Mission Objectives and Scientific Requirements

of the

Soil Moisture and Ocean Salinity (SMOS) Mission

Version 5

Executive Summary

The main scientific objectives of the Soil Moisture and Ocean Salinity (SMOS) mission are to observe two crucial variables: soil moisture over land surface and sea surface salinity over oceans. The mission should also provide information on root zone soil moisture and vegetation and contribute to significant research in the field of the cryosphere

SMOS is a demonstrator with broad and ambitious scientific objectives, as the lack of global observations of salinity and soil moisture are retarding progress in many research fields. The need for these data has been highlighted for a long time in major international scientific initiatives. The mission will give Europe a clear lead in this area. The SMOS concept may also pave the way for more ambitious concepts providing higher spatial resolution.

The baseline instrument of SMOS is a L-band (1.4GHz) 2D interferometric radiometer, Y shaped, with three arms each about 4.5m long. The instrument will be accommodated on a PROTEUS platform. The folded satellite is compatible with most launchers.

The technological solution is feasible as proven by several pre-developments (see Microwave Imaging Radiometer using Aperture Synthesis (MIRAS)). However, significant challenges are still to be addressed for the sea surface salinity retrieval over oceans, and in terms of accounting for mixed pixels and variable footprints for soil moisture retrieval over land. These issues will be studied further during Phase A studies supported by dedicated campaign activities planned to be conducted in the near future.

Contents

Acronyms and Symbols:

ACQUA	Second EOS MTPE mission (Ex EOS-PM)
ADEOS	Advanced Earth Observing Satellite “MIDORI”
CLIVAR	Climate Variability and Predictability Program
ENSO	El Niño - Southern Oscillation)
EOS	Earth Observing System
ESA	European Space Agency
ESTAR	Electronically Scanned Thinned Array Radiometer
FIFE	First ISLSCP Field Experiment
FOV	Field of View
GCIP	Global Change Continental-Scale International Project
GCRP	Global Change Research Program
GEWEX	Global Energy and Water EXperiment
GOALS	Global Ocean-Atmosphere-Land System
GODAE	Global Ocean Data Assimilation Experiment
HAPEX	Hydrologic and Atmospheric Pilot Experiment
METOP	Meteorological Operational satellites
MIRAS	Microwave Imaging Radiometer using Aperture Synthesis
MRD	Mission Requirements Document
MUREX	Monitoring the Usable soil Reservoir EXperimentally
NDVI	Normalised Difference Vegetation Index
NRC	National Research Council
OS	Ocean Salinity
PBMR	Push Broom Microwave Radiometer
PORTOS	Microwave radiometer (1.4 to 90 GHz) for ground or A/C Operations
SM	Soil Moisture
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SSM/I	Special sensor Microwave/Imager
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SVAT	Soil Vegetation Atmosphere Transfer
TERRA	First EOS MTPE Mission (ex EOS-AM)

Symbol	Signification	Unit
F	Frequency	GHz
P	Polarisation	
T_s	Surface temperature	K
W_2	Root zone soil moisture	m^3/m^3
W_c	Vegetation integrated water content	Kg/m^2
W_s	Surface soil moisture	m^3/m^3
ι	Incidence angle	Degrees
θ_e	View angle across track	degrees
τ	Vegetation opacity	Nepers
psu	Practical salinity units	$\%_0$
T_B	Brightness temperature	K

1. Introduction

For the post-2000 time-frame, two main general classes of Earth Observation missions have been identified by ESA to address users' requirements, namely:

- **Earth Watch Missions** - these are pre-operational missions concerned with the operational needs of the users' community ensuring the continuous provision of data.
- **Earth Explorer Missions** - these are research and demonstration missions concerned with advancing the understanding of the different Earth system processes and demonstrating the advantages and performances of new observing techniques.

In turn the Earth Explorer Missions are split into two categories, namely:

- **Core missions** (larger mission led by ESA)
- **Opportunity missions** (smaller and more flexible mission not necessarily ESA led)

The first call for Earth Explorer Opportunity missions was issued in summer 1998. In response to the announcement 27 proposals were received. Out of the 27 proposals, two were selected for implementation following the scientific advice of the Earth Sciences Advisory Committee late May 1999. The two selected missions are Cryosat (a mission to assess the polar ice) and SMOS (Soil Moisture and Ocean Salinity).

It is the scope of this document to outline the mission objectives and from it the derived scientific and mission requirements of the SMOS mission which is planned for launch in 2005. This Mission Requirement Document (MRD) is intended to provide guidelines for the technical implementation of the mission.

The document has been divided into 4 chapters including the introduction addressing the scientific background, the objectives of the mission, and the derived mission and observational requirements.

2. Scientific Background

Significant progress for weather forecasting, climate monitoring and extreme events forecasting rely on a better quantification of both Soil Moisture (SM) and Sea Surface Salinity (SSS). Several groups concluded in recently organised workshops that further improvements depend on the availability of global SM and SSS observations.

SM and SSS observations are of relevance to Theme 2 (Physical Climate) and to Theme 3 (Geosphere-Biosphere) of ESA's Living Planet programme. They contribute in particular to research studies related to the seasonal to inter-annual climate variations and processes.

A SM and SSS monitoring initiative will also directly address the national priority of the Global Change Research Program (GCRP) to develop improved capability to understand and predict the Earth’s environment especially for climate-sensitive sectors at regional scale. A new data stream on SM will also substantially impact international science programs such as Global Energy and Water Cycle Experiment (GEWEX) and the Global Ocean-Atmosphere-Land System (GOALS) component of Climate Variability and Predictability Program (CLIVAR) that are focused on the “fast” and “slow” components of climate variability. Recent reviews of these programs have consistently identified that the observation and characterisation of SM is the observation priority.

2.1. Soil Moisture (SM) Observations

Water and energy fluxes at the surface/atmosphere interface are strongly dependent upon SM. Evaporation, infiltration and runoff are driven by SM and in the vadose zone it governs the rate of water uptake by the vegetation. SM is thus a key variable in the hydrologic cycle. SM, and its spatio-temporal evolution as such, is an important variable for numerical weather and climate models, and should be accounted for in hydrology and vegetation monitoring.

Information on SM and vegetation water content enables modelling the hydrologic dynamics which helps furthering understanding and monitoring of the water reservoirs. These are critical to the climate and economy, and provide means for seasonal forecasting.

Further topics related to Physical Climate, which are covered within Theme 3 (Geosphere-Biosphere) of the Living Planet programme, would also benefit from a SM mission (e.g. role and influence of vegetation in the water and energy cycle, spatial and temporal distribution of evapotranspiration). This is because SM is not only a key variable for hydrological cycles but because it is also a key variable driving the interactions (fluxes) between the land surface and the atmosphere. Thus, there is a range of prospective impacts in different research fields by routinely observing SM, whereas major impacts are expected for research studies related to Earth climate and Earth environment systems.

In the US, the National Research Council (NRC) review (1995) by the Board of Sustainable Development recommends that NASA shall advance technology for small satellites to supply SM measurements from space. Similarly the NRC review (1998a) of the GEWEX Continental-Scale International Project (GCIP) has identified SM observations and monitoring as one of its six principal recommendations. GOALS has also identified measurement of SM as a requirement for understanding and predicting climate variability (NRC, 1998b).

The lack of a space-borne system for global SM observation is one of the most glaring and pressing deficiencies in satellite remote sensing and climate research. Ongoing programs such as GEWEX-GCIP and GOALS will undoubtfully benefit from a SM mission.

2.2 Sea Surface Salinity (SSS) Observations

Ocean salinity is a key-variable which characterises the ocean circulation. It's observation advances understanding of the water cycle. It is also an important circulation tracer for water masses. Unlike other oceanographic variables, it has not yet been possible to measure salinity from space. Thus, large ocean areas lack significant salinity measurements. Satellite-based sensors have the potential to provide consistent global SSS measurements at 50-100 km resolution and resolve at least seasonal to inter-annual time scales. It is stated in the scientific design plan for the Global Ocean Observing System: *"The improvement of the ocean salinity data base must have high priority since it is an important constraint in ocean models, an indicator of freshwater capping, and may have predictive uses in the tracking of high latitude salinity anomalies that could affect regional climate".*

SSS plays an important role in the Northern Atlantic sub polar area, where intrusions with low salinity influence the deep thermohaline circulation and the meridional heat transport. Salinity variations 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 inter-annual variability are thus tracers and constraints on the water cycle and on the coupled ocean-atmosphere models. Thus, SSS observations will provide important information on furthering the above mentioned research fields.

2.3 Cryosphere Observations

Obtaining additional information about sea ice is relevant in that it affects ocean-atmosphere heat fluxes and dynamics.

Significant research progresses are expected for the cryosphere, through improving the assessment of the snow mantle, and of the multi-layered ice structure. These quantities are of significant importance to the global change issue. Research on sea ice is intended to be also carried out.

