The use of a semi-empirical emissivity model for a rough estimation of sea surface salinity from an airborne microwave radiometer

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SUMMARY: In preparation for the European Space Agency SMOS (Soil Moisture and Ocean Salinity) satellite mission, radiometric and oceanographic measurements were performed in December 2000 and January 2001 and in November 2001 from a fixed platform in the NW Mediterranean to improve the modelling of the sea surface emissivity at L-band and new semi-empirical models were derived. Now one of these models has been used to retrieve sea surface salinity from L-band radiometric data acquired with a different instrument and different location. These data were acquired in August 2003 over the continental shelf within the influence of the Rio de la Plata, from Argentina to Brazil, southern Atlantic ocean with the STARRS airborne radiometer. Results show that the radiometer is capable of realistically detecting natural variations in surface salinity even though the model was derived in very different oceanographic conditions and from data collected by a different instrument.

Keywords: remote sensing, radiometry, SMOS, salinity measurements, oceanographic campaigns.

RESUMEN: USO DE UN MODELO SEMI-EMPÍRICO DE EMISIVIDAD DEL MAR PARA LA ESTIMACIÓN APROXIMADA DE LA SALINI-DAD SUPERFICIAL A PARTIR DE MEDIDAS REALIZADAS CON UN RADIÓMETRO AEROTRANSPORTADO. – Para preparar la misión satelital SMOS (Soil Moisture and Ocean Salinity) de la Agencia Espacial Europea, varias medidas radiométricas y ocea-nográficas se llevaron a cabo en el año 2000 y 2001 desde una plataforma fija en el Mediterráneo noroccidental. El objetivo de estas campañas era mejorar los modelos de la emisividad superficial del mar en banda L y de ellas se derivaron varios modelos semi-empíricos. Ahora, unos de estos modelos se ha usado para el cálculo de la salinidad superficial del mar a partir de datos radiométricos en banda L, obtenidos con un instrumento diferente y en un área distinta. Estos datos se adquirieron en agosto del 2003 en la plataforma continental desde Argentina a Brasil, en el Atlántico sur, donde hay una gran influencia del Río de la Plata, con el radiómetro STARRS a bordo de un avión. Los resultados muestran que el radiómetro es capaz de detectar las variaciones naturales de la salinidad del mar, independientemente de que el modelo semi-empírico usado fuera derivado en condiciones oceanográficas completamente diferentes y con un instrumento distinto.

Palabras clave: observación de la tierra, radiometría, SMOS, medidas de salinidad, campañas oceanográficas.

INTRODUCTION

Sea Surface Salinity (SSS) can be obtained from radiometric microwave measurements because the brightness temperature (T_B) of the sea surface depends on the sea water dielectric constant, which is related to the salt concentration, and on the frequency, the sea surface temperature, and the geometry of

observation. However, T_B is also sensitive to the sea surface roughness which should be corrected for. Several studies have shown that the sensitivity of the brightness temperature to salinity is maximum at low microwave frequencies (Swift and McIntosh, 1983) and since the 1400-1427 GHz range (within the L-band) is protected from man-made emission, it is the optimum frequency for performing salinity measurements with passive sensors (Lagerloef *et al.*, 1995).

Salinity remote sensing capability using L-band radiometers was first demonstrated in the late 1970s by the NASA/Langley Research Center team, with Skylab (Lerner and Hollinger, 1977). In 1993 several flights were performed with the Scanning Low Frequency Microwave Radiometer (SLFMR) instrument over the Chesapeake Bay by the US Naval Research Laboratory (NRL) and NOAA, and they showed that it was possible to map spatial salinity changes from an aircraft (Miller *et al.*, 1998).

The SMOS (Soil Moisture and Ocean Salinity) mission from the European Space Agency (ESA) will be the first space mission devoted to the measurement of sea surface salinity (Silvestrin *et al.*, 2001; Kerr *et al.*, 2001). It aims at generating global ocean salinity maps with an accuracy of 0.1 (in practical salinity units, psu) at a spatial and temporal resolution suitable for climatic studies, although the accuracy of the retrieved salinity on a single satellite overpass (before spatial or temporal averaging) is expected to be of the order of 1, due to the instrument limitations and low sensitivity of T_B to salinity changes (Font *et al.*, 2004). SMOS will use a Y-shaped dual/fully polarised L-band interferometric radiometer (Microwave Interferometric Radiometer by Aperture Synthesis, MIRAS) on board a Proteus satellite, and its launch date is scheduled for summer 2008.

