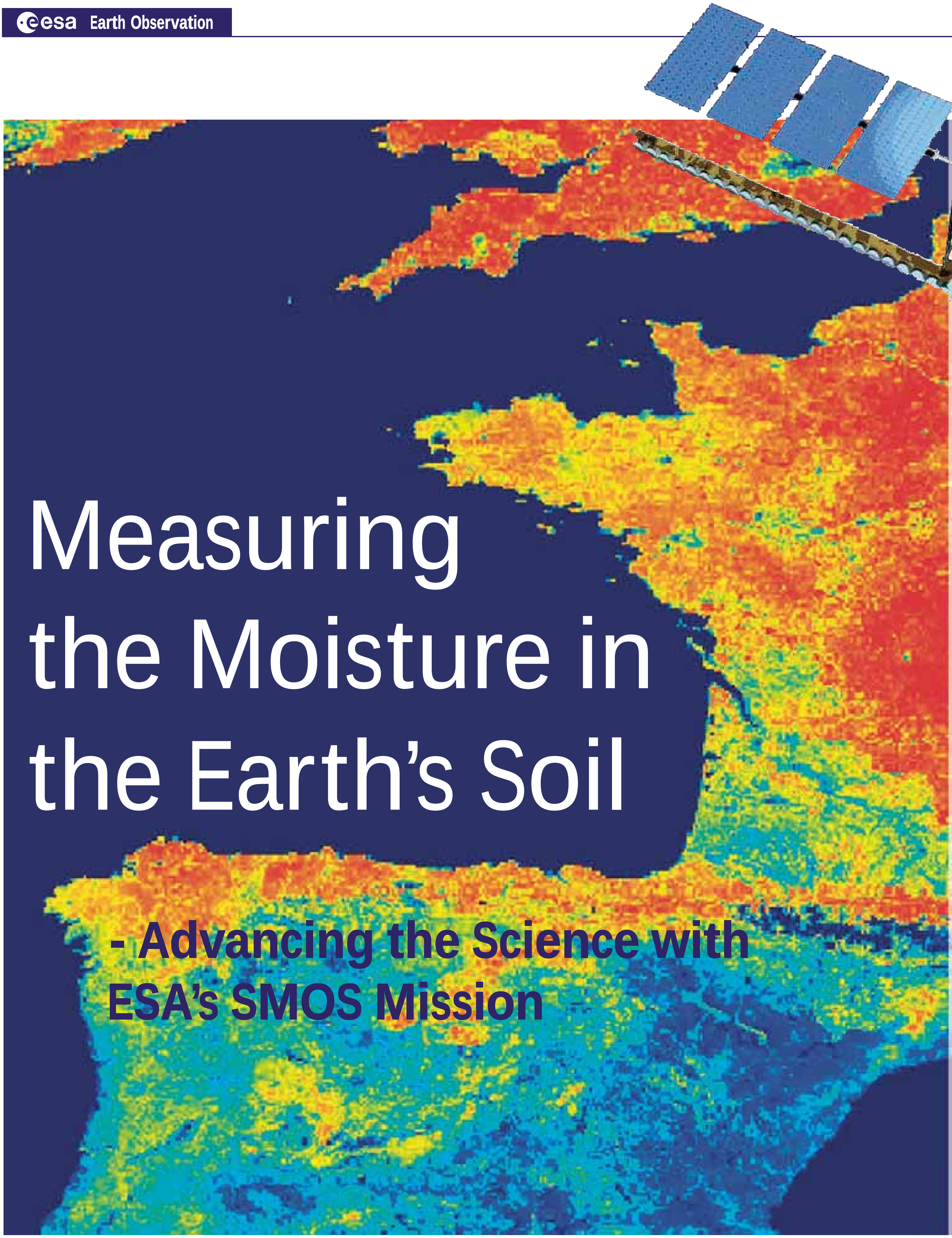