3. Objectives of the SMOS Mission

3.1 Introduction

Even though both SM and SSS are used in predictive atmospheric, oceanographic, and hydrologic models, no capability exists to date to measure these key variables on a global basis with adequate space/time coverage performances. The SMOS mission aims to fill this gap through the implementation of a satellite system that has the potential to provide globally, frequently, and routinely this information. It is also expected that the SMOS mission will provide significant information on vegetation water content, which will be very useful for estimates of the regional crop production. Finally, significant research progresses are expected for the cryosphere, through improving the assessment of the snow mantle, and of the multi-layered ice structure. These quantities are of significant importance to the global change issue. Research on sea ice is intended to be also carried out.

The reason this information is not available currently mainly stems from the fact that, while *in situ* measurements are very far from global, no dedicated, long term, space mission has been approved so far.

The most direct way to date to retrieve SM and SSS is by the use of L-band (21 cm, 1.4 GHz) microwave radiometer systems, which observe radiometric brightness temperature. The brightness temperature provides access to surface emissivity, which explicitly depends on SM and SSS. Other means (higher frequency radiometry, optical domain, active remote sensing) suffer strong deficiencies, due to vulnerability to cloud cover and/or various perturbing factors (such as soil surface roughness or vegetation cover), as well as poor sensitivity.

Even though the concept was proved by early L-band space experiments, such as the one on SKYLAB back in the 70's, no dedicated space mission followed, because achieving a suitable ground resolution ($\leq$ 50 km) required a prohibitive antenna size ($\geq$ 6 m). All the research work was consequently performed using either ground (PAMIR, PORTOS, etc.) or airborne radiometers (e.g. PBMR, PORTOS, ESTAR).

Recent development of the so-called interferometric design, inspired from the very large baseline antenna concept (radio astronomy), makes such a venture 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 D. LeVine et al., in the 80’s (the ESTAR project) and validated with an airborne system (Jackson et al., 1995). In Europe, an improved concept (MIRAS) was next proposed by ESA. While MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) capitalises on the ESTAR design, it embodies major improvements. The two-dimensional MIRAS interferometer allows measuring T_B at large incidences angles, for two polarisations. Moreover, the instrument records instantaneously a whole scene; as the satellite moves, a given point within the 2D field of view is observed from different view angles. One then obtains a series of independent measurements, which allows retrieving surface parameters with much improved accuracy (Wigneron et al., 1999).

In summary, the SMOS objectives are to demonstrate the use of L-band 2-D interferometric radiometry from space

- to monitor on a global scale the surface soil moisture over land surfaces,
- to monitor on a global scale the surface salinity over the oceans, and
- to improve the characterisation of ice and snow covered surfaces

for

- advancing climatological, oceanographic, meteorological, hydrological, agronomical, and glaciological science,
- assessing the potential of such measurements to contribute to improve the management of water resources.

3.2 Scientific Objectives for SM Observations

SM is the state variable of surface hydrology. Although it constitutes a small percentage of the global water, it is on the par with atmospheric water vapour in terms of its influence on the Earth’s physical capacity to sustain life. SM is the fastest component of the water cycle (residence time of a few days) and plays a key role in partitioning precipitation and radiation at the land surface. Through its dominant influence on key physical processes, SM is a variable that has always been required in many disciplinary and crosscutting scientific and operational applications (e.g. ecology, bio-/geochemical cycles, climate monitoring, flood forecasting). To date there are neither *in-situ* nor remote sensing systems that can provide direct estimates of global SM fields. The only option has been to estimate this key hydrologic variable as a residual of water balance calculations.

SM controls the proportion of rainfall that percolates, runs off, or evaporates from the land. It is the life-giving substance for vegetation. SM integrates precipitation and evaporation over periods of days to weeks and introduces a significant element of memory in the atmosphere/land system. There is strong climatological and modelling evidence that the fast recycling of water through evapo-transpiration and precipitation is the primary factor in the persistence of dry or wet anomalies over large continental regions during summer (Beljaars et al., 1996; Betts et al., 1993 and 96). Thus, SM is the most significant boundary condition that controls summer precipitation over large mid-latitude continental regions, and essential initial information for seasonal predictions.

Precise *in-situ* measurements of SM are sparse and each value is only representative of a small area. Remote sensing, if achievable with sufficient accuracy and reliability, would provide truly meaningful wide-area SM data for hydrological studies over large continental regions.

The strategic importance of world water resources and food production make SM a crucial variable for policy decisions. Since there are no regional, or global, SM data sets this mission provides completely new information. The impact factor across hydrology, ecology, and atmospheric sciences would be enormous.

From all the lower boundary conditions that drive the atmosphere, land-surfaces are of particular interest to mankind, as their direct and local impact is of great importance to human activities. Dealing with land-surfaces for meteorological and climatological applications is challenging, because they are very variable over a broad range of temporal and spatial scales. Diurnal variations of temperatures and fluxes are one order of magnitude larger than over the ocean. Another specificity is that moisture for evaporation, while available in limited supplies, constitutes at the same time a memory for the system. The surface hydrology is one of the keys to our understanding of the interaction between continental surfaces and the atmosphere, as it determines the portioning of energy between different fluxes. The science issues considered here are related to the parameterisation of land surface processes, in order to improve the representation of surface fluxes, soil moisture content, soil hydraulic characteristics, and plant stress in mesoscale and global models. The initialisation of soil moisture in atmospheric (including numerical weather forecast) models is of great concern and a subject of active research. The current methods to estimate soil moisture are indirect. New ways of inferring soil moisture, with global coverage, are needed.

For watershed hydrologic model applications, there is an urgent need to have access to distributed soil water fluxes at regular temporal resolutions over large areas. The yearly integrated land surface and base flow water budgets are generally well predicted by the recent generation of hydrologic models. However, the estimation of the ratio between base flow and surface runoff, as well as the ratio between deep drainage and soil moisture content, is still very imprecise. The soil stratum and in particular the unsaturated zone between the soil surface and the groundwater table (vadose zone) plays a crucial role. The estimation of SM in the vadose zone is an important issue for short and medium term meteorological modelling, hydrological modelling, and the monitoring of plant CO_2 assimilation and plant growth. The vadose zone hydrology being inaccurately described, attempts to monitor water quality and flooding risks often fail. New ways to parameterise effective soil characteristics are needed.

In most cases, the vadose zone hydrology and the surface fluxes are controlled by vegetation. Modelling the rate of soil water extraction by the plant roots and the stomatal feedback is important for atmospheric, hydrologic, and environmental studies (De Rosnay and Polcher, 1998). The current models manage to describe first order responses but do not encompass the complete behaviour of the plant, especially at the mesoscale, where several landscape units may contribute to the surface fluxes. In most of the world, plant water supply is the dominant factor that affects plant growth and crop yields. Monitoring SM is a valuable way to detect water stress period (excess or deficit) for yield forecasting or biomass monitoring, especially in areas where climatic stations are sparse. Time series of soil moisture at the mesoscale would be a very interesting input to the representation of vegetation in land surface schemes.

Concerning the characterisation of the atmosphere, there is a need to estimate the surface emissivity at the wavelengths of the atmospheric sounders in order to improve the retrievals. The all-weather surface characterisation capability of L-band radiometry could help in this respect. Finally knowledge of soil moisture time history may provide direct information about rainfall depths over the land surfaces.

The use of the near surface soil moisture w_S to help characterise the surface fluxes, bulk soil moisture and plant stress, must be considered through assimilation and aggregation or dis-aggregation techniques.

It is the objective of this mission to provide global coverage Soil Moisture observations over land, with a repetition rate and an accuracy appropriate for climatological, meteorological and large scale hydrological studies.

3.3 Scientific Objectives for SSS Observations

Knowledge of the distribution of salt in the global ocean and its annual and inter-annual variability, are crucial in understanding the role of the ocean in the climate system. Ocean circulation is mainly driven by momentum and heat flux through the atmosphere-ocean interface, but salinity is also fundamental in determining ocean density, and hence thermohaline circulation. In some regions (e.g. the Arctic), salinity is the most important variable in this respect, and thus can control processes as the deep water formation, a key component in the ocean themohaline circulation “conveyor belt”. Ocean salinity is also linked to the oceanic carbon cycle, as it plays a part in establishing the chemical equilibrium, which in turn regulates the CO_2 uptake and release. Therefore, the assimilation of SSS into global ocean bio-geo-chemical models could improve estimates of the absorption of CO_2 by the oceans.