To improve the understanding of sea surface emissivity at L-band and hence its modelling, including the dependence on the sea state (sea surface geometry), a number of field campaigns were carried out in the SMOS context funded by ESA: WISE (2000, 2001) (Camps *et al.*, 2004) from a fixed oil platform, EuroSTARRS (2001) (Etcheto *et al.*, 2004) , LOSAC (2001, 2003) (Sobjaerg *et al.*, 2003), and CoSMOS-OS (2006) (Reul *et al.*, 2007) from airplanes. In all cases real aperture radiometers (LAURA, STARRS, EMIRAD) were used to acquire L-band polarised data either for long periods or over large areas and on different dates, to cover a wide range of ocean conditions.

The data acquired during the WISE (WInd and Salinity Experiment) campaign from a fixed platform 40 km offshore in the NW Mediterranean were used to jointly analyse the sea surface L-band emissivity and the ocean and atmospheric environmental properties. Correlations were derived between the deviations of the measured polarised T_B with respect to the flat surface theoretical case (Klein and Swift, 1977) and the variables that describe the surface roughness (wind and wave fields). This allowed new semi-empirical models to be built for the L-band emissivity of a roughened sea surface, using either wind speed as a roughness proxy parameter (Camps *et al.*, 2004) or combinations of several roughness descriptors, such as wind speed and significant wave height (Gabarró *et al.*, 2004). However, due to the particularity of ocean conditions in the area of the WISE campaign (high sea surface salinity and temperature (SST), water depth around 160 m, wave field constrained by local topography, etc.), these specific empirical models may be of limited use in other ocean regions. It is necessary to test them in different environments and with data collected by different L-band radiometers in order to assess the validity of such an approach for describing the roughness effect in the algorithm that must be implemented for SSS retrieval from SMOS measurements (Font *et al.*, 2006).

In this paper we present one such comparison. From data collected by an airborne L-band radiometer in the coastal Southern Atlantic we demonstrate the feasibility of retrieving SSS with a reasonable quality, using one of the semi-empirical models derived from the WISE experiment and wind speed values provided by an operational meteorological service.

MATERIALS AND METHODS

Data set

The analysed data set was acquired over the continental shelf and slope around the Rio de la Plata (Plata hereafter) river mouth. The area is particularly interesting because the Plata outflow, with its mean annual discharge rate of about 23000 m³/s, produces a large scale buoyant plume of low salinity which can be traced beyond 1000 km from the river mouth (Piola *et al.*, 2000). North of about 34°S the Plata plume is bounded offshore by subtropical waters ad-
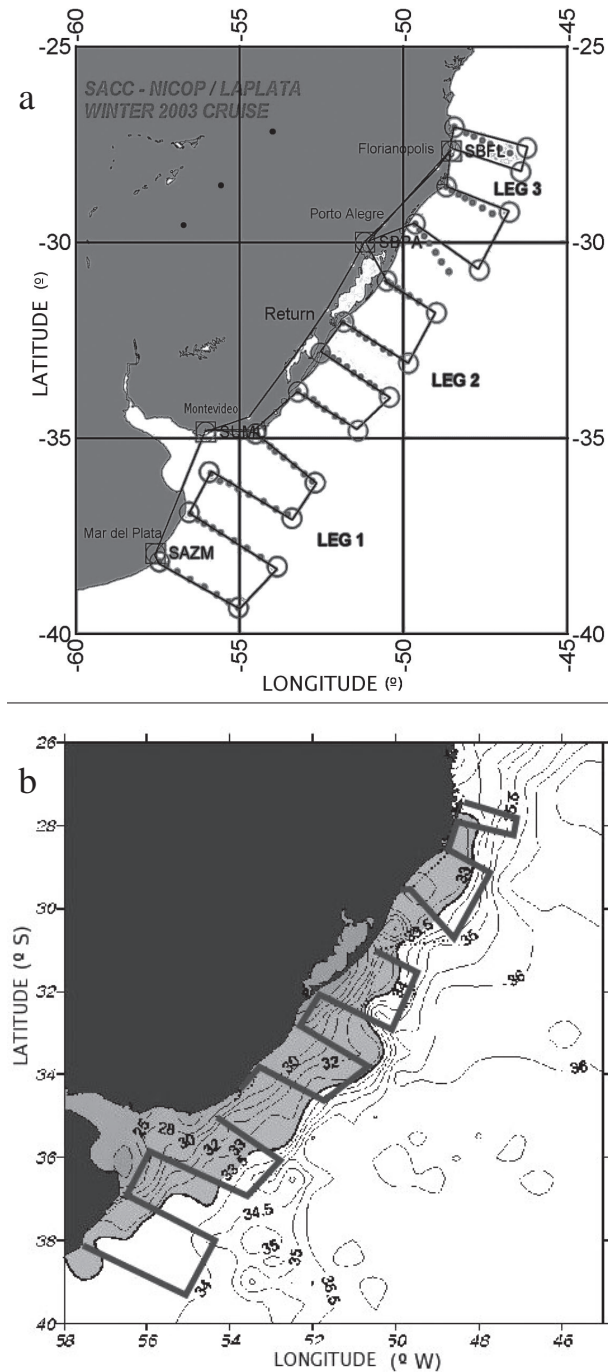
FIG. 1. – a) Ship CTD stations (solid small dots) and the aircraft track (continuous line). b) Sea surface salinity climatological winter distribution derived from historical hydrographic data. The highlighted contour is the 33.5 isohaline, which marks the outer edge of La Plata plume (from survey reports and (Piola *et al.*, 2000)). The aircraft track is overplotted.