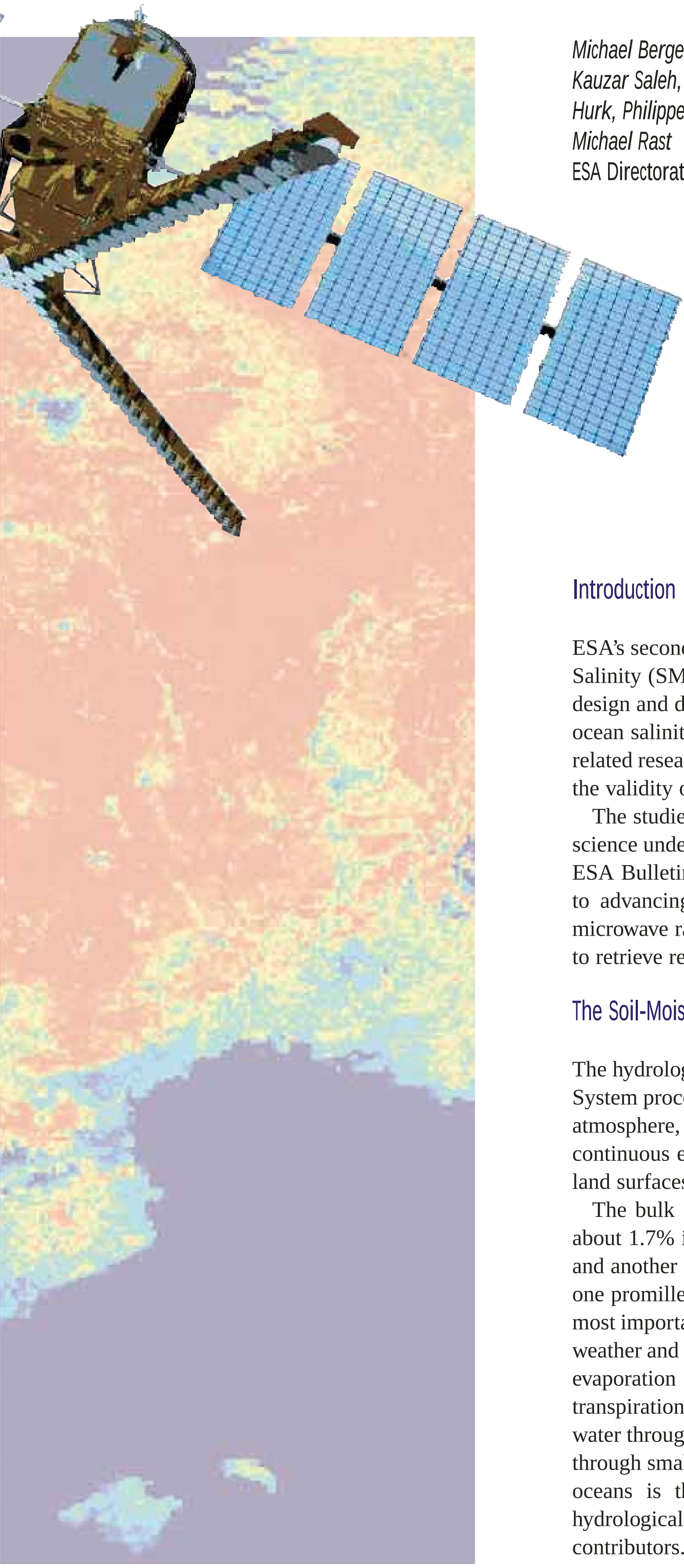


