigneron is with INRA-Unité de Bioclimatologie, 33883 Villenave d'Ornon Cedex, France.

Y. H. Kerr is with CESBIO, 31401 Toulouse Cedex 4, France (e-mail: kerr@cesbio.cnes.fr).

P. Waldteufel is with the Service d'Aéronomie (CNRS/IPSL), 91371 Verrières-le-Buisson, France.

E. Anterrieu is with CERFACS, 31057 Toulouse Cedex 01, France.

A. Chanzy, O. Marloie, and M. Bernardini are with INRA/CSE, 84914 Avignon Cedex, France.

S. Sobjaerg and N. Skou are with the Technical University of Denmark (TUD), Dk 2800 Lyngby, Denmark.

J.-C. Calvet is with Météo-France/CNRM, 31057 Toulouse, France.

Publisher Item Identifier S 0196-2892(02)03684-7.

ELSEVIER

Remote Sensing of Environment

Two-Dimensional Microwave Interferometer Retrieval Capabilities over Land Surfaces (SMOS Mission)

J.-P. Wigneron, P. Waldteufel,† A. Chanzy,‡ J.-C. Calvet§ and Y. Kerr¶*

This paper discusses the potential of an L-band 2-D microwave interferometric radiometer for monitoring surface variables over land surfaces. The instrument is the payload of the Soil Moisture and Ocean Salinity (SMOS) Mission recently selected for phase A studies by the European Space Agency (ESA) as the second Earth Explorer Opportunity Mission. The L-band radiometer is based on an innovative two-dimensional aperture synthesis concept. This sensor has new and significant capabilities, especially in terms of multiangular viewing configurations. The main aspects of the retrieval capabilities of SMOS for monitoring soil moisture, vegetation biomass, and surface temperature are presented in this paper. The analysis is based on model inversion. The standard errors of estimate of the surface variables are computed for various configurations as a function of both the uncertainties associated with the space measurements and those associated with the ancillary information used in the retrievals. The potential of SMOS and the possibility to retrieve one, two, or three surface variables are investigated, depending on the view angle configuration. These questions are key issues to optimize the SMOS mission scenario, to meet both the scientific requirements and the technical constraints of the mission.

* INRA Bioclimatologie, Agroparc 84914 Avignon Cedex 9, France

† CETP, 10-12 av de l'Europe, 78140 Vélizy, France

‡ INRA Science du sol, Agroparc 84914 Avignon Cedex 9, France

§ Météo France/CNRM, 42 av G. Coriolis, 31057 Toulouse, France

¶ CESBIO, 18 av E. Belin, 31401 Toulouse Cedex 04, France

Address correspondence to J.-P. Wigneron, INRA Bioclimatologie, Agroparc 84914, Avignon, Cedex 9, France. E-mail: wigneron@avignon.inra.fr

Received 23 June 1999; revised 1 February 2000.

INTRODUCTION

A number of experiments using both ground-based and airborne sensors have shown the high potential of microwave radiometry for monitoring surface soil moisture w_S (m^3/m^3) over large areas (Schmugge et al., 1974; Schmugge et al., 1994; Wang et al., 1983; Wang et al., 1990; Teng et al., 1993; Jackson et al., 1995; Calvet et al., 1995; Chanzy et al., 1997). Simple or complex modeling approaches have been developed and tested against experimental data sets (Ulaby et al., 1986; Tsang et al., 1985; Wigneron et al., 1993a; Wigneron et al., 1993b; Kerr and Wigneron, 1994; Raju et al., 1995; Ferrazzoli and Guerriero, 1996). Based on the acquired data sets and modeling expertise, it is now possible to characterize accurately the potential of microwave radiometers as a function of the sensor configuration (polarization, view angle, and frequency).

This paper aims at analyzing the potential capabilities of a two-dimensional (2-D) microwave interferometric radiometer for monitoring the surface variables over the land surface. This instrument is the payload of Soil Moisture and Ocean Salinity (SMOS) Mission, the second Earth Explorer Opportunity Mission recently selected by the European Space Agency (ESA) for phase A studies. The SMOS mission (Kerr et al., 1998) is scheduled for launch in 2004. The L-band interferometer is based on an innovative, 2-D aperture synthesis concept, which was explored by ESA within the MIRAS research program (Goutoule, 1995). The sensor has new and significant capabilities, especially in terms of multiangular viewing configuration (Waldteufel et al., 1999).

The multiangular viewing capability of a 2-D interferometric spaceborne radiometer stems from the fact that the instantaneous field of view (FOV) is two-dimensional,

REMOTE SENS. ENVIRON. 73:270–282 (2000)

655 Avenue of the Americas, New York, NY 10010

0034-4257/00/$–see front matter
PII S0034-4257(00)00103-6