vected southward by the Brazil Current, thus creating a strong cross-shore salinity gradient.

An oceanographic campaign sampled this area from 20 August 2003 until 1 September 2003 with the Argentinian ship ARA Puerto Deseado, in a

southwest to northeast along-coast survey performing several cross-shelf transects (Fig. 1). Eighty-three CTD stations were occupied and wind speed was measured at each station. Near-surface salinities (~3 m depth) were measured along the ship track using SeaBird Electronics Seacat 21 thermosalinographs, calibrated to within 0.05 based on CTD data and water samples (Piola *et al.*, 2004).

Several flights over the study area were performed with the US Naval Research Laboratory's STARRS (Salinity, Temperature, and Roughness Remote Scanner) instrument from 20 August to 5 September. STARRS has an L-band radiometer (an improved version of SLFMR) whose antenna has six 15º wide beams at vertical polarisation, as well as infra-red and C-band radiometers. The instrument was mounted horizontally on a CASA 212 Aviocar aircraft operated by the Uruguayan Air Force, so the L-band measurements were performed at incidence angles of -38.5º, -21.0º, -6.5º, 7.5º, 22.0º and 38.5º in the across-track direction. The beams are sampled simultaneously with a dwell time of 2 s. Three flights named LEG1, LEG2 and LEG3 covered all the positions of the oceanographic stations, as seen in Figure 1a. The flights were made at night, to avoid the interference from Sun glint and with a typical altitude of 900-1200 m. The in situ data set shows substantial variations in salinity, ranging from 28 to 36, due to the large amount of fresh water that the river brings to the ocean (see Fig. 1b). This is a good environment to investigate the detection of salinity changes with STARRS. Also, these data are very useful for studying the performance of the iterative inversion method used to retrieve salinity, and for evaluating the capability of the semi-empirical modelling approach in an ocean environment different from the one in which it was generated.

Sensitivity tests of the STARRS L-band radiometer reveal a precision of 0.3 K for each beam, with 12 s averaging (Burrage *et al.*, 2004). Radiometric measurements are extremely sensitive to the viewing geometry, which therefore has to be controlled with a high degree of accuracy. The manufacturer of STARRS specifies absolute accuracy of attitude (pitch and roll) measurements as 0.5º and repeatability as 0.1º. However, bias in the pitch and roll of the aircraft produce an increment/decrement in the measured T_B, depending on the incidence angle. For example, a 1º roll produces an increment in T_B of 1.23 K at the 38.5º incidence angle beam.

The misalignment of the aircraft navigation data have been considered in the inversion process by modifying the incidence angle in the modelled Tb, since an error of 1 K in T_B can imply an error of 2 on SSS.

