A new empirical model of sea surface microwave emissivity for salinity remote sensing

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[1] SMOS (Soil Moisture and Ocean Salinity) is a European Space Agency mission that aims at generating global ocean salinity maps with an accuracy of 0.1 psu, at spatial and temporal resolution suitable for climatic studies. The satellite sensor is an L-band (1400–1427 MHz) aperture synthesis interferometric radiometer. Sea surface salinity (SSS) can be retrieved since the brightness temperature of sea water is dependent on the frequency, angle of observation, dielectric constant of sea water, sea surface temperature and sea surface state. This paper presents a new empirical sea water emissivity model at L-band in which surface roughness effects are parameterized in terms of wind speed and significant wave height. For the SMOS mission these parameters can be obtained from external measurements and model diagnostics. An analysis has been done on the effect on SSS retrieval of different sources for this auxiliary information. *INDEX TERMS:* 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 6969 Radio Science: Remote sensing; 0619 Electromagnetics: Electromagnetic theory; 6924 Radio Science: Interferometry. **Citation:** Gabarró, C., J. Font, A. Camps, M. Vall-llossera, and A. Julià (2004), A new empirical model of sea surface microwave emissivity for salinity remote sensing, *Geophys. Res. Lett.*, *31*, L01309, doi:10.1029/2003GL018964.

1. Introduction

[2] The distribution and variability of salinity in the world's oceans is a key parameter to understand the role of the oceans in the climate system. However, until now, remote sensing of the sea surface salinity (SSS) from space has not been attempted. Using the interferometric microwave radiometry concept (MIRAS instrument, Microwave Imaging Radiometer by Aperture Synthesis), SMOS will fill this gap and will provide global sea surface salinity maps for climate and large-scale ocean circulation studies [*Kerr et al.*, 2000]. The SSS maps are expected to have an accuracy of 0.1 psu at a spatial resolution of 100–200 km every 10–30 days.

[3] Salinity modifies the dielectric constant of sea water and it is one of the parameters that determine the sea surface emissivity [*Klein and Swift*, 1977]. At L-band (1400–1427 MHz), a restricted band for passive observations, the brightness temperature (T_B, measure of the sea surface emission) presents a maximum sensitivity to SSS. However, the sensitivity is quite low: 0.5 K/psu at sea surface temperature (SST) = 20°C, and decreases to 0.25 K/psu at SST = 0°C [*Lagerloef et al.*, 1995]. On the other hand, T_B at this frequency is also sensible to sea surface roughness, 0–0.4 K/(*m*/*s*), (when roughness is parameterised in terms of wind speed) depending on the incidence angle [*Hollinger*, 1971; *Webster and Wilheit*, 1976; *Lerner and Hollinger*, 1977], and to SST, 0.2–0.4 K/°C. This situation indicates that it is necessary to have an accurate knowledge of the surface roughness and SST to retrieve salinity with enough accuracy.

[4] To increase the present understanding of the L-band T_B sensitivity to wind speed and direction, the European Space Agency (ESA) sponsored the WInd and Salinity Experiments (WISE). These experiments aimed, among other activities, at improving and validating the actual sea surface emissivity models at L-band.

2. Campaigns Description

[5] WISE 2000 and 2001 [*Camps et al.*, 2004] took place at the Casablanca oil rig platform in the Mediterranean Catalan coast, at 40°43.02′N 1°21.50′E, 40 Km offshore. They were performed during one month in autumn, when maximum wind speed is expected in the region. An L-band full-polarimetric radiometer measured T_B from 33 m above sea level at different incidence and azimuth angles, while several oceanographic and meteorological buoys measured SSS, SST, wind speed and direction, significant wave height (SWH) and period, and wave spectrum.

[6] Radiometer measurements were performed at different elevation angles from 25° to 65° to emulate the

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Table 1. Number of Data Points for Each Incidence Angle and Polarization in WISE 2001

θ_i	25°	30°	35°	40°	45°	50°	55°	60°	65°
H-pol	143	36	232	35	478	33	348	36	125
V-pol	305	34	532	56	656	57	511	49	190

performance of SMOS, since the two-dimensional imaging capability of MIRAS will allow the observation of pixels in a wide range of incidence angles. This is a unique characteristic of this data set to study SSS retrievals and to test several theoretical electromagnetic L-band emissivity models. Table 1 shows the amount of data acquired during the campaign for each elevation angle. The radiometric sensitivity is 0.2 K for 1 s integration time and the absolute calibration accuracy is lower than 0.5 K.

