An iterative convergence algorithm to retrieve sea surface salinity from SMOS L-band radiometric measurements


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Abstract—The European Space Agency SMOS (Soil Moisture and Ocean Salinity) mission aims at obtaining global maps of soil moisture and sea surface salinity from space for large scale and climatic studies. It uses an L-band (1400-1427 MHz) Microwave Interferometric Radiometer by Aperture Synthesis (MIRAS) to measure brightness temperature at the Earth surface at horizontal and vertical polarizations (Th and Tv). These two parameters will be used together to retrieve the geophysical variables. The retrieval of salinity is a complex process that requires the knowledge of other environmental information and an accurate processing of the radiometer measurements, due to the narrow range of ocean brightness temperatures and the strong impact in the measured values of different geophysical parameters (as sea state) other than salinity. Here we present the baseline approach chosen by ESA to retrieve sea surface salinity from MIRAS data, as it has been developed and implemented by the joint team of scientists and engineers responsible for the SMOS Ocean Salinity Level 2 Prototype Processor.

I. INTRODUCTION

In spite of the fact that sea surface salinity (SSS) is crucial to understanding ocean dynamics and its role in the water cycle and climate system, there is not an observing system to provide regular measurements of SSS over all the world’s ocean. SMOS (Soil Moisture and Ocean Salinity) is the second of the European Space Agency Earth Explorer Opportunity Missions [1], within the ESA Living Planet Program. SMOS was proposed in 1998 by an international team of land and ocean scientists and technologists, and is scheduled for launch in September 2007. It uses a dual polarized, L-band interferometric radiometer called MIRAS [2, 3] to retrieve both geophysical variables. The brightness temperatures Tb (Th and Tv) measured by the radiometer are linked to salinity through the dielectric constant of the sea water. The dependence on salinity (conductivity) increases with decreasing frequency and low microwave frequencies are needed to detect changes in salinity. The spectral window at L-band set aside for passive use only (1400-1427 MHz) provides sufficient sensitivity with modern radiometers for remote sensing [4]. Over land, at the same frequency MIRAS can also be used to determine soil moisture [5]. The principle of aperture synthesis employed by the radiometer on SMOS is similar to earth rotation synthesis developed in radio astronomy. Aperture synthesis permits the use of thinned antenna arrays as compared to an equivalent real aperture antenna, and therefore has advantages for use in a satellite mission. The radiometer on SMOS is dual-polarized (with an optional fully polarimetric mode) and has multi-angular imaging capabilities that are crucial for the development of new and more efficient retrieval methods [6].

The measurement of SSS requires special care: even in the ideal case (smooth surface), the sensitivity of brightness temperature to SSS is low [7], there are technical difficulties to achieve the very accurate radiometric calibration and high stability necessary, and it is impossible to fully account for all geophysical parameters that modify Tb. With the selected configuration [8], it will be necessary to average the SMOS pixels (whose individual resolutions are on the order of 30x30-50x50 km2) in both space and time to reduce measurement noise [9, 10]. As a result, the mission will focus only on large scale oceanography. However, several phenomena extremely relevant for large-scale and climatic studies can benefit from the SMOS observational 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 obtainable accuracy of 0.1-0.4 psu over 100x100-300x300 km2 in 10-30 days [11].

The retrieval of sea surface salinity (SSS) from radiometric information [12] can be performed either through a purely empirical approach, by developing a retrieval scheme based on neural network methods using as inputs the SMOS measured Tb and using a learning data basis involving auxiliary oceanographic data (in situ, model, satellites), or through an iterative convergence scheme that compares the measured values with those provided by an L-band forward model (that includes sea surface emissivity, atmospheric emission and absorption, galactic noise reflection) that considers the existing surface conditions, and including a guessed salinity that can be modified until obtaining an optimal fit with the radiometric measurement. As part of the Level 2 ground segment preparation for the SMOS mission we have developed a salinity retrieval algorithm based on the iterative
convergence approach, including a full forward model for the 
Tb emitted by the ocean surface at any specific environmental 
and observing conditions (sea state, temperature, viewing 
geometry). We present here the philosophy, structure and 
components of the SMOS salinity retrieval algorithm.

