ABSTRACT

ESA’s Soil Moisture and Ocean Salinity (SMOS) satellite was launched on November 2nd, 2009 from Northern Russia. The SMOS single payload consists of a synthetic aperture radiometer operating at L-band (1.4 GHz). Once the commissioning phase was over, SMOS global calibrated brightness temperatures of the sea surface are now available.

This paper presents a preliminary work to improve the definition of the Geophysical Model Function (GMF), which relates the sea emissivity on L-band with sea surface salinity (SSS) and other geophysical parameters. The GMF is a crucial ingredient in salinity retrieval, as it is used in the SMOS operational processor at DPGS.

The GMF definition should be as simple (i.e., avoiding parameter cross-correlations) and efficient (i.e., representing the best fit of the measurements) as possible. Nevertheless, non-linear dependencies and wind direction effects need to be thoroughly examined in order to produce a quality product. In this paper, we will set the grounds for the future development of a fully empirical GMF, and we discuss the methodological issues to be considered in such a development.

1. INTRODUCTION

The SMOS satellite was successfully launched on November 2009. The payload consists of a synthetic aperture radiometer operating at L-band (1.4 GHz). It is a challenging mission since this is the first time that such an instrument is put into orbit, and that surface salinity and soil moisture are measured from space. SMOS aims at measuring sea surface salinity over the ocean with an accuracy of 1 psu for each overpass at 30-50 Km spatial resolution or 0.1 psu after averaging areas of 200*200 Km in 10-30 days. The instrument provides global salinity and soil moisture maps every 3 days [1, 2].

In the L2 operational processing chain the Geophysical Model Function (GMF), which relates the emissivity of the sea to the SSS (among other geophysical parameters), is defined as the sum of two contributions: the first one is the emissivity due to a flat sea, which is presently assumed to be well explained by the Klein and Swift 1977 model [3]; the second one is the emissivity increase due to the sea surface roughness. For the second term, three different models have been considered in the operational processor, therefore producing three different retrieved salinities [4]. Two of the models are theoretically based (Small Slope Approximation and Two-Scale). The third one is a fully empirical linear model that has been derived from the WISE 2000/2001 field campaign in which an L-band radiometer measured the emissivity of the sea in the north-western Mediterranean Sea [5, 6].

Several airborne campaigns have also been performed, such as COSMOS (2006) and SMOS Validation Rehearsal Campaign (2008). However, the limited amount of data of sea surface emissivity collected in the different campaigns is not representative of the global ocean, nor representative of all sea state conditions. As such, there was, until now, a lack of global measurements of sea surface emissivity to define a global GMF roughness induced model. At the moment, the fully-empirical roughness term defined in the operational processor is linear, and depends on incidence angle and two geophysical parameters: wind speed (WS) and significant wave height (SWH). However, other parameters are expected to contribute to the roughness term. In particular, the Level 2 prototype processor can accommodate up to 3 additional parameters to describe the roughness-induced emissivity: wave age (Ω), wind stress (U*) and mean square slope of waves (MSQS). To tune the empirical
GMF and determine which parameters significantly contribute to the modulation of the emissivity, a large amount of auxiliary data co-located in space and time with emissivity measurements is required. With the SMOS launch, global calibrated brightness temperatures are available and together with in-situ data (e.g., buoys) and model output (e.g., atmospheric and ocean models) will allow to review and redefine (if needed) the GMF, in particular the fully-empirical roughness term.

2. TRANSFORM SMOS DATA TO TB\textsubscript{SEA}

To derive an emissivity model from SMOS measurements, it is necessary to translate measurements at the antenna reference to a bottom of the atmosphere frame of reference, in order to obtain the sea-surface brightness temperature, TB\textsubscript{sea}, which is the term that can be related to the geophysical model. Therefore several steps are needed: first, since TB\textsubscript{X} and TB\textsubscript{Y} are not related to the geophysical model. Therefore several steps are needed: first, since TB\textsubscript{X} and TB\textsubscript{Y} are not acquired simultaneously, it is necessary to interpolate the measurements to have coincident TBs in time. A cubic interpolation has been applied, in which each measurement is weighted with the inverse of its radiometric noise. Then measurements from antenna reference are transformed to Earth reference, by rotating the TB vector with Faraday and geometric angles. This rotation, when applied to dual polarization data, leads to a singularity at some pixels (those not over the dwell line), since for a specific combination of Faraday and geometric rotation angles, a division by zero occurs. This problem is avoided by using full-pol data (for which Stoke’s parameters T3 and T4 are also acquired). Finally, the contributions by external sources (galactic and atmospheric) are also subtracted [7].

3. FITTING ALGORITHM

We have devised an optimized code to perform automated multilinear regressions of the whole TB (sea) and of the roughness terms. As explaining variables we have taken the incidence acquisition angle, $\theta$, and three geophysical variables: Sea Surface Temperature (SST), Sea Surface Salinity (SSS) and Wind Speed (WS). The incidence angle $\theta$ is given by the acquisition process at SMOS, while SST and WS are ancillary variables provided by the European Center for Medium-Range Weather Forecast (ECMWF). Having not a reliable, instant source for SSS, we have used climatological estimates derived from World Ocean Atlas (WOA), e.g. Levitus [8]. This obviously leads to a decreased accuracy in the value of SSS used for the fitting, implying a greater minimum uncertainty on TB for any possible fit.