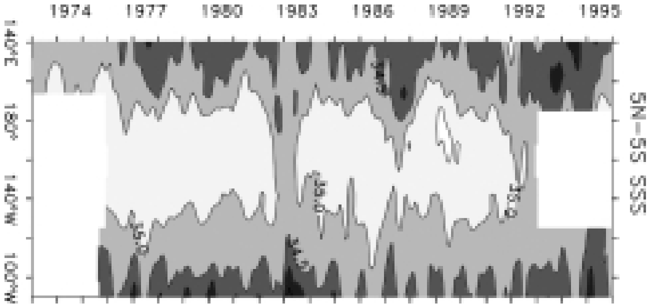

Figure 1: Longitude-time distribution of 5°S-5°N averaged SSS in the Pacific Ocean as deduced from ship measurements (Delcroix, 1998). *Eastward (westward) displacements of low-salinity water (S<35) which marks the eastern edge of the warm pool are clearly related to El Niño (La Niña) events, as in 1982-83,1987 and 1992 (1988-89). Radiometer measurements should help to assess the width and location of the sea surface salinity gradient between low-salinity water in the warm pool and saltier water in the equatorial upwelling. Such a gradient is related to changes in local mixed-layer T and S, to barrier layer thickness, its formation and variability, and to the world's most important tuna harvest. It is clear that remotely sensed SSS would complement in situ measurements which are by nature, accurate but limited in space and time, to characterise spatial and temporal variations of SSS front. Methods should be developed to assimilate SSS data in ENSO prediction models.*

Seasonal predictions systems using coupled ocean-atmosphere models, such as the one in use at ECMWF (Stockdale et al., 1998) use surface and subsurface temperature observations for the ocean initial conditions, but rely on a weak relaxation to climatology for salinity. Monitoring SSS could be used to improve the quality of ENSO (El Nino – Southern Oscillation) prediction by numerical models. Presently, the models assimilate temperature and/or altimeter derived sea level only. The absence of any specific treatment of salinity can lead to significant errors in the ocean model. For example, recent work at ECMWF (Troccoli et al., 2000) has shown that correcting temperature without updating salinity could generate spurious convection and lead to first order error in the subsurface temperature and salinity fields. This problem can be solved by deriving salinity corrections based on temperature-salinity relation conservation properties. Since this relation is not preserved in the mixed layer, this method however does not provide salinity correction near the surface, and would be nicely complemented by remotely sensed salinity data. Other recent results (Maes et al., 1999, Ji et al., 2000) have shown that 5-8 cm dynamic height differences are associated with interannual salinity variations. Methods have been developed to estimate salinity profiles S(z) from temperature profiles T(z), altimeter heights and SSS using empirical orthogonal function techniques. Because most of the variability is near the surface, the SSS data reduces the error of pseudo S(z) profiles from these empirical orthogonal functions. Assimilating the data in the NCEP (U.S. National Centers for Environmental Prediction) model produces the largest changes near the date-line, where an estimated S(z) error of about 0.5 psu (practical salinity unit: 1 psu = 1 g/kg) over the top 130-150m of the upper ocean will contribute to about 5 cm sea level error. If this is not accounted for, any attempts to initialise the climate prediction models with altimeter data will error and degrade predictability.

Such a failure is especially relevant in the western equatorial Pacific where there is a strong ENSO-related near-surface salinity signal, and where zonal advection is of main importance for ENSO mechanisms (Picaut and Delcroix, 1995: see figure 1). Techniques presently used to assimilate data into ocean models must be adapted to assimilate either retrieved SSS or brightness temperatures. The compromise between measurement accuracy, spatial resolution and data delivery delay will be analysed to produce near-real-time data (few days delay) usable in operational models.

Surface ocean salinity is correlated with estimates of net evaporation minus precipitation (E-P) balance. (E–P) is difficult to measure accurately over the ocean, so global maps of SSS would provide a means to constrain the (E-P) estimations at global scale. This would give insights into the phenomena driving the thermohaline circulation and allow to verify the latent heat flux determinations. The water flux through the surface is critical for the stratification of the surface layer of the ocean, and hence strongly influences the mixed layer depth and the intensity of the surface currents.

Primary scientific objectives for SSS remote sensing have been recently defined by a Salinity Sea Ice Working Group (Lagerloef et al., 1998 - see http://www.esr.org/lagerloef/ssiwg/ssiwgrep1.v2) as:

- **Improving seasonal to inter-annual [ENSO] climate predictions:** Effective use of SSS data to initialise and improve the coupled climate forecast models, and to study and model the role of freshwater flux in the formation and maintenance of barrier layers and mixed layer heat budget in the tropics.

- **Improving ocean rainfall estimates and global hydrologic budgets:** The "ocean rain gauge" concept shows considerable promise in reducing uncertainties on the surface freshwater flux on climate time scales, given SSS observations, surface velocities and adequate mixed layer modelling.

- **Monitoring large-scale salinity events:** This may include ice melt, major river runoff events, or monsoons. In particular, tracking inter-annual SSS variations in the Nordic Seas is vital to long time scale climate prediction and modelling.

It is the objective of this mission to provide global coverage of Sea Salinity fields, with a repetition rate and an accuracy appropriate for oceanographical, climatological and hydrological studies.

3.4 Scientific Objectives for Cryosphere Observations

About 10 % of the world ocean are covered by ice during certain periods of the year. Sea ice influences the key large-scale processes of the Earth's climate system, involving the atmosphere, the ocean, and the radiation field (Carsey, 1992). These are:

- **radiation balance:** changes in the sea ice extent cause drastic changes in the surface albedo of the high-latitude seas (Barry, 1989);

- **surface heat and brine fluxes:** areas of open water and thin ice lose heat rapidly during the cold seasons (Maykut, 1986);

- **freshwater fluxes:** melting ice supplies fresh water to the upper ocean, obviously having a significant role in global oceanic circulation (Aagaard and Carmack, 1989);

- **ice margin processes:** abrupt transition to open water or a coastline gives rise to many processes, including oceanic upwelling, eddy formation and atmospheric instability generation (Muench et al., 1987).

Since the sea ice extent responds early to altered conditions (Stouffer et al., 1989) observations of ice caps provide a prediction tool for greenhouse gas-induced climate change. Accurate predictions of sea level rise require improved knowledge of the processes controlling the accumulation upon the ice sheets. The total snow accumulation over the Antarctic ice sheet is equivalent to 5-7 mm of sea level (IPCC, 1995). The scarcity of accumulation rate observations, both spatially and temporally, has hindered the furthering of this understanding.

Further, snow covers about 40 million km^2 of the land area of the Northern Hemisphere during the winter season. The accumulation and depletion of snow is dynamically coupled with global hydrological and climatological processes (Chang et al., 1987). Snow cover is also a sensitive indicator of climate change: the position of the southern boundary snow cover in the Northern hemisphere is of particular significance, as it is likely to move northward as a result of a sustained climate warming (Barry, 1984).

It is an additional objective of this mission to provide coverage of L-band brightness temperature observations over ice/snow covered regions to characterise the ice and snow layers for glaciological and climatological studies.

4. Requirements of the SMOS Mission

4.1 Requirements for SM estimates

Water storage in the soil, either in the surface layer (e.g. 5 cm) or in deeper levels, affects not only direct evapo-transpiration but also the heat storage ability of the soil, its thermal conductivity, and the partitioning of energy between latent and sensible heat fluxes (Dirmeyer, 1995). It is therefore a key variable of land surface-atmosphere interaction.

The amount of water content in the surface layer w_S regulates the evaporation from soil (whether bare or partially covered by vegetation), and determines the possibility of surface runoff after rainfalls.

Evaporation, infiltration and recharge of the groundwater usually occur through the unsaturated vadose zone that is the hydrological connection between the surface water component of the hydrological cycle and the groundwater component. Because the root zone of the vegetation, the zone where vegetation takes up water, is within the vadose zone, the vadose zone is the interface between the vegetation and the hydrological systems. The amount of water within the vadose zone (w_{VZ}) controls plant transpiration and CO_2 uptake through stomatal aperture and possible damage to the photosynthesis apparatus. Furthermore, w_{VZ} is directly linked to the ability of the soil to produce drainage after a rainfall. The soil-vegetation-atmosphere transfer (SVAT) schemes now used in meteorology and hydrology are designed to describe the basic evaporation processes at the surface, together with the water partitioning between vegetation transpiration, drainage, surface runoff and soil moisture variations. The current trend in SVAT modelling is towards integration of both biological processes (such as photosynthesis and plant growth), and hydrological transfers; the ‘classical’ SVAT part performs atmosphere interface calculations, while new modules provided by the research in physiology and hydrology simulate interactive vegetation and river flow. This is the reason why improved SVAT models would be a benefit for meteorology, climatology, hydrology, and agronomy.

In operational simulations, a realistic initial value of w_{VZ} must be provided to the SVAT model. One of the main difficulties in using such parameterisations is the initialisation of w_{VZ}. Soil wetness is one of the least understood and poorly simulated components of the climate system and is also one of the most sparsely measured (Dirmeyer 1995).

Water movement in the unsaturated zone is affected by intrinsic parameters such as hydraulic characteristics depending upon structural properties and, to a lesser extent, upon soil texture. The textural properties are characterised by a smaller variability than the structural properties, mainly due biological and anthropogenic factors having a much larger impact on structural properties than on textural ones. Most SVAT models rely on the use of pedotransfer functions which estimate soil characteristics from readily available data, such as texture (i.e. particle size distribution) which is the most common measured soil data across the world. However, pedotransfer functions are doomed to fail when used for the estimation of structural parameters.