[7] EuroSTARRS was an airborne campaign also organized by ESA in November 2001 as part of the SMOS preparatory studies [*Berger et al.*, 2002]. An L-band V-polarized multi-angular radiometer [*Miller and Goodberlet*, 2003] of different technology was flown over the same oil platform area in coincidence with WISE 2001.

3. Models

[8] The brightness temperature of the sea surface can be modeled by equation 1, composed of a term due to the emissivity of a flat surface plus the term that accounts for the effect of the sea roughness,

$$T_{B,p}(\theta, SST, SSS, U_{10}) = e_p(\theta, SST, SSS) \cdot SST + \Delta T_{B\ rough,p}(\theta, U_{10}) \quad (1)$$

where $e_p = 1 - \Gamma_p$ is the emissivity of the flat sea surface for each polarization (horizontal and vertical), Γ_p is the Fresnel power reflection coefficient and θ is the elevation angle. In this formulation, the information on sea surface roughness is parameterized through the wind speed measured at 10 m above sea level (U_{10}).

[9] *Camps et al.* [2004] have proposed an empirical model of $T_{B\ rough}$ derived from WISE data, by fitting the sensitivity of T_B to wind speed at different incidence angles, and the two polarizations.

[10] *Gabarró et al.* [2003] retrieved surface salinity from WISE measurements using in the computation different theoretical sea surface emissivity models and the above-mentioned empirical model, all depending on wind speed. Two models for electromagnetic surface scattering (Two-scale, and Small Slope Approximation) and two theoretical wave spectrum models [*Durden and Vesecky*, 1985; *Elfouhaily et al.*, 1997] were tested. The retrieval of SSS appeared to be more efficient when using the empirical model derived from WISE measurements than any other combination of theoretical models.

[11] All these models consider the surface wave spectrum only dependent on the local wind speed, and consequently fully developed sea conditions. So, they do not include either the possible situation of growing and decaying winds or the swell effect. *Miranda et al.* [2003] demonstrated that the measured spectra frequently are not well approximated using fully developed models.

[12] New formulations for the modelisation of the sea surface are being developed now based on the Local Curvature Approximation concept [*Elfouhaily et al.*, 2003]. The effects of sea roughness on L-band emissivity occur in the range of decimetric wavelengths, but the present situation indicates that we will probably have to rely only on the regularly available diagnosed parameters at global scale: wind speed and direction, if necessary, and SWH.

[13] From these considerations, a new empirical model of $\Delta T_{B\ rough,p}$ derived from WISE 2001 measurements is presented here (Equation 2). It explains the variability of T_B depending on local wind speed (U_{10}), and also on SWH, by fitting simultaneously the T_B data to both variables recorded in situ.

$$\begin{aligned} \Delta T_h &\approx 0.12 \cdot \left(1 + \frac{\theta}{24°}\right) \cdot U_{10} + 0.59 \cdot \left(1 - \frac{\theta}{50°}\right) \cdot SWH \\ \Delta T_v &\approx 0.12 \cdot \left(1 - \frac{\theta}{40°}\right) \cdot U_{10} + 0.59 \cdot \left(1 - \frac{\theta}{50°}\right) \cdot SWH \end{aligned} \quad (2)$$

Then, this model considers the effects on surface roughness of both the local wind and other processes that can contribute to SWH formation.