Measuring the Moisture in the Earth's Soil

- Advancing the Science with ESA's SMOS Mission



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Introduction

ESA's second Earth Explorer Opportunity Mission, the Soil Moisture and Ocean Salinity (SMOS) mission scheduled for launch in early 2007, is currently in the design and development phase. Given that today's lack of global observations of ocean salinity and soil moisture is holding back progress in many environment-related research fields, the mission has broad and ambitious scientific objectives, the validity of which is internationally recognised.

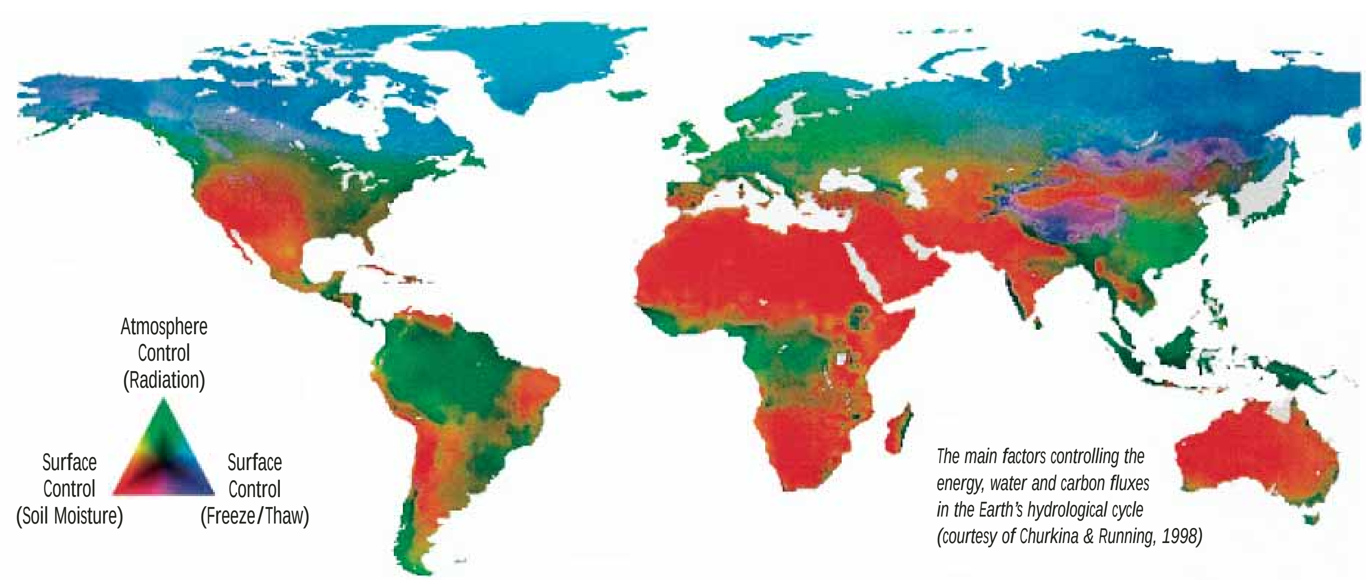
The studies and campaign activities undertaken by the Agency to advance the science underlying the ocean-salinity objectives of the mission were presented in ESA Bulletin No. 111. This article therefore focuses on the activities dedicated to advancing our knowledge of the 'brightness temperature' associated with microwave radiation emitted by the Earth's land surfaces and thereby our ability to retrieve reliable soil-moisture data.

The Soil-Moisture Objectives

The hydrological cycle is one of the most important but poorly understood Earth System processes. It involves the journey of water from the Earth's surface to the atmosphere, and back again. This gigantic system, which is responsible for the continuous exchange of moisture between our planet's oceans, atmosphere, and land surfaces is powered by the energy from the Sun.

The bulk of the Earth's water (about 96.5%) is stored in the global oceans, about 1.7% is stored in the polar ice caps, glaciers, and permanent snow fields, and another 1.7% is stored in groundwater, lakes, rivers, streams, and soil. Only one promille of our planet's water is present in the atmosphere, but it is still the most important 'greenhouse gas' and therefore has a very strong influence on our weather and climate. About 90% of this atmospheric water vapour is produced by evaporation from bodies of open water like oceans, lakes, and rivers. Plant transpiration and soil evaporation supply the remaining 10%. Plants take up water through their root systems to deliver nutrients to their leaves, and release it through small pores in their leaves, called 'stomata'. While evaporation from the oceans is the primary driver of the surface-to-atmosphere portion of the hydrological cycle, plant transpiration and soil evaporation are also significant contributors.

The unsaturated zone between the Earth's soil surface and the water table – known as the 'vadose' zone – is penetrated by the roots of vegetation, which take up some of the water. Hence the amount of water in this zone, which determines the 'soil moisture', varies with time as a function of the amount of precipitation and the root water take-up, governed by the degree of vegetation cover, the energy being received from the Sun, and run-off and percolation. The properties of the soil determine its storage capacity and the transport process within the soil.



The main factors controlling the energy, water and carbon fluxes in the Earth's hydrological cycle (courtesy of Churkina & Running, 1998)

Soil moisture therefore plays a crucial role in our planet's hydrological cycle. In most of the world, the water supply is the factor that most affects plant growth and crop yields, and hence food supplies. The strategic importance of world water resources and food production make soil moisture a crucial variable for policy decisions also. Remote sensing by satellite, if achievable with sufficient accuracy and reliability, would provide truly meaningful soil-moisture data for hydrological studies over large continental regions.