Since microwave techniques provide information about the moisture w_S of a shallow surface layer (about 5 cm at L-band) only; it was investigated to what extent vadose zone soil moisture w_{VZ} and soil hydraulic characteristics can be inferred from near surface soil moisture.

Time series of surface soil moisture (w_S) allow for the determination of w_{VZ} and that of the surface fluxes (evapo-transpiration). When dealing with bare (or sparsely covered) soils, evaporation rate and runoff can be calculated from w_S time series (Chanzy and Bruckler, 1993; Schmugge *et al*., 1994; Goodrich *et al*, 1994). When dealing with soil surfaces covered with vegetation, information on the vadose zone soil moisture (w_{VZ}) is generally needed to describe water and energy fluxes in the soil-plant-atmosphere continuum. Furthermore, the inclusion of CO_2 assimilation algorithms in SVAT schemes made it potentially possible to simulate vegetation growth and, hence, to explore biosphere feedback mechanisms in response to changes in rainfall patterns, temperature, and soil water store.

The use of passive microwaves for deep soil moisture retrieval was first investigated theoretically by Entekhabi et al. (1995) for bare soil. They showed that it is possible to retrieve soil moisture profiles using such data (at frequencies less than 10 GHz). In a recent study Calvet et al. (1998) tested the possibility of using an operational SVAT scheme to retrieve root-zone soil moisture and evapo-transpiration fluxes from *in situ* measurements of the near-surface soil moisture content (the 5 cm top layer) applying atmospheric and precipitation forcing (figure 2). The SVAT scheme chosen for the inversion procedure was the ISBA code developed by Noilhan and Planton (1989). The experimental data collected during the MUREX (South of France) field campaign (3 years) were used for ground validation. The authors derived assimilation rules for either surface soil moisture or surface temperature and showed that four or fife w_S values measured once every four days are sufficient to retrieve w_{VZ} as well as the evapo-transpiration flux.

Time series of surface soil moisture (w_S) may allow for the determination of mesoscale, effective soil hydraulic characteristics. Recent studies of Hollenbeck et al. (1995), and Mattikali et al. (1998) showed that such data, obtained through microwave radiometry during a continuous hydrological event (e.g. drying period), provide estimates of the corresponding surface hydraulic conductivity value. A similar approach was used by Calvet et al. (1998), who determined soil moisture content at field capacity from *in situ* measurements of w_S.

Either meteorological mesoscale models or hydrological lumped rainfall-runoff models (e.g. Cognard *et al*., 1996) usually work with grid sizes ranging from 5 to 50 km. Thus, w_S and w_{VZ} world-wide database obtained using SMOS data will enable to validate the model parameterisations at the same scale. It will be a unique opportunity to foster many improvements in the way effective soil parameters are computed. Meanwhile, existing *in-situ* measurement networks and extensive field campaigns will provide the possibility to validate aggregation and disaggregation techniques which involves:

- the effective surface parameters obtained at the satellite resolution will need to be aggregated towards the scale of general circulation models to establish reference climatologies;

- for specific hydrological and agricultural applications, we need to consider homogeneous areas within the pixel which may be characterised with disaggregation techniques.

Due to the non-linear processes at the surface, simple averaging will not be sufficient. One way of accounting for the effects of sub-grid heterogeneity is to dis-aggregate the pixel into sub-grid elements. This will ensure the consistency of large-scale effective parameters with remotely sensed fluxes. The same method can be applied to evaluate the impact of the small-scale surface variability on retrieved w_S. Simulated L-band radiances over instrumented test catchments can be compared to a flux aggregated to the scale of the remote sensed variable.

After more than 20 years of research on the use of microwave radiometry for soil moisture sensing, the basic capabilities are well understood. Due to the large dielectric contrast between dry soil and water, the soil emissivity ε at a microwave frequency F depends upon moisture content. Over bare fields (Wang *et al.*, 1983), ε is almost linearily related to the moisture content of a soil layer whose thickness depends upon F (~3-5cm at 1.4 GHz, 1-2cm at 5 GHz). The vegetation cover attenuates soil emission and adds a contribution to the radiation temperature T_B. However, at L-band, this attenuation is moderate; T_B

is sensitive to soil moisture for vegetated areas with biomass ≤ 5 kg m^{-2} (circa 65% of the Earth's land surface).

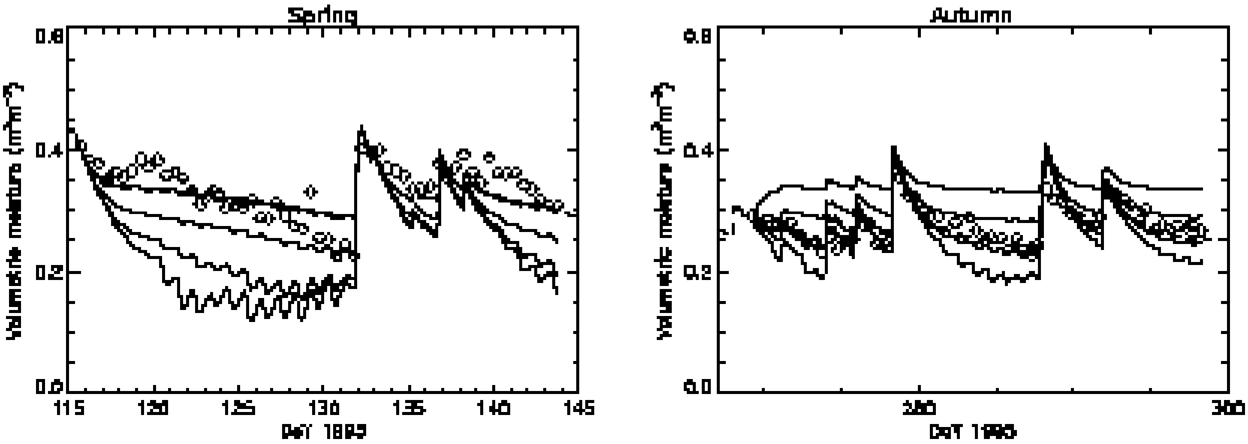

Figure 2: Sensitivity of surface soil moisture (w_S) to total soil moisture content (w_{VZ})
w_S is measured over the top 5-cm soil layer (diamonds) and simulated by the ISBA SVAT scheme (thick dashed lines) during (left) a spring and (right) an autumn 30-day period in Southern France (MUREX). Solid lines correspond to simulated w_S obtained with different values of w_{VZ} imposed at the beginning of each period: 0.20, 0.25, 0.30, and 0.35 m^3m^{-3}. Higher prescribed values of w_{VZ} impose higher values of the simulated w_S (reproduced from Calvet et al. (1998)). Different initial values of w_{VZ} result in very distinct evolutions of the simulated w_S. This suggests that it is possible to obtain information about the total water content by observing the surface soil moisture. Calvet et al. (1998) employed a simple assimilation technique to retrieve w_{VZ} from w_S time series: the cost function to be minimised is the rms difference between measured and simulated w_S values during an assimilation period of about 15 days; the analysed variable is the initial w_{VZ} value prescribed to the model. It is shown that including only one measurement of w_S every 3 or 4 days in the cost function is enough to obtain about the same accuracy as using twice-a-day observations. This result was confirmed by Wigneron et al. (1998) over an irrigated soybean. The obtained precision of the w_{VZ} retrieval is excellent for the autumn period (rms error less than 14 mm) whatever the interval between consecutive w_S values (0.5 to 4 days). The rms error of the retrieved w_{VZ} during the spring period increases with the time interval; this is related to the better ability of the model to simulate the measured w_S during the autumn period than during the spring period.

Previous research has shown the strong advantages of L-band microwave radiometry for measuring surface soil moisture. At higher frequencies, vegetation attenuation increases, and a much smaller portion of the Earth would be accessible. While both active and passive microwave techniques have all-weather capabilities, the signal-to-noise ratio from dry to wet soils is significantly higher for a radiometer than for radar. Furthermore, the radar signal is more sensitive to structural features of the surface (such as soil roughness or canopy geometry).

The brightness temperature T_B depends on three surface variables namely:

- soil moisture w_S ($m^3\ m^{-3}$),
- vegetation layer optical depth τ (Nepers),
- effective surface temperature T_S (K).

To discriminate between the effects of these factors, the radiometry offers the possibility of acquiring data for different polarisations P (H & V), different incidence angles ι (0° to about 55°) and possibly different frequencies F. Theoretical models have been developed to investigate the sensitivity of the passive observations depending on P, ι & F (Tsang *et al.*, 1985; Ferrazzoli and Guerriero, 1996).

