Demonstration of ocean surface salinity microwave measurements from space using AMSR-E data over the Amazon plume

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Microwave Sea Surface Salinity (SSS) measurements can be performed by isolating the emissivity response to conductivity changes from numerous geophysical effects, including surface temperature and wind waves. The sensitivity to salinity peaks near 1.4 GHz and falls off quickly as frequency is increased. Nevertheless, methods using higher microwave frequencies with much lower SSS sensitivity than at 1.4 GHz, can already be tested. In particular, combining 6 and 10 GHz data in vertical polarization efficiently minimizes sea surface roughness and thermal impacts. Using AMSR-E data, the retrieved bi-monthly maps of SSS at 0.5° resolution over the well-monitored region of the Amazon plume show relative accuracy in-line with the future dedicated mission objectives. Methods employed here can be used to aid in the new era of SSS monitoring from space, and these independent estimates incorporated into the coming retrieval efforts in the tropics.
1. Introduction

Upwelling ocean surface microwave emission is controlled by a variety of physical and chemical factors such as temperature and conductivity as well as wave-generated surface roughness, foam and spray. The sensitivity of the emitted radiation to small variations in such factors is a function of frequency, probing angle and polarization state. Microwave Sea Surface Salinity (SSS) measurements can then be achieved by isolating the emissivity response to conductivity changes. This typically requires that the Sea Surface Temperature (SST) and surface roughness information are very well known.

Based on such measurement principles, low frequency microwave radiometers onboard the ESA’s Soil Moisture and Ocean Salinity (SMOS) and the NASA Aquarius missions will soon provide the first global measurements of SSS dynamics from space, with an expected resolution of the order of 0.1 psu (practical salinity unit). The frequency window at 1.413 GHz (L-band) where SMOS and Aquarius sensors will operate, is an optimum choice for remote sensing of salinity because it resides very near the peak in sensitivity for microwave brightness temperature ($T_B$) changes due to seawater conductivity. Yet, this study demonstrates that there already exists a capability in space to retrieve and refine ocean satellite salinity measurements and methods. We utilize the C- and X-band data from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E). While these bands have significantly lower SSS sensitivity than that at L-band, they offer an opportunity to evaluate salinity inversion budget issues - this using on-orbit data with temporal and horizontal resolution scales in line with or exceeding the coming missions.
To retrieve SSS from C (6.9 GHz) and X (10.7 GHz)-band $T_B$s, there are a number of challenging issues that must be considered. According to the model developed by Klein and Swift [1977] (hereafter denoted KS) for the dielectric constant of seawater at low microwave frequencies, $T_B$ sensitivity to SSS varies with incidence angle, frequency, polarization state and temperature. At incidence angles near 53°-55°, where existing radiometric missions operate, the SSS sensitivity in vertical polarization (V-pol) is larger than that at horizontal polarization (H-pol), and the warmer the sea surface, the more sensitive is $T_B$ to SSS. The shift from L-band to C- and X-bands lowers $T_B$ sensitivity to changes in salinity by a factor of 10 to 20. At an SST $\sim 30^\circ$C, the sensitivity reaches a V-pol maximum magnitude of about 0.06 K/psu, and 0.03 K/psu, at C- and X-bands, respectively, whilst at L-band, it is $\sim$0.9 K/psu. Moreover, the $T_B$ sensitivity to SST is 0.6-0.7 K/°C at these frequencies, i.e. about ten times higher than the impact of a 1 psu change in SSS. Finally, surface waves can cause significant changes in the observed brightness temperature that may mask the weak salinity signature.