II. ITERATIVE ALGORITHM

MIRAS allows at each satellite overpass to measure a 2D 
image of the ocean surface under a wide range of incidence 
angles [3], then providing a series of different Tb values 
corresponding to a single salinity at a fixed ocean location. 
This overdetermination can be used to reduce the 
measurement noise and to adjust several geophysical variable 
parameters that characterize the sea state (for example sea 
surface temperature, wind speed, significant wave height), in 
addition to SSS, in the iterative minimization process. Besides 
the low sensitivity of Tb to salinity (even at L-band, the best 
suited frequency), three other major problems make the SMOS 
determination of SSS a real challenge: 1. The instrument limitations (radiometric noise, calibration 
stability, image reconstruction techniques), 2. The need for precise and simultaneous auxiliary information 
on the sea surface properties (temperature, roughness, …) to 
be estimated from external sources, and, 3. The accuracy of the forward model of the sea surface 
emissivity to be used in the iterative convergence.

While a reasonably accurate model for the L-band emissivity 
of a flat sea (as function of temperature, salinity, viewing 
angle and polarization) exists [13], the different processes that 
impact on the emission of a roughened surface are not fully 
described or considered in the several theoretical formulations 
available until now. A comparative analysis of the use of these 
formulations in numerical simulations has shown that this 
forward model has a strong impact on the quality of the 
retrieved salinity, as it could introduce a bias on the results 
[14]. This is a key issue that deserves an important effort in 
improving and testing the existing models, and, refining them 
after the SMOS launch in September 2007. Three different 
roughness model options have been selected for 
implementation in the salinity retrieval algorithm, to be further 
checked until identification of an optimal solution for the 
SMOS SSS operational processing chain. Two of them are 
theoretical models, including the statistical description of the 
sea surface and the asymptotic solution for electromagnetic 
scattering. They are based respectively on the two-scale 
approach [15, 16, 17, 18] and the small slope approximation 
[19, 20]. The third option is a semi-empirical formulation 
derived from the few existing data sets, provided by 
campaigns that have measured the L-band polarised emission 
of the sea surface together with oceanographic and 
meteorological parameters [21, 22]. An additional specific 
model has been developed to account for the effect of foam on 
the sea surface emissivity (thickness and coverage), which can 
have a strong impact when winds are above 10-12 m/s [23, 24].

Figure I Comparison between measured and calculated sensitivities of the sea 
surface emissivity at L-band to wind speed at 10 meter height as function of 
incidence angle. Figure 1a: horizontal polarisation; Figure 1b: vertical 
polarisation. (•): Cape Code Canal data [25]; (○): Data from Skylab S-194 
[26]; (+): WISE 2000-2001 [21, 27]; (▲): Argus Island Tower data [28]; (▼): 
Bering Sea Experiment [29]; (□): JPL experiment [7]; (●): EuroSTARRS 
[30]; (-o-): predictions from the SSA/SPM (blue) and two-scale (green) 
models at SST=15°C and SSS=35 psu. Error bars show uncertainties in the 
data of [25] and [28]. The red curve shows a best-fit through the observations.

As illustrated in Figure 1, available data reporting rough sea 
surface emissivity dependencies with wind speed does not 
allow to discriminate the best adapted correction between 
these three models of the roughness impact.

After considering the Tb emitted by a rough surface, the 
forward model has to take into account the rest of sources that 
are able to produce radiation at L-band that can be directed or 
scattered to the radiometer antenna. Previous to this, an 
important step of the SMOS SSS retrieval algorithm is an 
accurate selection of the radiometric measurements that can 
be used, either directly or after correction, in the retrieval 
process. Once the SMOS data processor will generate a 
sequence of Tb maps that correspond to successive sampling 
snapshots along an orbit, each grid point on the ocean surface 
included in the resulting field-of-view, together with all the

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different angular measurements of this point, have to be analysed to discard incorrect data or flag values than can require a specific processing. The measured Tb can be contaminated, due to the characteristics of the antenna beam and through side lobes, by the nearby presence of land or sea ice, or even by radio frequency interferences. Intense rainfall can also distort the sea surface emissivity. Radiation emitted by the sun, the moon and the galaxy can be reflected by the ocean surface and reach the satellite receivers, then introducing spurious Tb values that have to be removed.