Significant examples of the capability of microwave radiometry to produce a soil moisture database can be illustrated by the soil moisture mapping during large scale experiments (FIFE (1987-1989), Monsoon'90, Washita'92, HAPEX Sahel-92, Great Plains Experiment (1997)). These experiments were used to analyse the spatial variability and temporal variations of soil moisture, in relation with atmospheric heterogeneity, including rainfall amounts, and variations of soil hydrological properties (Schmugge *et al.*, 1994; Jackson *et al.*, 1995).

Over bare soils, *e.g.* in semi-arid and arid regions, there is a direct link between brightness temperature T_B and soil moisture. Chanzy *et al.* (1997) showed that w_S could then be obtained using a single linear relationship between T_B and the surface soil moisture. Moreover, such a relationship depends only slightly on the site characteristics, as shown by comparing this result with the one obtained by Schmugge *et al.* (1994) over the Walnut Gulch (Arizona) site.

Over areas covered by vegetation, the retrieval of w_S requires ancillary data to evaluate the effect caused by the vegetation. The vegetation optical depth τ can be related to the amount of water in vegetation W_C (kgm^{-2}): $\tau = b\ W_C$, where b is a parameter depending mainly on the crop type and vegetation hydric status (Kerr & Wigneron, 1994). It is claimed that W_C values can be estimated from vegetation indices (e.g. Normalised Difference Vegetation Index: NDVI) derived from remote sensing observations (Jackson *et al.*, 1995). The possibility of simultaneously obtaining w_S & τ from dual-polarised, multi-angle L-band data such as those collected by SMOS was demonstrated by Wigneron *et al.* (1995); over both green and senescent vegetation covers, using a simple model (hereafter referred to as τ-ω approach; ω is the vegetation single scattering cross-section (Ulaby *et al.*, 1986, Kerr & Njoku, 1990)). Retrieving directly both w_S & τ is a major asset:

- **There is no need for ancillary W_C and b values to estimate τ.** This improves considerably the retrieval process, since obtaining these two parameters at large spatial scales from ancillary remote sensing data is difficult and uncertain;

- **The retrieved τ parameter may be a very useful product**: this variable is a meaningful index to monitor vegetation dynamics (development and senescence) at a global scale (Choudhury, 1990; van de Griend and Owe, 1993) and to estimate forest characteristics.

Several surface characteristics, which are second order effects, are needed in the retrieval process: effective surface temperature T_S, soil surface roughness, dew, as well as topography, soil texture, land cover. Most effects can be considered as relative stable with time (considering the proposed SMOS mission lifetime and spatial resolution), and thus be estimated or calibrated once prior to the start of the mission (from soil maps, high spatial resolution data in the optical domain, digital elevation models). Ancillary information from meteorological analyses and remote sensing data can be used to estimate T_S. Airborne observations during large scale experiments in the USA showed that low values of the roughness parameter are typical of agricultural areas; however, seasonal changes of soil roughness conditions in agricultural areas are unknown and will require analysis by the Science Team. The effects of dew on the microwave emission needs to be studied in more detail at L-band (no study could detect dew effects during either ground or airborne experiments).

Finally, Wigneron *et al.* (1995) showed that rainfall intercepted water has almost the same effect as water contained in the vegetation, and thus can be well accounted for by the optical depth τ.

The τ-ω approach has been coupled to a minimisation routine which computes the standard deviation on retrieved parameters w_S (or w_S & τ), accounting for uncertainties affecting both measured T_B and T_S. All the retrievals consider dual polarised data. The range of available incidence angles ι depends on the distance between the pixel and the sub-satellite path, parameterised by the equivalent half-swath angle (θ_E). A large range of ι values is available in the central part of the Field Of View (FOV) ($\theta_E < 25°$), then becomes narrower until a single view angle is available for θ_E # 35°. The evaluation is shown on figure 3 for wet soil and high biomass conditions ($W_C \approx 3$ kg m^{-2}), which corresponds to the case of a minimal sensitivity to w_S.

In the central part of the FOV ($\theta_E \leq 25°$), the large range of ι values allows simultaneous retrievals of both parameters, yielding accuracy better than: 0.04 m^3m^{-3} on w_S and 0.025 on τ (case a). Near FOV edges ($25<\theta_E<35$), w_S can be correctly retrieved assuming accurate τ values are available (case c). Such values are provided by 2 parameter retrievals: indeed, since τ varies slowly in time, it may be estimated using a lower revisit time (associated with the narrower FOV) than needed for w_S.

In conclusion, it appears possible to obtain surface soil moisture estimates with a standard error of less than 0.04 m^3 m^{-3} on a global basis from SMOS data. In addition, retrievals of the vegetation optical thickness enables to monitor the vegetation dynamics (Wigneron et al., 1999).

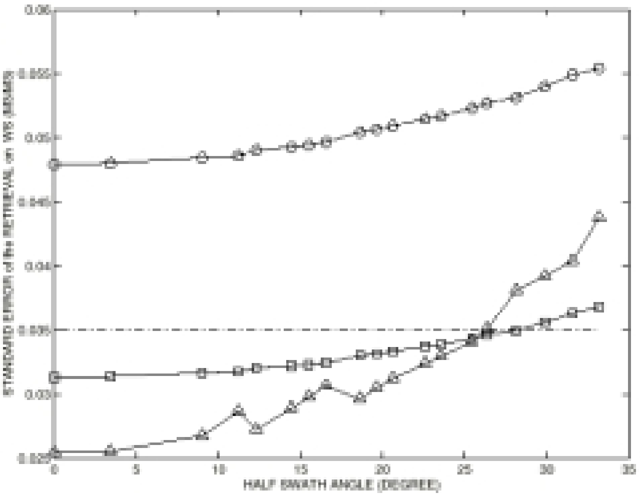

Figure 3: Accuracy obtained on w_S for three inversion schemes.
a (Δ): *both w_S and τ retrieved from SMOS data (σ_{T_S} =2K);* ***b (o):*** *w_S retrieved from SMOS data (τ estimates obtained from ancillary sources); σ_{T_S} =2K, σ_τ=0.05;* ***c (□):*** *same as (b), but accurate τ estimates obtained from previous SMOS data ; σ_{T_S} =2K, σ_τ=0.025; The evaluation is carried out for surface conditions combining wet soil (w_S=0.33 $m^3 m^{-3}$) and a well-developed vegetation cover (τ=0.4). The value τ=0.4 at L-band corresponds to the attenuation of a well-developed green crop. (W_C~3 kg/m^2). Standard values are used for vegetation (ω=0) and soil parameters (silty clay loam; T_s set equal to 290K).*

In summary the requirements for SM 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 w_S on surface water fluxes is strong, Chanzy et al. (1995) have shown that a random error of 0.04 m^3 m^{-3} allows an good estimation of the evaporation and soil transfer parameters. Moreover this value corresponds to the typical rms dispersion of *in situ* w_S observations.

Spatial Resolution [< 50 km]. For the purpose of providing soil moisture maps to global atmospheric models, a 50 km resolution is adequate. The same resolution will allow hydrological modelling with adequate detail for the largest (few tens of) hydrological basins over the world. Therefore the 50 km value is stated as a minimum requirement, for most hydrological studies as well as mesoscale modelling, a higher spatial resolution <50 km is desired.

Global Coverage: ± 80° latitude or higher

Revisit time [2.5-3-days]: A 3-5 day revisit time is found to be adequate to retrieve w_{VZ} and evapotranspiration, keeping in mind that ancillary information on rainfalls are then required (Chanzy et al. 1995; Calvet et al. 1998). To track the quick drying period after rainfalls, which is very informative to determine soil hydraulic properties (Ahuja et al. 1993), a one- or two-day revisit time is optimal. The stipulated 2.5-3 days bracket will satisfy the first objective always, the second one most of the time. The revisit time is for ascending passes only. The rationale here is to optimise the orbit so that revisit is not too bad in dry tropical areas where water availability is much more important than at the equator (in general) where revisit is usually computed. The concept is that at latitude in the range 10 to 15° N the temporal frequency of acquisitions is high enough to follow rain events and subsequent drying out phases. The "memory" of topsoil in these areas is of 3 days. So it is a requirement to have a revisit time of less than 3 days in these areas. The processing should thus be done separately for ascending and descending passes.

Observation time: The precise time of the day for data acquisition is not critical but early morning data acquisition at about 06:00 is preferred. The rationale is to find the optimal observation time. At 6 am, Ionospheric effects can be expected to be minimal but dew could affect the measurements. Actually, dew effects on w_S estimation is not considered critical. Morning frosts might be a more significant problem. However, an acquisition time close to sunrise has the big advantage of presenting enabling measurements in conditions as close as possible to thermal equilibrium which means that the thermal gradient in the soil and in the vegetation canopy is reduced and, consequently retrievals will be more accurate. Moreover the water gradient near the surface should also be minimal. Therefore early morning (06h00) is preferred.