To compensate this expected weak sensitivity, this study is limited to the Amazon plume region in the Northwestern Tropical Atlantic characterized by large (100-200 km) and persistent salinity contrasts that exceed the 0.1 psu salinity science mission requirement by a factor of 10-100, and by warm surface waters. This region is of great importance within the salinity mission context due to the large freshwater flux from the discharge of the Amazon and Orinoco rivers, and their interactions with northward propagating eddies from the retroreflection of the North Brazil Current (NBC).
To minimize the impact of competing terms carried in the ocean $T_B$ measurements, foremost being SST and ocean surface roughness, and to isolate SSS signatures, we propose to use a $T_B$ difference measurement obtained with AMSR-E data, $\Delta T^v_B = T^6.9_v - T^{10.7}_v$, where $T^6.9_v$ and $T^{10.7}_v$ are the $T_B$ at the ocean surface in V-pol at C- and X-band, respectively. This quantity is selected for two reasons. First, according to KS model, differentiating $T_B$’s in V-pol strongly minimizes the SST impact while weakly affecting the sensitivity to SSS. At SST=30°C, the sensitivity of $\Delta T^v_B$ to SSS and SST is about -0.05 K/psu and 0.025 K/°C, respectively. Second, we will show $T^6.9_v$ and $T^{10.7}_v$ respond similarly to changes in surface wind speed, hence $\Delta T^v_B$ exhibits very little sea surface roughness dependence.

To estimate SSS from $\Delta T^v_B$, we use a satellite-based data set for year 2003 in the Northwestern Tropical Atlantic. The compilation includes $T_B$ data at C and X-band frequencies and Ocean Products from the AMSR-E satellite. $\Delta T^v_B$ is estimated at the sea surface level after correcting for atmospheric influence using the latter products. SSS is then estimated by minimizing the difference between AMSR-E $\Delta T^v_B$ at the surface level along the swath and the predictions from the KS’s model, assuming the true SST is given by the merged AMSR-AVHRR analysis product developed by Reynolds et al. [2007]. The retrieved SSS are then averaged bi-monthly and monthly.

AMSR-E SSS estimates are then validated using a complement of sources. Recent ocean color work (e.g., Hu et al. [2004]) demonstrated the strong negative correlation between satellite-derived colored dissolved organic matter (CDOM) and the surface salinity in the Amazon plume region. To support spatial validation in this study, composite of SeaWiFS and MODIS products are used to produce CDOM maps as a proxy for delineating
the spatial extent and patterns of the Amazon and Orinoco freshwater plumes. In addition, both a climatology and a match-up data base between \textit{in situ} upper layer salinity measurements and AMSR-E estimates are used for quantitative evaluation.

2. Data

The AMSR-E instrument onboard the NASA EOS Aqua satellite is a forward-looking, conically scanning radiometer operating at 55° incidence and 9 frequencies between 6.9 and 89 GHz. We use the 6.9 and 10.7 GHz L2A $T_B$ product, resampled at 56 km spatial resolution, from the National Snow and Ice Data Center (NSIDC). The radiometer noise for 6.9 GHz and 10.7 GHz observations along scan is 0.3 K and 0.6 K, respectively. During the L2A processing, adjacent observations are averaged to reduce the noise to 0.1 K. In addition, we used the L2B ocean swath product (\textit{Wentz and Meissner} [2000]), also available at NSIDC, that contains SST, near-surface wind speed, columnar water vapor, columnar cloud liquid water, and quality flags.

The L2B ocean products, including SST, are retrieved by applying a salinity correction to the L2A $T_B$ data. The correction is based on monthly climatology of surface salinity from the National Oceanographic Data Center (NODC) World Ocean Atlas and SST values from the Reynolds climatology. Therefore, variation in actual SSS from climatology may have an impact on the retrieved AMSR-E SST, which in turn, may affect the quality of the SSS retrieval if this product is used as ancillary data in the retrieval algorithm. To minimize this potential effect on SST, we used the merged AMSR-AVHRR analysis product developed by \textit{Reynolds et al.} [2007] as the ancillary SST for our study. That product, available at the National Climatic Data Center (NCDC), is developed using
optimum interpolation; it has a spatial grid resolution of 0.25° and a temporal resolution of 1 day. Systematic biases (such as the SSS impact on AMSR-E SST) on this merged SST product is reduced because (i) it includes a large-scale adjustment of satellite biases with respect to in situ data and (ii) because the error characteristics of both infrared and microwave instruments are independent. Note as well that this product is based on night-time acquisitions to avoid diurnal cycle signatures.