A drawback of the Plata data set is that in situ measurements performed by the oceanographic ship were, most of the time, not simultaneous with the aircraft overflight. Simultaneity was only achieved during the first transect of LEG1, at a few stations located to the south of the river mouth and therefore not affected by the fresh water. This should not be a significant problem when the retrieved salinity is compared with in situ measured salinity, since this variable varies relatively slowly. However, the difficulties appear with the measured wind speed, which can change dramatically in a few hours. Therefore, the lack of precise auxiliary parameters makes the validation of the emissivity model more difficult outside of LEG 1. To solve this issue QuikSCAT wind scatterometer data were considered, but found to be under-sampled. As an alternative, operational model outputs were obtained from the European Centre for Medium-Range Weather Forecast (ECMWF). The ECMWF TL511L60 atmospheric model with 60 vertical levels was used (Raoult, 2003), with a spatial resolution of 0.35° in the area of interest. Temporal resolution was 6 hours. This model provided the wind speed parameterisation of sea surface roughness that was introduced as a reference value in the iterative convergence scheme used to retrieve salinity. The wind speed mean error was expected to be about 1.5 m/s.

The retrieval analysis was performed over two transects of the aircraft and ship. The first one was transect 1 on LEG1, the only transect where in situ and aircraft measurements were coincident in time. In fact the ship took almost 22 hours to perform this transect, while the aircraft took 1.5 hours to fly the area. The aircraft crossed the ship between stations 3 and 4. Moreover, along this transect the salinity was quite uniform (from 33.8 to 34.3), since there was little influence of the River La Plata at this time. Consequently, this transect was optimum for testing the efficiency of the inversion method and emissivity model. The second analysed dataset was the third onshore-offshore transect of LEG2. This transect was chosen because it shows large salinity changes ($\approx$7) but small anomalies and roll/pitch effects. LEG2 data allowed us to study the capability of the radiometer to discern different salinities.

Analysis methods

The method used to retrieve salinity was an iterative convergence with a cost function (function to be minimised that compares N measured T_B values of the sea surface with those modelled), constrained as follows (Gabarró *et al.*, 2004):

$$\chi^2 = \sum_{i=0}^{N-1} \frac{1}{N} \frac{\left[T_{Bi}^{meas} - T_{Bi}^{model}(\theta_i, SSS, SST, Rough) \right]}{\sigma_{T_B}^2} +$$
$$+ \sum_j \frac{\left[P_j - P_{j\,ref} \right]^2}{\sigma_{P_j}^2} \tag{1}$$

where P are the parameters to be adjusted in the iterative convergence (in this case they can be SSS, SST and several sea surface roughness descriptors), $P_{j\,ref}$ are reference values for these parameters from which the final solution should not be far, and σ_P^2 is the variance of the expected error of the reference values. The value of each P_j at the first iteration is the so-called ''first guess'' value. N is the number of different radiometric observations that correspond to a single ocean spot and were used together to retrieve the salinity; here N is 6 for the six beams of the STARRS instrument. It should be noticed that on the earth's surface the distance between the two side beams is $\approx$1400 m, so we consider this area homogeneous (for SMOS this distance, resolution of a pixel, is 50 km).

The analysis of the data reveals that, in general, increasing the number of measurements to be averaged (averaging the T_B) improves the quality of the retrieved salinity (due to a reduction in measurements noise). Thereby, 300 points (acquired in $\approx$45 km, similar to SMOS) were averaged for the analysis.

The semi-empirical model of L-band sea surface emissivity used to retrieve salinity provides the polarised brightness temperature as the sum of two components:

$$T_{B,p}(\theta_i, SST, SSS, C_n) = T_{B\,Fresnel,p}(\theta_i, SST, SSS) + $$
$$+ \Delta T_{B\,rough,p}(\theta_i, C_n, SST, SSS) \tag{2}$$

One, describing the emission of a flat surface, is dependent on the incidence angle, SST and SSS, and uses the permittivity model determined by (Klein and Swift, 1977). The second one, describing the additional effect of the surface roughness (through n

parameters C_n), here depends only on incidence angle and wind speed (Camps *et al.*, 2004):

$$\Delta T_h \approx 0.25 \ (1 + \frac{\theta_i}{118°}) \ U_{10}$$

$$\Delta T_v \approx 0.25 \ (1 - \frac{\theta_i}{45°}) \ U_{10} \tag{3}$$

If reference values and their precision are not provided, the convergence to the correct minimum is not guaranteed, as shown in (Gabarró *et al.*, 2007). The reference values used for the inversion algorithm here are: $SSS_{ref} = SSS_{insitu} + N(1.5)$, N being the normal distributed function with standard deviation of 1.5, and $U_{10\ ref} = U_{10model}$. The authors decided to use a salinity reference value far from the true number in order to better test the convergence algorithm and to simulate the analysis as in the real SMOS case in which the true salinity is not known. A Monte Carlo exercise was performed, since the reference value for SSS is a distribution function. Retrieval exercises were performed 500 times and averages were computed.