4.2 Requirements for SSS estimates

The measurement of sea surface salinity (SSS) is one of the challenges of SMOS. The dielectric constant for seawater is determined, among other variables, by salinity (Klein & Swift, 1977; Swift & McIntosh, 1983). In principle it is possible to retrieve SSS from microwave measurements as long as other variables influencing the brightness temperature (T_B) signal can be accounted for. The sensitivity of T_B to SSS is maximum at low microwave frequencies and the good conditions for salinity retrieval are found at L-band (1.4 GHz). However, it must be stressed that at this frequency the sensitivity of T_B to SSS is low (0.75 K per psu for an SST of 30°C, decreasing to 0.5K per psu at 20°C, and 0.25K per psu at 0°), placing demanding requirements on the performance of the instrument (see figure 4, Lagerloef et al., 1995)

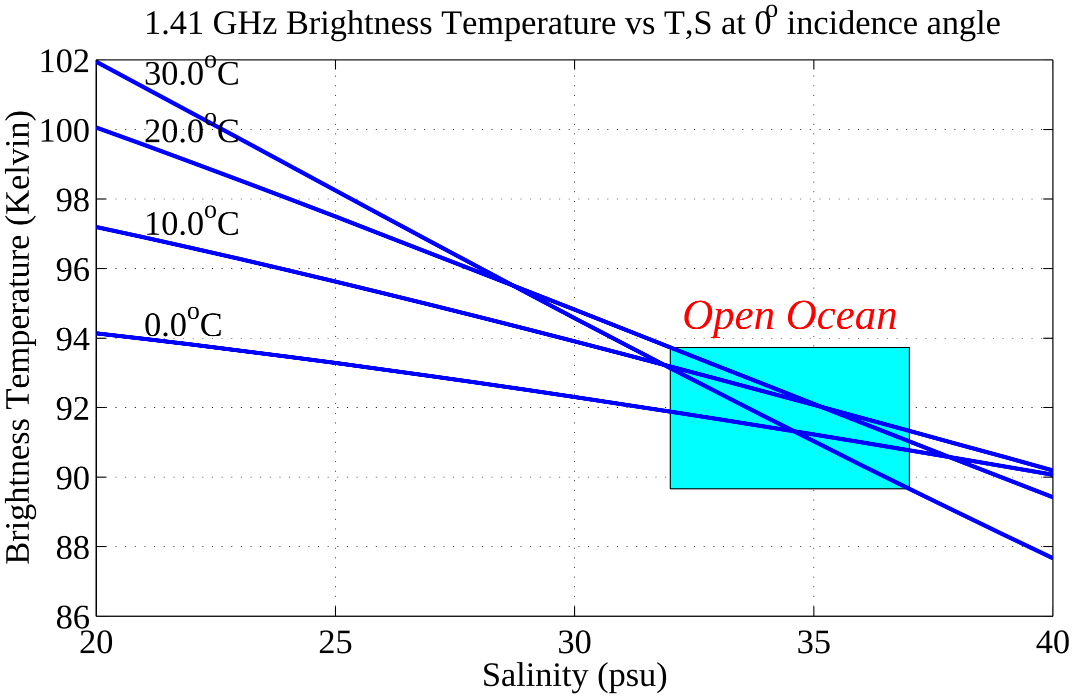

Figure 4: Variation of T_B due to SSS at L-band as a function of SST for nadir observations (from Lagerloef et al., 1995).

Use of L-band radiometry for the measurement of SSS from aircraft has been demonstrated (most recently by Miller et al., 1998); earlier, Lerner & Hollinger (1977) were able to recover SSS estimates from the Skylab 1.4GHz radiometer using a combination of modelling and ancillary data on SST and wind speed. Therefore the feasibility of obtaining SSS estimations with L-band is not in doubt. However, retrieval accuracy will depend on SMOS calibration stability and measurement noise. Furthermore, important efforts (observations and modeling) are still needed to understand how wind speed and direction, as well as precise incidence angle, have to be included into the SSS retrieval from measured T_B.

Due to the low radiometric sensitivity, and the spatial resolution that can be expected with a space-borne microwave interferometric radiometer, we are still not in a position to obtain SSS data for mesoscale or regional studies. However, several phenomena extremely relevant for large-scale and climatic studies can benefit from such an observation approach: barrier layer effects on tropical Pacific heat flux, halosteric adjustment of heat storage from sea level, North Atlantic thermohaline circulation, surface freshwater flux balance, etc. These require an accuracy of 0.1-0.4 psu over 100-300 km in 10-30 days (Lagerloef, 2000).

The Global Ocean Data Assimilation Experiment (GODAE), a pilot experiment set up by the Ocean Observations Panel for Climate, aims to demonstrate the feasibility and practicality of real-time global ocean data modelling and assimilation systems, both in terms of their implementation and in terms of their utility. Following recommendations of the Ocean Observing System Development Panel, the proposed GODAE accuracy requirement for satellite SSS is specified as 0.1 psu for a 10 day and 2°x2° resolution requirement for global ocean circulation studies. Lagerloef and Delcroix (1999) have analysed time series of SSS data in the tropical Pacific and estimated decorrelation scales to be ~70-90 days temporal and 3-4° spatial, based on the zero crossing of the auto-correlation function. Signal strengths as indicated by the standard deviations range from 0.4 to 0.6 psu. The use of the GODAE requirements represents 7-9 samples within the de-correlation time scale and 1-2 in the spatial scale, giving relatively much higher temporal than spatial resolution with respect to these estimated scales of variability. Similar retrieval error can be obtained with either 10 day and 2°x2° averages or with ~30 days and 1°x1° averages from a generic satellite sensor whose footprint is ~40 km and revisit time is 3 days. The advantage with the latter may be to provide more balanced spatial-temporal resolution in the western pacific warm pool; about 3 samples within the respective de-correlation scales. A different balance of spatial and temporal filtering may be more suitable in other regions. It appears that 1°x1° or finer spatial resolution is an important scientific requirement for the warm pool SSS.

Considering the exploratory nature of the SSS measurement with SMOS, the GODAE open ocean requirement (0.1 psu over 200km every 10 days) represents a technically challenging objective. The presently unknown image reconstruction errors, their correlation characteristics, and the calibration stability, raise doubts about the capability of SMOS in achieving these requirements, particularly in higher latitudes. This has to be carefully addressed with the continued development of the SMOS demonstrator and numerical simulator to analyse the SMOS ocean retrieval accuracy. It will be sufficient to average data over 30 days or longer periods for many climate studies and further reduce random measurement noise. 10-day resolution will be less accurate but may be used retained for certain operational applications related to GODAE. Monthly averages over 100km boxes would give data comparable to the standard climatologies, such as Levitus et al. (1994), but with the time dependence which is not available from current climatologies.

Lower accuracy, higher resolution measurements (typically 0.5 psu, 50 km, 3 days) provide a mean to monitor moving salinity fronts in various regions of the world: extension of the warm pool in the equatorial Pacific (1psu/200km), limit between the upwelled waters (of equatorial or coastal origin) and the subtropical waters (1 psu in 200 or 300km), confluence of currents (1 to 2 psu Brazil-Malvinas), large river plumes (Amazone). With a SSS retrieval to 1 psu and a spatial resolution ~30 km, from a single satellite pass, the data are useful for enclosed seas with high salinity contrast (e.g. the Baltic).

From the MIRAS development studies (Camps et al., 1998) it follows that a SMOS-like radiometer should provide an average radiometric resolution of 0.4 K from a satellite overpass. Since the radiometric sensitivity is low, it is clear that from a single pass SSS cannot be recovered to the required accuracy. However, if the errors contributing to the uncertainty in T_B are random, the requirement can be obtained by averaging the SMOS individual measurements in both space and time (Lagerloef *et al.,* 1995, 1998; Srokosz, 1995). The averaging procedure requests excellent stability (0.02 K/day) and calibration of the radiometer receiver.

Factors that influence T_B in addition to SSS, and are to be corrected for include Sea Surface Temperature (SST), surface roughness, foam, sun glint, rain, ionospheric effects and galactic/cosmic background radiation. Estimates for the uncertainties associated with some of these have been made (e.g. Swift & McIntosh (1983); Lagerloef *et al.* (1995, 1998)). A complete error balance has to be made after careful analysis of the effects of all these factors through dedicated studies. In any case, the SSS retrieval from L-band radiometric measurements implies the use of ancillary data sources for wind and SST. As the ancillary data will not be recorded simultaneously to SMOS, the averaging procedure will allow using data acquired (or analysed) at different times within the average window. The effects of the spatial and temporal variability of these data on the SSS retrieval have to be analysed.

4.3 Requirements for Cryosphere

It must be stressed that measurements over the cryosphere are not a primary objective for SMOS. This field will not, therfore, be a driver for the specifications throught its requirements.

Up to date, space-borne multi-channel SMMR data (6.8 to 37 GHz) and SSM/I data (19 to 85 GHz) have been used to develop retrieval algorithms for sea ice, land ice, and snow. Retrieval of ice concentration is based on the contrast between brightness temperatures T_B for sea ice and open water.