To demonstrate that AMSR-E retrieved SSS products contain enhanced information with respect to climatologies, we develop a match-up data set between AMSR-E bi-monthly averaged SSS estimates and in situ data provided at the French Coriolis Argo Data center. The in situ data originate from different sources such as profile data (selected at the uppermost level located between 5 m and 10 m depth), with the addition of underway collection on research vessels and voluntary observing ships (VOS), and from moorings in the tropical Atlantic (PIRATA array). The monthly SSS climatology of the tropical Atlantic developed by Reverdin et al. [2007] and generated at a spatial resolution of 1° × 1° is also used in the present work. The satellite-derived maps of CDOM absorption coefficient derived at 443 nm ($a_{cdom}(443)$) as a proxy to detect patches of low salinity surface waters come from the monthly merged data product (9 km resolution) obtained through the NASA/Giovanni server. It is a composite of SeaWiFS and MODIS products derived using the Garver-Siegel-Maritorena (GSM) semi-analytical ocean optics model. This product provides a CDOM estimate similar to the absorption retrieval approach of Del Vecchio and Subramaniam [2004] and will be noted as $a_{cdom}$ in the remainder of the
paper. All datasets were compiled for the year 2003 over the spatial domain between 20° S and 20° N and 70° W and 20° W.

3. Methods

AMSR-E Swath data flagged for rain, low sun glint angles and low Geostationary Radio Frequency Interference (RFI) angles were first discarded. The vertically polarized L2A $T_B$ products at each AMSR-E frequency $f$, hereafter denoted $\tilde{T}_v^f$, can be expressed as

$$\tilde{T}_v^f = T_{up}^f + \tau^f \left[ e_v^f T_s + r_v^f (\tilde{\Omega}_v^f T_{down}^f + \tau^f T_C) \right]$$  \hspace{1cm} (1)

where $e_v^f$ is the sea surface emissivity in v-pol and the corresponding reflectivity is $r_v^f = 1 - e_v^f$. $T_{up}^f$ is the upwelling atmospheric brightness temperature at the top of the atmosphere, $T_{down}^f$ is the downwelling atmospheric brightness temperature at the surface, $\tau^f$ is the atmospheric transmisivity and $T_s$ is the SST. $T_C \sim 2.7$ K is the cosmic background radiation temperature. The $\tilde{\Omega}_v^f$ term is a correction factor to account for nonspecular reflection of the atmospheric downwelling radiation from the rough surface. Given the AMSR-E Level2B water vapour, cloud liquid water and surface wind speed products, as well as the co-localized daily AVHRR-AMSR SST products, $T_{up}^f$, $T_{down}^f$, $\tau^f$ and $\tilde{\Omega}_v^f$ can be evaluated using the algorithm described in Wentz and Meissner [2000]. The surface reflectivity in v-pol at frequency $f$ can then be estimated using (1) as:

$$r_v^f = \frac{\tilde{T}_v^f - T_{up}^f - \tau^f T_s}{\tau^f \tilde{\Omega}_v^f T_{down}^f + \tau^f T_C - T_s}$$  \hspace{1cm} (2)

Using (2), the difference $\Delta T_b^v$ in brightness temperature estimated at the surface level between 6.9 GHz ($T_v^{6.9}$) and 10.7 GHz ($T_v^{10.7}$) vertical polarization channels is

$$\Delta T_b^v = T_v^{6.9} - T_v^{10.7} = T_s \left( r_v^{10.7} - r_v^{6.9} \right)$$  \hspace{1cm} (3)
where $\Delta T_b^w$ includes the sum of two contributions. The first one is the difference in the flat surface ocean reflectivity between the two channels ($\Delta r_{flat}$) and the second is due to a possibly differing surface roughness impact on the reflectivity at the two frequencies ($\Delta r_{rough}$). To evaluate the latter effect, the ensemble of surface $T_B$, evaluated at each frequency for the year 2003, are bin-averaged as function of the L2B ocean wind speed product. As illustrated in Figure 1, we find that on average, $T_6^{10.7}$ and $T_10^{9.9}$ behave very similarly as a function of wind speed. Although residual differences in reflectivity between the two channels may locally exist due to slightly differing roughness impacts, we assume here that $\Delta r_{rough} \approx 0$. Thus, the SSS retrieval methodology from the estimated $\Delta T_b^w$ follows. First, we evaluate $\Delta r_{flat}$ using KS’s model applied to the AVHRR-AMSR SST and for salinity values ranging from 0 to 40 psu. The retrieved SSS along swath is then determined by minimizing the difference between the KS prediction and the AMSR-E $\Delta T_b^w$’s. Swath retrieved SSS is then mapped onto a 0.5° resolution grid, averaged over 15 days or 1 month periods and spatially smoothed by a 1° by 1° block average.