Soil-Moisture Retrieval

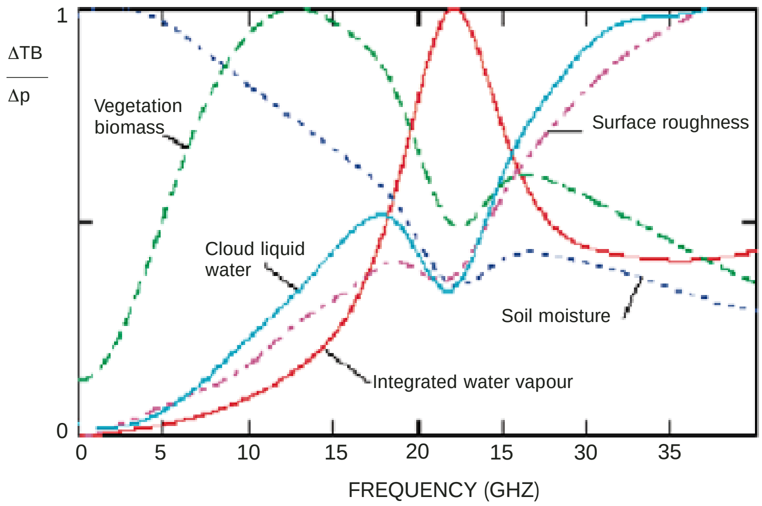
While both active and passive microwave remote-sensing techniques can be used in all weathers for land-surface monitoring, the signal-to-noise ratio from dry to wet soils is significantly higher for passive radiometers than for active radars. In addition, the radar signal is more sensitive to structural features such as soil roughness or vegetation canopy geometry than to soil-moisture variations. Correcting for the effects of vegetation is in fact the main issue in monitoring soil moisture using passive microwave measurements because the vegetation absorbs part of the microwave emission from the soil surface, and contributes to it. Research has shown that L-band (1.4 GHz – 21 cm) microwave radiometry has considerable advantages, because both vegetation attenuation and atmospheric effects are greater at higher frequencies. At L-band, however, this attenuation is moderate and can be corrected for, and the 'brightness temperature' signal is sensitive to soil moisture for vegetated areas with biomasses of up to 5 kg/m^2, which represents about 65% of the Earth's land surface.

The 'brightness temperature' of a given land surface depends on the vegetation layer's optical thickness, the effective surface temperature, and the soil type and roughness as well as the soil moisture. In order to discriminate between these effects, microwave radiometry offers the possibility of acquiring data at different polarisations, different incidence angles, and possibly different frequencies. The SMOS payload will therefore have dual-polarisation (optional full polarisation) and multi-angular imaging capabilities.

Since L-band microwave data only provide information about the moisture content of a relatively shallow surface layer (about 3–5 cm at L-band), special techniques have been developed to derive the moisture content within the vadose zone from time series of near-surface soil-moisture data. It was shown that surface soil-moisture values measured once every three days from space are sufficient to retrieve the water content in the vadose zone as well as the evapo-transpiration flux.

Scientific Support Studies

A number of scientific questions related to the physics of the signal-retrieval process and the derivation of near-surface soil moisture needed to be addressed at the beginning of the feasibility study phase for the SMOS mission. In addition, appropriate experiment campaigns had to be organised and conducted to provide suitable data. The following paragraphs briefly outline the main activities initiated by ESA and their preliminary results. Additional study and campaign activities were initiated by national programmes. Activities were coordinated via the SMOS Science Advisory Group and relevant workshops involving the various study and campaign teams.



Sensitivity of 'brightness temperature' to different variables as a function of frequency

Studies initiated by ESA have included:

• *'Soil Moisture Retrieval by a Future Space-borne Earth Observation Mission'*
This study, kicked-off in October 2000 and completed in March 2003, was managed by the University of Reading (UK) and involved 10 European institutes. The overall goal was to determine the soil-moisture product and accuracy requirements for a spaceborne Earth-observation mission for scientific and semi-operational applications. Specific objectives of the study were to:
– demonstrate the soil-moisture retrieval capability of polarimetric brightness-temperature observations acquired by an L-band interferometric radiometer, review existing soil-moisture retrieval techniques, and determine the attainable accuracy
– improve existing retrieval techniques and/or develop new retrieval algorithms for soil moisture taking due account of surface heterogeneity and rugged terrain, and
– validate the retrievals via case studies.

• *'Soil Moisture Retrieval for the SMOS Mission'*
This one-year study, kicked-off in July 2002, is managed by ACRI-ST and involves 5 research institutes within Europe. The main goal is to review existing, and develop and analyse new soil-moisture retrieval schemes compatible with the observation characteristics of the SMOS mission and by taking into account spatial and temporal land-surface variability. The study makes extensive use of the simulated dataset generated within the earlier study, and the resulting soil-moisture retrieval scheme will be implemented in the SMOS End-to-end Performance Simulator (SEPS).