L-band interferometric data will improve the retrieval of cryospheric parameters due to four reasons: improved observation capability in difficult weather conditions (all-weather mapping), improved spatial resolution for ice drift monitoring, improved penetration in cryospheric media (discrimination of thin sea ice and detection of snow layering on ice sheets), decreased effect of surface roughness (improved ice extent/concentration mapping capability).

All-weather mapping: Absorption, emission and scattering effects by the atmosphere increase with increasing frequency (Ulaby et al., 1986). Whenever separation of target from atmospheric contribution in the data is not possible, the data may not be useful. The capability of a space-borne radiometer to measure cryospheric surface parameters through the atmosphere is practically independent of weather at L-band, as opposed to higher frequencies.

Monitoring of ice drift: Current methods to retrieve information on ice drifting are based on the use of 36.5 GHz or 85 GHz data, in order to have adequate spatial resolution. At such frequencies, surface melt and large amounts of atmospheric water affect the retrieval of ice displacements (Emery et al., 1997). Interferometric L-band data with good ground resolution are free of such limitations; moreover, improved tracking of sea ice will result of higher contrast between ice and water signatures.

Discrimination of thin sea ice: the T_B for sea ice increases with increasing ice thickness and finally saturates. Thin ice can be discriminated from thick ice only if the attenuation of the ice layer is so low that emission from the ice bottom contributes significantly to the observed T_B. The total ice layer attenuation is determined primarily by its dielectric properties and ice thickness. Dielectric properties of sea ice as a function of temperature and salinity are known reasonably well (Vant et al, 1978; Hallikainen et al., 1983; Hallikainen and Winebrenner, 1992). Based on this information, it can be safely predicted that L-band radiometry is useful for discrimination of thin ice. The T_B oscillation as a function of ice thickness, due to multiple reflections between the ice-water and ice-snow/air interfaces, is eliminated assuming reasonably small ice thickness variations within the antenna footprint.

Based on experimental data for Arctic sea ice, the L-band T_B is 10 to 15 K lower for thin Arctic sea ice (thickness on the order of 20 cm) than for regular thick first-year and multiyear sea ice (Gloersen et al., 1973). Experimental L-band data on sea ice grown in an outdoor pool showed that the T_B saturates at an ice thickness of 20 cm; the saturation thickness was predicted to be 20 to 50 cm, depending on ice salinity (Grenfell et al., 1998). The ice salinity is lower in semi-enclosed areas than in Arctic areas (Vant et al., 1978), improving the thin ice detection capability. Since thin ice exists often next to open water, the mixed pixel problem will have to be solved.

Detection of snow layering on ice sheets: L-band interferometric data will improve our knowledge of the ice sheets snow characteristics, mainly layering. Therefore the L-band data, with other remote sensing data (passive and active) and a good knowledge of the snow metamorphism, will help to understand the snow accumulation processes. The knowledge of the spatial and temporal variability of snow will also benefit other remote sensing data interpretation such as altimetry, which is an essential tool for ice sheet mass balance studies.

Improved ice extent/concentration mapping capability: the emissivity difference between sea ice and seawater determines the capability of microwave radiometry to discriminate the two media. Although the dielectric contrast between ice and water is practically the same at 1.4 GHz as at 6.8 GHz (Ulaby et al., 1986), the effect of surface roughness of ice and water to their emissivities is substantially smaller at 1.4 GHz. Hence, the effects of sea waves on the brightness temperature of water are partly eliminated by using 1.4 GHz data, resulting in better estimates for the ice extent. In areas where open water, first-year ice and multiyear ice are present, higher-frequency channels (from AMSR, for example) are needed in addition to the two L-band channels.

As the measurements on ice covered surface correspond to a secondary objective, no specific requirements are given, apart from the fact that the latitude coverage ought to extend as high as possible. Furthermore, algorithms to interpret L-band radiometric measurement in terms of ice surface quantities need to be investigated and developed, in order to assess the impact of measurement performances.

4.4 Requirements for brightness temperature measurements

To obtain the end product of the SMOS mission implies retrieving SM and OS from surface emissivities, which are in turn derived from the brightness temperatures T_B extracted from radiometric data. Therefore insight in actual mission requirements, as well as the identification of areas where specific studies are necessary are discussed under consideration of required performances in terms of intermediate quantities.

4.4.1 Overall radiometer features

The instrument required for the mission is a 2-D interferometric radiometer. This design is, at the time of the proposal, the only practical way to achieve an acceptable space resolution for land surface measurements from a moderately large space platform, in compliance with opportunity missions.

The capability to observe dual polarisation is required to significantly improve the SSS retrieval and SM (as it allows discrimination of vegetation optical thickness) retrieval. In addition, dual polarization capability may prove useful for removing Faraday rotation effects. Finally, dual polarized signals are required to correct unavoidable polarisation leakage effects.

Further studies are required to analysis improvements of full polarimetric versus dual polarisation capabilities.

4.4.2 Brightness temperatures measurement accuracy

The requirements for the measurement accuracy are much more severe for SSS than for SM, as the sensitivity of T_B to OS is quite small, in particular for cold seas.

The most prominent source of random errors is linked to the radiometric sensitivity. It is estimated that T_B of better than 2 K (about 1.5-1.7 K) will be adequate over the ocean (for a 3 seconds integrating time and representative target T_B values). Over land, specifications will be met with radiometric sensitivities of about 2.5-3 K.

The SSS measurements are extremely sensitive to systematic errors on the T_B. This has technical implications (concerning particularly the knowledge and stability of the receiver noise and gain, the copolar antenna patterns, as well as most of the features of the receiving system. Resulting unknown biases over T_B are required to be smaller than 0.04 K (over warm seas), even 0.02 K (over cold seas). This will be a challenge designing the instrument, as well as validation/calibration procedures, for which specific studies are needed.

4.4.3 Retrieval accuracy issues

As the instantaneous field of view (FOV) of the radiometer is 2-dimensional, it supplies a variety of T_B values for various incidence angles at the same location. These values are next considered together in order to retrieve emissivities, and ultimately SM or SSS. Performing the retrieval implies that theoretical models for emissivities (including their variation with incidence angle) are fully known and validated. In this respect, the major uncertainty to date concerns the effect of sea state on ocean emissivities, and the way sea state parameters should be expressed as a function of the surface wind speed. Studies on this point are needed and are being prepared.

In the case of SSS accuracy requirement can only be met through averaging in space and time, provided the number of independent samples available for averaging is large enough (which will be the case if the space resolution meets the requirements for land surfaces and the instantaneous FOV is large enough), and provided the averaging process does decrease the uncertainties (see below).

Another source of random errors arises from uncertainties in the ancillary data. Over the ocean, requirements for the wind speed (assuming the model for dependence of sea state over surface wind is validated) are of the order of 2.5 m/s ; over land and ocean, requirements for surface temperature is of the order of 2 K standard deviation. This implies however that over the sea, errors due to wind uncertainties decrease through a space-time averaging process. This requires investigation of the spatial structure of sea state characteristics.

Further, ancillary data are required for the galactic noise sources, the Faraday rotation and the possible atmospheric phenomena. All of them are in particular relevant for ocean measurements. For land surface, parameters concerning the soil, as well as topography, will be needed. Further studies are required to assess the availability and accuracy of the relevant data.

4.4.4 Spatial resolution

In order to meet requirements for land surface, it is expected (assuming a 700-900 km flight altitude bracket) that the needed angular resolution of the synthetic antenna pattern should come close to 2° when nadir looking. This readily translates into the size of the interferometer arms, antenna plane tilting angle, and apodisation window.

Obviously, there is no specific spatial resolution requirement for ocean measurements. While spatial resolution is relevant for coastal waters, the performances here will be set by requirements for land surfaces.

For a given line of view within the FOV, the spatial resolution is not expressed by a single figure (as the resolution cell is most of the time elongated). Furthermore, every data in the multi-angular retrieval processing – i.e. along a segment located at a given distance from the sub-satellite track -correspond to different spatial resolutions. In addition, the spatial resolutions vary across the FOV. Finally, the definition itself of spatial resolution (which originates in a threshold on the radiometer antenna pattern) requires caution. Summarising those four indications, the issue of spatial resolutions likely to be achieved by SMOS, and of comparing them to requirements, is a complex one, where the homogeneity of the scene is likely to play a role. Specifically, a detailed analysis of the exact pixel shape, as well as investigating optimal ways to process data with varying spatial resolutions (and making the best of partial oversampling), are needed.

Spatial resolution worsens as the incidence angle increases; this will limit the range of available incidence angles (from nadir) to 45-50°. This has no major consequences: what matters more than incidence angle is the range of available incidence angles, which decreases inexorably whenever looking away from the ground track

4.4.5 Time resolution

This requirement as such concerns the land surface measurements, since for ocean measurements multiple revisit times are to be taken advantage of for reducing random errors through averaging. Since for low circular orbits the number of orbits per day does not vary much (about 14-15), the main factor for determining the mean revisit time is the actual instrument useful swath.