Once some angular measurements have been discarded in this selection step, the rest of measured Tb for a grid point have to be compared with the modeled ones. For each incidence angle the SMOS radiometer, situated at a height of 755 km, will record the emission coming from the ocean surface (modified along its path through the atmosphere) plus other energy in the same frequency originated by several external sources. In the forward modelling, we take into account radiation by celestial sources illuminating the ocean surface that are further reflected (through scattering produced by the surface roughness) towards the radiometer. The brightness temperature of the source brightness can be estimated from sky surveys (not enough precise nowadays). The surface level scattered signals are estimated through a proper weighting of the sky brightness temperature illuminating the considered earth target by the rough sea surface bistatic scattering coefficients estimated at that point. The corresponding Tb correction is further introduced in the SMOS processor to account for antenna level transformations. Although rare, reflected solar radiations are extremely intense at L-band and their contribution need to be accounted for [31]. However, sun glint events being rare, the few affected grid points and angular measurements will be flagged for salinity retrieval instead of attempting a correction.

Thus, the Tb values computed by the forward emissivity model at the ocean surface have to be modified by the galactic and cosmic contributions, plus the effect of atmospheric radiation, both upwards directly to the antenna and downwards reflected by the surface, and atmospheric attenuation (due to oxygen, water vapor). The resulting Tb components are also affected by the ionosphere (Faraday rotation) and at the end have to be expressed in the antenna reference frame, in a geometric transformation that will allow the direct comparison between modeled and measured values.

The algorithm can make use of dual or fully polarized Tb, as the way SMOS will be working is not yet fixed and could evolve during SMOS lifetime. An option for using the first Stokes parameter (I=Th+Tv) is also considered as it avoids Faraday rotation correction and does not degrade much SSS retrieval [9], while at the same time it minimizes errors in the model for dielectric constant and effect of swell [32].

The part of the retrieval algorithm that performs the iterative comparison uses a cost function that incorporates reference values and associated uncertainties (as weights) for the external geophysical parameters that provide information on the roughness state conditions, and that will be themselves adjusted during the convergence process.

The validity of retrievals, and in particular the accuracy of estimators, depends on the overall reliability of radiometric measurements, of auxiliary data and of direct models used in the retrieval algorithm [33]. If the direct models were linear and identical to those used to generate SMOS simulated data and if Tb and auxiliary parameters were bias free, the estimator for sea surface salinity would be bias free and the theoretical estimates for uncertainties would be correctly estimated. When implementing a Bayesian approach with a convergence loop, the influence of the prior values (initial conditions) depends on the theoretical uncertainty put on these values. In case this uncertainty is large with respect to the uncertainty claimed on the a priori values, a bias may be generated by errors in a priori values.

Actually, the direct models used in the retrieval are both slightly non linear and approximated. Hence, one may expect retrieval biases as well as underestimation of the theoretically estimated retrieval uncertainties. It will be the role of Cal/Val exercise to minimize these biases.

The adequate provision and characterization of auxiliary data is a very important component of the overall process. A specific Auxiliary Geophysical Data Processor has been designed and implemented into the SMOS SSS retrieval algorithm to manage this information. The different selected options for the roughness effect model include the use of different roughness descriptors (e.g. wind speed, wind stress...). Other parts of the algorithm, as for example the computation of the atmospheric effects on Tb, also make use of external information. All the required data will be obtained operationally from the European Centre for Medium range Weather Forecast (ECMWF), and then preprocessed to generate derived variables and to interpolate them at the required spatial and temporal grids. The computation of the associated uncertainties, as well as the possible existence of regional biases in the provided fields, is a subject now under study that has an impact on the SSS retrieval quality and consequently has to be properly characterized.

The resulting retrieval algorithm will be carefully tested and corrected before launch through dedicated simulations, and several parts of it will necessarily be modified and improved once SMOS is in orbit and real data start to be available. A secondary algorithm, based on the neural network philosophy, will also be developed and implemented after launch as an alternative to the approach described here.

After launch, quality of the algorithm will be estimated based on comparison between retrieved SSS, wind and SST and in situ measured parameters, and between SMOS Tb and airborne Tb recorded during dedicated flight campaigns.
REFERENCES