Scientific Requirements for Soil-Moisture Measurements

The scientific requirements for the SMOS mission have been formulated to gain maximum information on the surface-emitted 'brightness temperature' to allow the retrieval of surface soil moisture with an accuracy in the range of its natural variability. These requirements are:

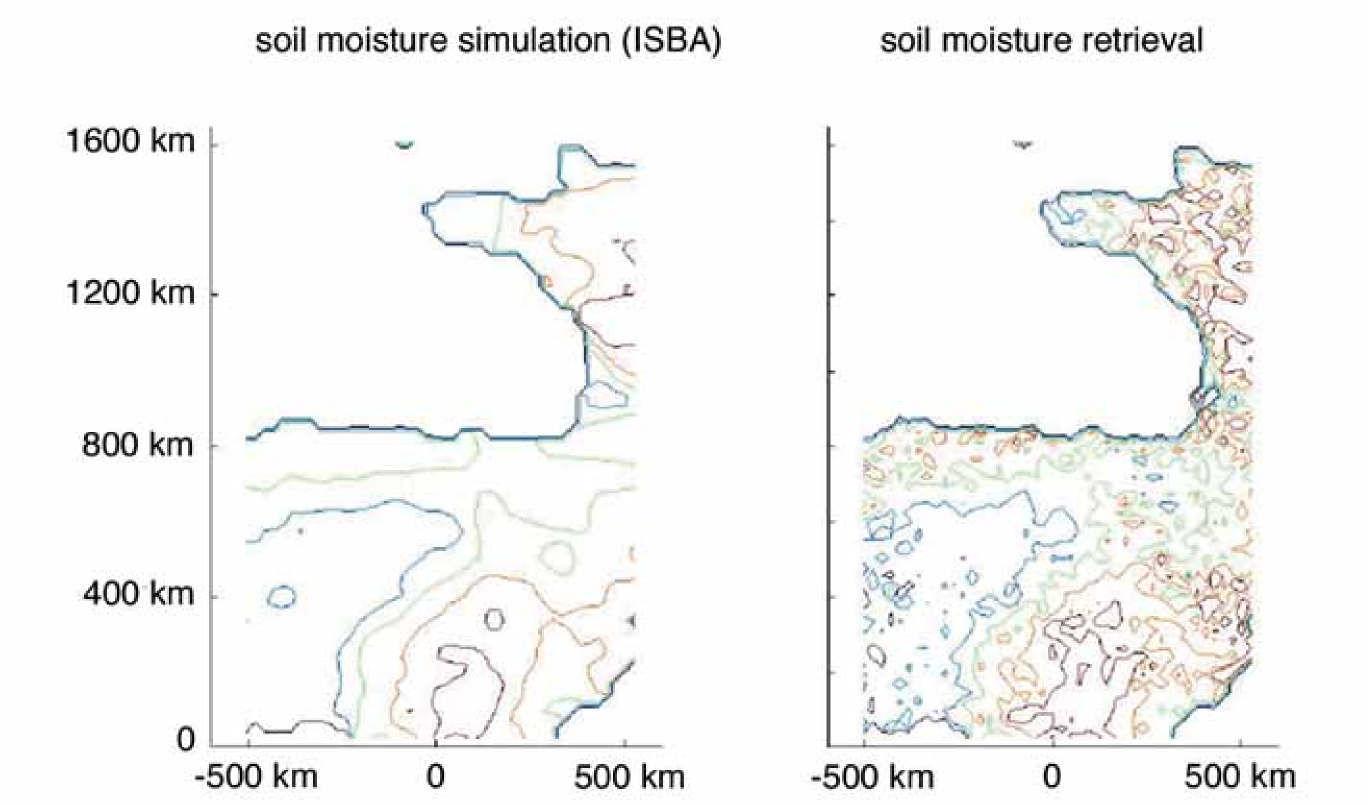
- Soil-moisture Accuracy: 0.04 m^3 m^{-3} (i.e. 4% volumetric soil moisture) or better
For bare soils, for which the influence of near-surface soil moisture on surface water fluxes is strong, it has been shown that a random error of 0.04 m^3 m^{-3} allows a good estimation of the evaporation and soil transfer parameters.

- Spatial Resolution: < 50 km
For providing soil-moisture maps to global atmospheric models, a 50 km resolution is adequate, and will allow hydrological modelling with sufficient detail for the world's largest hydrological basins.