4. Sea Surface Salinity Retrieval

4.1. WISE Field Experiment

[14] Inverting this new forward model, SSS has been retrieved again from WISE T_B data. The algorithm used is a recurrent Levenberg-Marquardt least-square fit [*Press et al.*, 1992], applied to ensembles of data recorded in a series of multi-angular radiometric observations performed under constant sea and wind conditions. T_B is computed setting an initial guess for SSS into the direct emissivity model (Equations 1 and 2). The Klein and Swift model (*Klein and Swift* [1977]) has been applied in order to calculate the dielectric constant from SSS and SST, and then e_p. This T_B value is compared with the T_B measured by the radiometer, and then an increment δSSS is added to the previous SSS to initiate a new computation. This recursive system stops when the difference between the measured and the computed T_B is smaller than a threshold. The retrieved salinity is mostly insensitive to the initial guess for SSS.

[15] An assessment of the retrieval error is obtained by the difference between the retrieved SSS and the one measured in situ by a SeaBird 37 instrument (effective accuracy 0.02 psu) during the series of T_B observations. The average error when using the new model dependent on wind speed and wave height (ΔSSS = 0.33 psu and $\sigma_{\Delta SSS}$ = 0.05) is considerably smaller than using the empirical model that considers only local wind speed (ΔSSS = 0.52 psu and $\sigma_{\Delta SSS}$ = 0.12) [*Gabarró et al.*, 2003]. The standard deviation has also been reduced. A reduction in error budget is expected in any regression when the degree of freedom is increased. But in this case it has a physical meaning since SWH data contain information from processes that modify the sea surface spectrum other than contemporaneous local wind. The substantial reduction on the SSS error (about 35%) confirms that swell and varying winds have an important role in the final balance of emissivity of the sea.

4.2. EuroSTARRS Field Experiment

[16] This model has also been tested to retrieve salinity from the EuroSTARRS data set. Although the data resulted

Table 2. Comparison of Different Sources for Wind Speed and Significant Wave Height

SOURCE	Spatial resolution	Temporal resolution
HIRLAM	0.12°	3 hours
ARPÈGE	0.25°	6 hours
QuikSCAT	25 Km	3 days
WAM	0.12°	3 hours
RA-ERS	15 Km	35 days

to be very noisy and some beams were affected by calibration problems, a series of 800 data points along a straight line over relatively homogeneous fields were averaged to retrieve salinity. The results confirm that this new model retrieves salinity much better (ΔSSS = 0.13 psu) than the model only dependent on U_{10} (ΔSSS = 0.24 psu). These EuroSTARRS errors are highly improved with respect to WISE results due to the much larger number of radiometer snapshot measurements averaged before retrieval, and hence reducing the experimental noise. Nevertheless, the model should be tested with other data sets measured in different locations and sea conditions to validate this conclusion.

5. Sea Surface Salinity Using Auxiliary Data

[17] To retrieve salinity from SMOS, auxiliary variables (wind speed, wave height and SST) are needed with good quality, and as simultaneous in time and space as possible to the spaceborne radiometer measurements. One possibility is to use observations made by other sensors (scatterometers, altimeters, SAR) embarked on satellites with similar orbit, but these measurements will hardly be simultaneous. On the other hand meteorological and oceanographic marine models could also be used, with the advantage of having much higher temporal resolution, and having assimilated satellite and other sources of information. Both cases will present inaccuracies on the measurements due to instrumental errors and sampling limitations.

[18] The determination of sea roughness non-coincidental to SMOS overpasses is a major problem due to its high variability and accuracy limitations in satellite measurements and models. Sea surface temperature, nevertheless, is not as critical as roughness, since its variability is much lower, the sensitivity of T_B to SST is also lower, and satellite measurements are very accurate (0.3 K) and frequent. We have analyzed here the effect on SSS retrieval of using different sources for roughness information.

[19] The following numerical model outputs and satellite measurements of wind speed and SWH were obtained for the area and time of the WISE 2001 campaign,

[20] 1. Wind speed information:

[21] (i) HIRLAM: numerical model with assimilation of satellite data (Spanish Instituto Nacional de Meteorología)

[22] (ii) ARPÈGE: numerical model with assimilation (Météo-France)

[23] (iii) QuikSCAT: radar scatterometer on board SEA-WINDS NASA polar orbit satellite

[24] 2. Significant wave height information:

[25] (i) WAM: numerical model with assimilation of satellite data, only for atmospheric parameters