In this study SST was not retrieved since the accuracy of the auxiliary information (provided by the STARRS infrared radiometer) was high and would not negatively impact the SSS retrieval (for SMOS, SST can be known with good precision thanks to satellite observations). The standard deviation of these reference parameters was fixed to $\sigma_{SSS} = 2.0$ and $\sigma_{u10} = 3.0$ m/s, a value that takes into account the non-spatial and temporal simultaneity between EC-MWF grid data and the radiometric measurements. The standard deviation for the brightness temperature was set to $\sigma_{TB} = 1.0$ K, which considers both the instrumental errors and the modelled errors.

To take into account other processes besides sea surface emission, which can contribute to the T_B values actually measured by the radiometer, we introduced in the model the upwelling and downwelling atmospheric emission corrections, as well as a correction for the cosmic noise reflected on the surface (Goodberlet and Miller, 1997). The contribution from galactic noise was considered with a mean value of 3.7 K (at the moment of calculating the values, a galactic map of the southern hemisphere was not available). Pitch and roll were also corrected for. Geometrical effects were neglected, since at a small angle of pitch, the roll changes mainly the incidence angle, but not the polarisation angle, and only measurements with small pitch angles were considered. The possibility of not using any of the individual

antennas was investigated, but worse results were obtained.

All the sections analysed here were chosen to be 300 radiometric measurements long, to be comparable with the method used during the WISE campaign (which provided the data for deriving the semi-empirical model) (Camps *et al.*, 2004).

RESULTS AND DISCUSSION

The retrieval algorithm was applied to the first transect of LEG1, the one in which in situ and radiometric measurements were simultaneous. The mean value of in situ measured SSS was 34.07, while the mean value of wind speed recorded on board was 2.79 m/s. This value is used as reference in Equation 1.

Figure 2 shows the in situ salinity and the retrieved values (noisy line) when the retrieval process was applied to each single radiometric measurement (a set of 6 beams), using the mean wind speed as reference. The mean difference between measured and retrieved SSS for the whole transect was 0.17, with a standard deviation of 0.94. Despite the very noisy character of the results (radiometric data are intrinsically noisy), the average agreement is good.

If we first average the radiometric data to reduce noise (300 points averaged for each beam), and then perform the inversion, the retrieved values are $SSS_{ret} = 33.86$ and $U_{10\ ret} = 3.32$ m/s. Then the salinity retrieved from averaged data shows a very good agreement with in situ value $\Delta SSS = 0.20$, while the adjusted wind speed is slightly above the measured one used as a reference. We have thus been able to
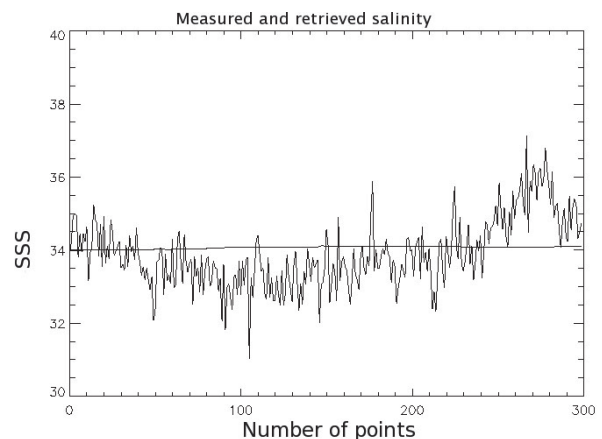