We have fitted the data with a multinomial expansion, with terms of up to order 3 in $\theta$ and up to linear in SST, SSS and WS. In future implementations, other parameters will be added in the fitting as significant wave height (SWH), wave age ($\Omega$), wind stress ($U^*$) and mean square slope of waves (MSOS). The fitting is carried out by standard multilinear least square regression with a quality control to avoid numerical errors in the computation of the inverse correlation matrix.

In order to quantify the minimum attainable uncertainty for any fit of TB (either TH\textsubscript{sea}, TV\textsubscript{sea}, T\textsubscript{Through} or T\textsubscript{Vrough}) as a function of $\theta$, SST, SSS and WS (the independent or explaining variables), we have computed the conditional expectation value and conditional variance of TB for given intervals of the four explaining variables. The intervals for the explaining variables are defined by their accuracy (2 psu for climatological SSS, 0.05 Celsius degrees for SST, 2 m/s for WS and 2 sexagesimal degrees for $\theta$), while their range of variation is given by their natural dynamics (5 to 40 psu for SSS, 0 to 40 Celsius for SST, 0 to 30 m/s for WS and 0 to 60 degrees for $\theta$). The residual uncertainty is hence calculated as the residual standard deviation, which is the square root of the average conditioned variance. This number represents the minimum attainable error for any fitting of the data with the explaining variables. This number is important, as it sets a threshold; fittings leading to smaller uncertainties must be considered overfitted.

The expectation of TB conditioned by the four explaining variables is, in fact, a numerical implementation of the empirical model (as a lookup table), although not very practical for a direct application. On the other hand, the conditioned variance of TB provides an estimate of the minimum uncertainty on TB, measured in terms of its square root (the conditioned standard deviation). This uncertainty includes all randomness associated with unknown sources of variability and the variability inside the intervals of the explaining variables, as well as any source of noise. When these conditional quantities are integrated with respect a one or more variables, the resulting quantities are the conditional surrogates for the remaining variables, having a greater uncertainty as the integrated variables now contribute to the unknown sources of variability.

4. RESULTS

Three days of SMOS L1c data from the DPGS have been processed (from 9th to 11th June 2010). Data acquired after Commissioning Phase (end of May) are in full polarization mode. However, Stokes 3 parameter was erroneous due to a bug in the L1OP 330, so we decided to use $T_X$ and $T_Y$ only for the analysis, even if in doing so our results would be affected by the singularity problem described above. The $T_X$ and $T_Y$ (as acquired in the satellite) are transformed to TB\textsubscript{sea} as
explained in section 2.

The conditioned TBsea for all incidence angles and specific wind speeds have been calculated, as shown in fig. 1 and 2. As commented above, conditioned TB’s represent the best, non-parametric fits of the data. Fig. 1 shows the averaged of measured TBsea for H and V pol for 70 semi-orbits, considering only grid points acquired when wind speed was 10±1 m/s. The shown error bars are given by the conditioned standard deviation, which as already stated are related to the minimum variability or uncertainty in the value of TB once the values of θ and WS are given.

![Figure 1](image1.png)

Figure 1: Averaged measured TBsea for H (blue) and V pol (red) for 90 semi-orbits, considering only grid points with WS = 6±1 m/s.

In principle, as we have explained, the main uncertainties are linked to the quantization of parameters, to the unsolved dependence on SST and SSS, and to unknown processes. However, uncertainties are larger in this case due to systematic inversion errors, as for instance in the regions of singularities of the rotation matrix, as shown in fig. 1 in the range of 10º to 20º incidence angles.

Fig. 2 shows the averages of measured TBsea on the 70 semi-orbits, considering measurements acquired when WS = 2±1 m/s, WS = 10±1 m/s and WS=16±1 m/s. Figure shows the roughness induced emissivity, which increases with wind speed, having an increment on brightness temperature of the order of 5K for wind speed increments of 14m/s.

![Figure 2](image2.png)

Figure 2: Averaged measured TBsea for H and V pol for 90 semi-orbits, considering only acquisitions with WS = 2±1 m/s (in blue), measurements with WS = 10±1m/s (in green) and measurements with WS = 16±1m/s (in red).

An expansion of the TBs in order-3 polynomials in θ and linear in WS attained similar uncertainty (of order 3.8K and 3.5K, respectively). Using the variance conditioned by all the four explaining variables, θ, SST, SSS and WS, we have evaluated the residual uncertainties for TB, as explained in Section 3. The residual uncertainties are 3.3K for total and roughness TH, and 3K for total and roughness TV. These residual uncertainties preclude any appropriate fitting of the data at the required accuracy; our more complex fitting is already close to this minimum threshold. Hence, we cannot expect a better fit than the one we have presented here.

5. CONCLUSIONS

Almost 70 semi-orbits have been transferred to bottom of the atmosphere to obtain TBsea. Conditioned averages of TBsea for all incidence angles and specific wind speeds have been calculated. Results show that an increment on TBsea of 5K is observed when increments of 14m/s on wind speeds are measured.

However, some problems have been identified:

- Measurements are noisy and biased, not allowing to fully characterize the dependencies in TBrough. A very strict filtering is mandatory.
- Measurements near the singularity are affected by the method used to invert the matrix. Methodology needs to be refined.
- Good quality T3 and T4 are required to test the methodology with full pol measurements.
- The calculation of the fully conditioned histogram, required in order to evaluate the minimum attainable
uncertainty, settles the basis for a general, non-parametrical, full empirical modelling of the whole TB.

In the positive side, our methodology allows to calculate a minimum threshold of significance for parametric and non-parametric fittings. In addition, our implementation gives direct access to a numerical implementation of the fully empirical model, from which an analytic expression can easily be derived.

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REFERENCES