[26] (ii) RA-ERS: radar altimeter on board ESA ERS-2 satellite

[27] Table 2 summarizes the spatial and temporal resolutions of each data source. Figures 1 and 2 show the temporal sequence of wind speed and wave height obtained from these sources. For wind speed, the models and satellite outputs are quite similar to in situ measurements except for some punctual occasions. The mean difference between wind speed in situ measurements and HIRLAM model output is 1.98 m/s, with respect to ARPÈGE model output is 1.93 m/s, while to satellite data is 1.59 m/s (although in this last case there are much less data points available). These differences are above the 1.5 m/s accuracy in wind speed initially required for SMOS SSS retrieval from preliminary simulations.

[28] The SWH given by the model is similar to the buoy measurement, except for high wave height events, where the model overestimates it. The satellite measurements are not very realistic, which is not surprising since their temporal resolution is very low and a lot of spatial averaging has to be done to cover the WISE area. The mean difference between in situ measurements and WAM model is 0.22 m,

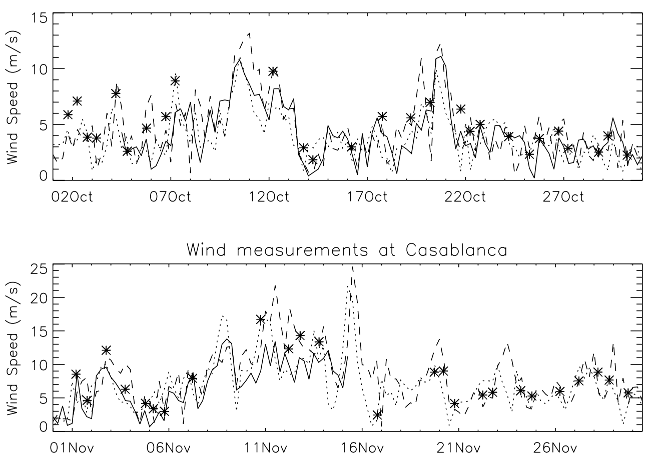

Figure 1. Comparison of different sources of wind speed information during WISE campaign. In situ buoy (plain line), HIRLAM model (dashed line), ARPÈGE model (dotted line) and QuikSCAT satellite (*).

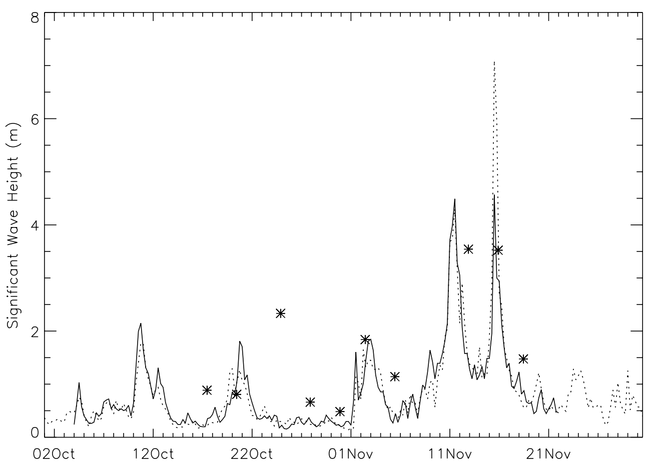

Figure 2. Comparison of different sources of significant wave height information during WISE campaign. In situ buoy (plain line), WAM model (dotted line) and Radar Altimeter-ERS (*).

while the mean difference grows to 1.16 m with respect to satellite measurements.

[29] The retrieval of SSS in the WISE case has been tested using different combinations of these sources of wind speed and wave height information. For SST in situ measurements have always been used.

[30] An alternative way to retrieve salinity, in case of missing or bad quality auxiliary data, is to consider the two variables as unknown parameters in the forward model, and then allow the inversion algorithm to converge simultaneously to a value for salinity, and also for U_{10} and SWH. In this case the cost function to minimize would have three parameters instead of only one. This option has also been tested for WISE and the selected first guess values for U_{10} and SWH have been the HIRLAM and WAM model outputs.