FIG. 2. – Retrieved salinity (noisy line) for LEG1 compared with measured salinity (stable line).
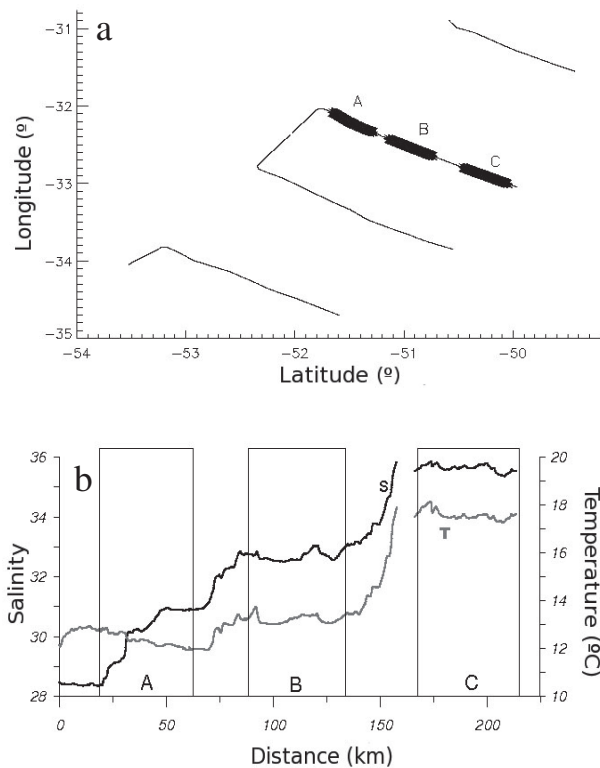
FIG. 3. – a) LEG2 track map. b) Surface salinity and temperature measured by the vessel. The three study areas are marked by A, B and C.

determine the sea surface salinity with a good performance, taking into account the limitations of the radiometer (calibration, noise, only six angular measurements, 1 polarisation).

Transects of LEG2 are located north of the river mouth and extend 185 km offshore. They cross a significant surface salinity gradient, with fresher water near the coast (due to the Plata plume and the Patos Lagoon outflow) and saltier offshore (see Fig. 1b). Three areas in one of these transects (Fig. 3a) were selected to perform the retrieval process, as each one has reasonably homogeneous salinity (except in case A) and they showed especially small variations in pitch and roll of the aircraft that provide a constant viewing geometry and hence allow measurements to be averaged.

Figure 3b shows the surface temperature and salinity measured by the vessel for the whole LEG2 transect. It should be noted that the ship survey in the area took place 4 days before the STARRS aircraft measurements, but SSS should not suffer great changes in this period of time, except perhaps near the Plata plume offshore front, where observed cross-shore salinity gradients are large ($\approx 2 \cdot 10^{-4}$ practical

salinity unit/m). For this reason we chose the data segments away from such sharp transitions.

The three areas used for the analysis are marked as A, B and C (see Fig. 3). The mean in situ measurements for each area are:

Area A: $\overline{SSS_{insitu}} = 30.18$, $\overline{U_{10\,model}} = 2.90$ m/s

Area B: $\overline{SSS_{insitu}} = 32.69$, $\overline{U_{10\,model}} = 2.45$ m/s

Area C: $\overline{SSS_{insitu}} = 35.64$, $\overline{U_{10\,model}} = 2.68$ m/s

Salinity was calculated first from individual T_B measurements before any averaging was performed. The differences between in situ and retrieved salinity for each area, after some anomalous points had been removed, are shown in Figure 4, and the mean and the standard deviation are also calculated (see Fig. 4). The fluctuating line is the retrieved salinity while the stable line is the in situ one. The plot shows that the retrieved values follow the measured SSS, except on area C, where they are highly underestimated. In area A, the retrieval clearly follows the salinity increasing all along the section. For area A and B the retrieval exercise indicates that, using the semi-empirical model derived in the Mediterranean Sea and reference wind speed provided by the ECMWF atmospheric model, the STARRS L-band measurements are able to reproduce the in situ salinity with quite good agreement.

Retrieved results for the three areas, after averaging 300 T_B measurements, are summarised in Table 1. In areas A and B the mean SSS is retrieved with very good accuracy, considering the quality of the radiometric data. Averaging the radiometric meas-
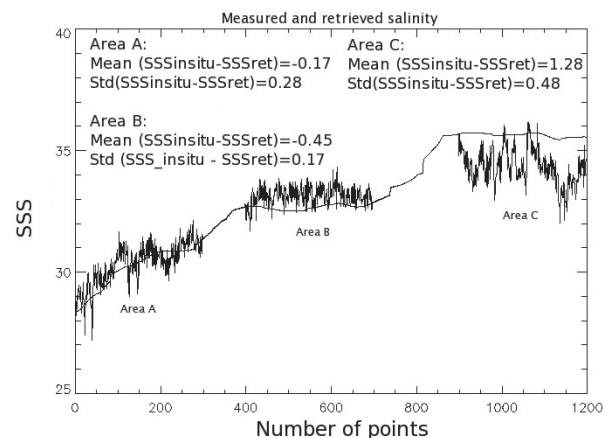

FIG. 4. – Retrieved salinity (noisy line) for the three areas (each area contain 300 measurements) compared with measured salinity (stable line).