- Global Coverage: ± 80° latitude or higher

- Revisit Time: 2.5 to 3 days
A 3 to 5 day revisit cycle is sufficient to retrieve vadose-zone soil-moisture content and evapo-transpiration, provided ancillary rainfall information is available. To track the quick-drying period after rain has fallen, which is very informative about the soil's hydraulic properties, a one- or two-day revisit interval is optimal. The stipulated 2.5 to 3 day bracket will satisfy the first objective always, and the second one most of the time.

- Observation Time:
The precise time of the day is not critical for data acquisition, but the early morning (about 06:00 h) is preferable, when ionospheric effects can be expected to be minimal and conditions are as close as possible to thermal equilibrium. The retrievals will then be more accurate, but dew and morning frost can sometimes affect the measurements.



Preliminary results achieved with the soil-moisture retrieval algorithm for the SMOS mission over Western Europe (summer season). Left: contours of reference surface soil moisture used to create the synthetic SMOS data. Right: contours of retrieved soil moisture. Dark blue, light blue, green, orange and chestnut-coloured contours correspond to soil moistures of 0.1, 0.15, 0.2, 0.25 and 0.3 $m^3.m^{-3}$, respectively

The study should also provide recommendations with regard to several open options in the design of the SMOS mission, including the polarimetric operating mode and the final design of the soil-moisture retrieval algorithm. The recommendations and conclusions will be based on a series of simulation scenarios, for which adequate assessment tools have already been defined.

The experiment campaigns that have also been carried out to refine the SMOS mission include:

• *EuroSTARRS*

The main objective behind the first use of the Salinity Temperature and Roughness Remote Scanner (STARRS) sensor in Europe, from 16 to 23 November 2001, was to acquire SMOS-like observations in order to address a range of critical issues related to the mission's soil-moisture objectives. The STARRS L-band sensor, belonging to the US Naval Research Laboratories, was operated for the campaign aboard a Dornier 228 by the German Aerospace Center (DLR).

The campaign objectives for the 'land' test sites were to:
– characterise the relationship between vegetation optical depth and incidence angle for a range of vegetation types (orchards, coniferous trees, deciduous trees, shrubs)
– study scaling issues and validate the retrieval techniques accounting for mixed pixel effects
– study the effects of topography
– investigate the L-band emission from urban areas and the level of radio-frequency interference.

Five very different test sites in France and Spain were used:
– a site northwest of Valencia (Requena) with low natural vegetation and agricultural fields (olive and almond trees)
– a deciduous forest site north of Toulouse (Agre)
– a coniferous forest site near Bordeaux (Les Landes)
– a site in the Pyrenees (for measuring topographic effects), and
– a flight path over the city of Toulouse.

Intensive fieldwork by large ground teams provided in-situ information for surface temperature, characterisation of the surface cover (vegetation type, biomass,

The STARRS instrument mounted beneath DLR's Dornier 228 aircraft for the ESA EuroSTARRS campaign litter mass, fractional vegetation cover, fractional soil cover, soil texture and roughness, etc.), and soil moisture (gravimetric and theta-probe measurements) during the aircraft overflights.

The data set generated by the EuroSTARRS campaign is extremely large, and a great deal of effort still has to be invested to analyse it in its entirety. The campaign itself was an opportunity to unite the efforts of several teams, and proved instrumental in structuring the SMOS scientific community.

Outlook

The studies and campaigns conducted so far have been instrumental in encouraging international collaboration and generating interest and momentum within the science community. Many potential applications have been identified, and retrieval concepts have been developed which are currently being fine-tuned. The studies and campaigns have also proved extremely useful in identifying the next steps to be taken in preparing for the mission.

When launched in 2007, SMOS will be able to observe the brightness temperatures of all of the Earth's land surfaces at least once every three days, regardless of weather conditions and largely unaffected by atmospheric effects. These observations will allow the retrieval of soil-moisture data with unprecedented accuracy, thereby greatly improving our knowledge of the water content of continental soils and its representation in our hydrological, meteorological and climatological models. This in turn will substantially improve our understanding of, and ability to monitor, the water resources of our planet on a global basis. These are critical factors in our mastery of the economic and political consequences of climate change and our ability to manage the world's food and water resources in the longer term.

Acknowledgement

The authors would like to express their gratitude to the study and campaign teams and to the SMOS Science Advisory Group for their invaluable contributions.