[31] Table 3 summarizes the error on the SSS retrieved for different sources of auxiliary data with the model presented in equation 2. It shows that better results are obtained when leaving the auxiliary data free as variables to optimize, than fixing them with excessively erroneous values. Furthermore, the error on the wind speed and wave height retrieved with the optimization process ($\Delta U_{10} = |U_{10\ in\ situ} - U_{10\ retrieved}|$) is smaller than the error of the model outputs and satellite measurements. Figure 3 plots the results of retrieved U_{10} respect to in situ measurements and HIRLAM output model for several data sets. It shows that the retrieved U_{10} is nearer to in situ measurements than HIRLAM output, even though the first guess parameter was that model. So it seems that by leaving U_{10} as free parameter for retrieval, the algorithm can improve its initial values.

[32] Table 3 shows also that the use of meteorological model data (with assimilation of space-borne observations) is better than to use satellite data directly, since the latter have much worse temporal resolution.

6. Conclusion

[33] This paper describes a new empirical model of L-band sea surface emissivity dependent on wind speed and significant wave height derived from radiometric and in situ data gathered in the NW Mediterranean. Salinity is retrieved with smaller errors when using this model than other models dependent on wind speed and then considering only the presence of fully-developed wind waves.

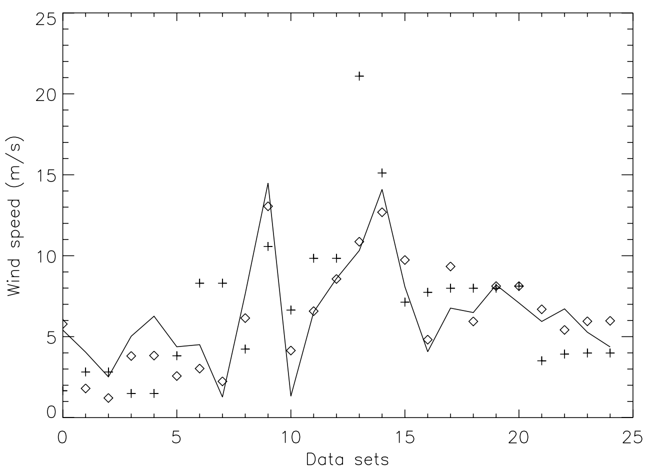

Figure 3. Comparison of wind speed measurement U_{10} determinations: measured in situ (diamonds), output from HIRLAM analysis (crosses), and retrieved by the algorithm when it is set to be free (line). It can be seen that retrieved wind speed is nearer to in situ measurements than model output.

Table 3. Errors on the Retrieved Salinity $\Delta SSS = |SSS_{in\ situ} - SSS_{retrieved}|$, Error on Wind Speed ΔU_{10} and on Wave Height ΔSWH for Different Ancillary Data

Source U_{10}	Source SWH	ΔSSS	ΔU_{10}	ΔSWH
In situ	in situ	0.33	–	–
HIRLAM	WAM	0.59	1.98	0.22
ARPÈGE	WAM	0.49	1.94	0.22
QuikSCAT	ERS	0.61	1.59	0.46
Free	free	0.40	1.22	0.22

[34] Since T_B is sensitive to surface roughness, it is necessary to have accurate auxiliary data to obtain accurate estimates of SSS. In this paper different sources for acquiring auxiliary data during the SMOS mission have been presented. The error with respect to in situ measurements and the influence of this error on the accuracy of the SSS retrieval have been analyzed.

[35] An important conclusion is that using data from meteorological models to retrieve salinity is better than using direct satellite data, since the former have smaller temporal resolution. From the analysis of WISE dataset, it appears that in absence of accurate in situ observations, the best method to retrieve salinity is to leave U_{10} and SWH as free parameters, and let the retrieval algorithm to take advantage of the multi-angular view capability of SMOS imaging configuration.

[36] These conclusions are only applicable to the WISE field site, in the north Mediterranean, and can not be automatically extrapolated to other ocean areas. This empirical model may need to be adapted to different oceanographic characteristics. The accuracy and resolution of meteorological models can also vary in other regions, as well as the accuracy of satellite data. This work is a regional study, but could be a first step for a global scheme applicable to SMOS observations.

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