A first limit to the useful swath is set by the space resolution requirement, since space resolution worsens as the viewing angle increases, i.e. away from the antenna axis and from the vertical of the satellite

The swath is linked to the flight altitude. While achieving the best space resolution suggest to select low altitudes, this is only true for looking near to the nadir and antenna axis directions. In order to broaden the swath with respect to the space resolution requirement, higher altitudes are actually to be preferred.

The swath is next bounded by aliasing FOV limits, which depend largely upon element antenna spacing ratio (i.e. the ratio of the element spacing to the wavelength). (Optimal values for this figure seem to lie around 0.8, and even smaller; however reducing it deteriorates the radiometric sensitivity and enhance problems due to coupling effects between element antennas.). Note that aliasing limits should actually be narrowed with respect to theoretical boundaries, in order to avoid contamination by aliased zones. The exact way to define the margin to apply to aliasing limits needs further study.

When this is carried out, a sensible requirement over the reduced alias free zone is that it should not further restrict the useful FOV with respect to limits set by the space resolution requirement.

Finally, the accuracy of retrieved soil moisture worsens as the distance to the satellite ground track increases (due to diminishing number of data, restricted incidence angle range, reduced element antenna gain), which sets a final limit (depending on accuracy requirement) on the useful swath. In order to achieve a maximum revisit time of 3 days, which results in a figure of about ±480 km for the useful swath.

Studies are needed, and under way in order to determine the condition for achieving that figure for every scene, as the accuracy on SM is scene dependent.

4.5 Orbital requirements – mission duration

The orbit should be circular, sun synchronous, and the latitude coverage should cover at least +/-80° (for ice surface measurement purposes) or better and be as near as possible to full global coverage (accounting for an expected swath width of about ± 480 km).

The preferred data acquisition local time is 6 a.m: This choice both minimises Faraday effects and ensure that ground and vegetation temperatures on land surface are close to homogeneity (see Kerr et al, 2000).

In order to avoid biases or slowly varying errors due to pointing inaccuraries, the requirement for satellite attitude knowledge is better than 0.05°, with the aim of 0.02 °. This requirement is driven by ocean measurements.

The mission minimum duration is 3 years (5 years expected). Since the main scientific domain of SMOS concerns climate, it is obvious that the longer the duration the better. It is necessary that the mission should cover at least two complete seasonal cycles, which leads, as launch date can be in the course of one cycle, to a minimum three year duration. Extending to 5 years would both enhance the probability to hit special events (ENSO, droughts…) and contrasting seasons (wet/dry), and increase the time span available for testing possible operational developments.

A launch in the period 2004 –2006 would be highly satisfactory since it would enable synergies with ENVISAT, METOP, ADEOS II, and EOS PM. This is not crucial however, as the most important data set required are SST and wind speed which will be available routinely as they are operational products.

4.6 Summary of Requirements

Developing an effective soil moisture remote sensing system based on passive radiometry requires the deployment of large antennas (or realisation of a correspondingly large synthetic aperture) in order to achieve meaningful spatial resolution at the low microwave frequencies necessary to penetrate moderately dense vegetation. The primary objective of an experimental soil moisture measurement mission is to produce a synoptic global 3 to 5 year data set that will advance science.

The mission should carry an L band radiometer achieving a ground resolution of the order of 50 km or higher, a swath allowing global coverage in 3 days or less, with two polarisation and possibly the 3rd and 4th Stokes parameter (polarimetric), and enabling the simultaneous acquisition of several angles. The radiometric sensitivity should be better than 2 K, depending upon nature of the target and location within the instrument field of view.

Such characteristics are based upon the requirements for SMOS which aims at providing, over the open ocean, monthly global salinity maps with an accuracy better than 0.1 psu, with a 200 km spatial resolution. Over the land surfaces, global maps of soil moisture, with an accuracy better than 0.04 m^3/m^3 every 3 days, with a space resolution better than 50 km, as well as vegetation water content with an accuracy of 0.2 kgm^{-2}.

In order to process SMOS data, corrections due to atmospheric, ionospheric and galactic effects have to be applied. SSS retrieval requires knowledge of sea surface temperature and sea roughness. Over land surfaces, knowledge of the temperature is needed. Over ice, higher frequency microwave data are useful.

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Glossary

Aliasing:	Replication when Nyquist criteria is not matched
Barrier layer:[1]	shallow, freshwater stratified, ocean surface layer created by intense rainfall. It isolates the deeper layers from exchanging heat with the atmosphere
Base flow:	subsurface flow of water
Buoyancy of the surface layer:	buoyancy of the ocean surface layer respect to deeper layers due to differences in water density
Brightness temperature:	temperature observed by a radiometer and corresponding to the product of the physical temperature and the emissivity at the observation wavelength.
Deep drainage:	water going to the water table
Deep water formation:	production of dense water in the ocean surface by intense cooling and/or evaporation
Effective temperature:	temperature, which is relevant to emitted brightness temperature. Corresponds to the temperature weighted and integrated over the sampling depth and convoluted with the antenna gain pattern.
Equatorial upwelling:	upwelling of intermediate waters to the ocean surface due to wind effects in the equatorial region. The wquator acts as a boundary due to change in sign of the planetary vorticity (Coriolis force)
Evapotranspiration:	total flux of water between the surface and the atmosphere. It corresponds to the sum of evaporation and transpiration by the canopy.
Faraday Rotation:	(see ionospheric effects)
Field capacity:	total amount of water that can be absorbed before saturation
Full polarimetric:	All four Stokes parameters
Galactic/cosmic background:	amount of energy coming from deep sky and associated sources (for instance the Galactic center or Cygnus).
Groundwater table:	water stocked in the ground (usually above a waterproof substrate).

Halosteric adjustment of heat storage:	adjustment of the calculated ocean surface layer heat storage when considering salinity contribution to dynamic height
Ice caps	Large areas covered with ice (i.e; Antarctica, Greenland)
Intercepted water:	water which, usually after rainfall, remains on the vegetation
Interferometric radiometer:	Concept where the antenna is not a filled on but an array of radiometers. The correlations between all the pairs of radiometer give a pseudo fourier transform of the observed scene. The concept was first developed for Very Large Base antennas. It is put to use here to achieve a ground resolution corresponding more or less to the largest distance between two antennas. 2-D means here that the synthesis is done in two dimensions.
Intrusions:	ocean water mass extending inside a region occupied by another water mass of different thermohaline characteristics
Ionospheric effects:	the total electron content (TEC) of the ionosphere induces a frequency dependent effect leading to the polarisation rotation (also called Faraday rotation) The TEC varies with solar activity, time of day and year and latitude
L-band.	Usual name for the 1 GHz part of the spectrum. In the text it refers more exactly to the allocated protected frequency band 1.4 to 1.427 GHz which corresponds to a wavelength of 21 cm.
Mixed layer	ocean surface layer with vertically homogeneous temperature and salinity due to wind mixing
Mixed Pixel:	non-homogeneous pixel, i.e. Pixel containing more than one elements (for instance crops and forests)
Plant water supply:	Water available for plants in the root zone area
PROTEUS	generic platform for mini satellites provided by CNES
River plumes:	differentiated fresh and light water area extending over the sea surface from a river mouth
Root Zone soil moisture:	corresponds to the volumetric soil moisture (m^3 / m^3) of the unsaturated area
Sea Surface salinity:	salinity content of the probed depth and expressed in practical salinity units (psu: g/kg)

Soil moisture:	Corresponds to the volumetric soil moisture (m^3 / m^3) of the first 5 cm of the soil
Soil texture:	Composition of the soil in terms of Clay, Loam and Sand percentages (particle size distribution)
Soil water extraction by the plant roots:	Capacity of a plant to extract water through its roots.
Sun glint:	Reflection of the sun on the surface If the center can be assessed from geometrical considerations, strength and extent depends on surface conditions
Surface albedo:	ratio of shortwave reflected and incoming radiation integrated over the solar spectrum and hemisphere. Albedo is an important variable of the energy budget.
Surface roughness:	Characterisation of a non planar surface. Usually described by the standard deviation around the mean level and the correlation length
Surface runoff .	Water flowing on the surface (not infiltrating in the ground)
SVAT:	Soil Vegetation Atmosphere Transfer
Thermohaline circulation	ocean circulation due to temperature and salinity differences between water masses
Vadose zone:	portion of the sub-surface which is unsaturated (i.e. Between surface and bed rock or watetr table.
Vegetation water content:	total amount of water contained by the vegetation. (difference between fresh weight and dried weight). Expressed per surface unit in Kg of water per m^2.
Warm pool	large pool of warm near-surface water (higher than 28.5°C) in the western equatorial Pacific
Zonal advection	ocean water motion along a constant latitude