TABLE 1. – Retrieved parameters for the three different areas from LEG2, after averaging 300 T_B measurements. $\Delta SSS = \overline{SSS_{insitu}} - \overline{SSS_{ret}}$.

	$\overline{SSS_{ret}}$	$Std(\Delta SSS_{ret})$	ΔSSS	$Std(\Delta SSS)$	$\overline{U_{10\,ret}}$	$Std(U_{10\,ret})$
Area A	29.84	0.79	0.34	0.79	1.95	0.34
Area B	32.62	0.79	0.07	0.79	1.42	0.37
Area C	33.82	0.69	1.82	0.69	3.74	0.34

urements over the homogeneous area B has produced a significant improvement with respect to averaging the retrieved salinity values. However, large retrieval errors are obtained for area C, similarly to what happened when date were retrieved from individual measurements.

The analysis of the impact of the model that provides the surface roughness effect was completed with the exercise of performing the retrieval without considering a roughness model (only a flat sea model). Worse results were obtained for SSS retrieved in area A $\Delta SSS=0.81$, area B $\Delta SSS=0.45$, and area C $\Delta SSS=2.76$ (being $\Delta SSS=SSS_{insitu}-SSS_{ret}$), which means that our semi-empirical model was able to efficiently introduce the correction in T_B caused by the roughened surface. For all the areas, retrieved salinity is lower in the flat case than in the measured one, as is expected, since the roughness produces an increment in T_B (for angles lower than 45-50º), and to compensate for this increment salinity has to decrease (lower salinity produces higher T_B).

Bad retrieval results were obtained from area C, as salinity was always strongly underestimated. This area is the most offshore region from the analysed transect. A possible explanation for this underestimation of salinity could be that the wind speed is significantly higher than is considered by the analysed model output. An underestimation of the wind speed produces a decrease in the T_B of the direct model, and to compensate for this SSS has to decrease (at nadir an error of 1 m/s represents an error of 1 K in T_B, which means an error of 2 in SSS). If a wind speed of 12 m/s is considered, then the retrieved salinity error is of the same order as in areas A and B (the wind speed measured by the ship four days before in area C was 10 m/s). However we cannot know the exact wind speed at the position and time in which the plane passed.

Another possibility for explaining the bad retrieval of area C could be the presence of water filaments of low and high salinity produced by shear eddies in the river plume boundary, which were observed during the field campaign (Piola *et al*, 2008) and are usual

in the region (Souza and Robinson, 2004). These surface filaments can be created in two or three days. Therefore, since there is a 4-day elapse between the in situ and the radiometric measurements, these filaments could be the reason for the large difference between retrieved and measured salinity.

CONCLUSION

Sea surface salinity averaged over less than 50 km was retrieved from L-band radiometric measurements performed by the STARRS instrument mounted on an aircraft during the Plata campaign with an accuracy better than a few tenths of practical salinity units in most areas. Results show that the instrument is, in some cases, capable of distinguishing between waters with different salt concentrations. Particularly relevant are the results of the case in which in situ and airborne radiometric data were acquired simultaneously.

The limitation of STARRS in terms of having one single polarisation and measuring at only 3 different incidence angles, together with possible additional instrumental problems, did not prevent the suitability of the retrieval approach from being demonstrated. It is expected that future tests using the now existing airborne demonstrators of the SMOS-MIRAS instrument (with a very wide range of incidence angles and two polarisations) will improve the present results and give better spatial resolution for a similar SSS retrieval quality.

A sea surface L-band emissivity model that includes a correction for surface roughness derived from data recorded in the Mediterranean Sea has been successfully used in retrieving salinity from STARRS data in the Brazil-Argentina continental shelf region. This correction is capable of improving the retrieved salinity by around 0.5. This approach will also be tested during the SMOS commissioning phase to identify the most efficient forward model (either theoretical or semi-empirical) to be used in the salinity retrieval. The selected model could have a global character or be adapted to the specific conditions (bathymetry, wind regimes, fetch, etc.) of different oceanic regions.

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