4. Results

We illustrate the methodology by considering here the results for July 2003. The monthly-averaged $\Delta T_b^w$ and SST maps are shown in Figure 2. Patches of high $\Delta T_b^w$ values exceeding their surrounding water counterparts by more than 0.4 K are observed centered near 7°N 50°W and following the NBC retroflection. Assuming a constant salinity of 36 psu along a north-west/south-east section across these patches, KS applied to the AMSR-AVHRR SST predicts that the evolution of $\Delta T_b^w$ along that section cannot be explained solely by the spatial changes in SST. The model prediction for $\Delta T_b^w$, assuming
that SSS along the transect evolves as in the monthly climatology, shows a much better agreement with the data, although significant local differences can be observed around the measured $\Delta T^v_b$ peak. This analysis strongly suggests that the large amplitude $\Delta T^v_b$ variations observed within the domain ($0^\circ$N-$20^\circ$N, $70^\circ$W-$40^\circ$W) are dominated by the impact of SSS variations.

The July 2003 monthly composite map of the CDOM absorption coefficient (see Figure 3. a) clearly shows that the area where $\Delta T^v_b$ exceed about -2.5 K systematically exhibit high $a_{cdom}$ values. This further indicates the potential signature of the Amazon plume in AMSR-E signals. The monthly-averaged AMSR-E retrieved SSS map given in Figure 3.b shows that these areas indeed correspond to predicted patches of low-salinity water (below 35-34 psu). The extent and dispersal patterns of the Amazon freshwater plume seen by AMSR-E is well correlated with the highly colored waters, as indicated by the superimposed $a_{cdom}$ contours on the SSS map of Figure 3.

In July 2003, the voluntary observing ships (VOS) MN/ Colibri, equipped with a thermo-salinograph, performed SSS measurements along the transect shown in Figure 3.b, collecting seawater at about 5 m depth. The SSS measured by the ship is shown in Figure 4.a, together with the 15 day-average retrieved AMSR-E SSS and the July climatology interpolated along the transect. The large-scale spatial structure of the freshwater Amazon plume, extending about 600 km offshore, is clearly observed in the AMSR-E SSS product. On the other hand, the climatology strongly underestimates the salinity gradient across the plume. Local discrepancies between the satellite and in situ SSS are nevertheless observed at scales smaller than about 100 km. Comparison results similar to
this July example are found throughout the year, and the satellite SSS data capture the seasonal cycle in the extent and dispersal patterns of the Amazon and Orinoco plumes. Regardless of the season, note that the measured $\Delta T_B$ are corrected for a constant bias of $\sim -0.15$ K to align the mean satellite-retrieved SSS to the in situ and climatological values. It may indicate an absolute calibration offset between the two AMSR-E frequency channels in 2003.

The overall in situ - satellite data collocation are shown in Figure 4.b. The root-mean square difference between in situ and satellite observations is 1.5 psu. The strong spatio-temporal variability of the plume may contribute to generate significant differences when comparing in situ measurements with large footprint satellite products sampled at a 0.5$^\circ$ resolution and averaged over 15 days. Another source is certainly be the differing salt content in the vertical as probed by very near surface satellite measurements (sub cm) and deeper-level in situ observations, usually conducted at depth between 5 to 10 m. Moreover, errors in the retrieval algorithm are certainly included due to (i) neglecting the difference in the roughness impact between the two channels (ii) errors in the ancillary geophysical products, such as SST (e.g., diurnal cycle impact on the $\Delta T_B$) (iii) errors in the atmospheric contribution removal, (iv) inaccuracies in the dielectric constant model, and (v) instrumental noises. All these factors and data intercomparison issues will also be present in the coming L-band mission calibration and validation activities. The encouraging point is that this study demonstrates that, even using sensors at least 10 times less sensitive to SSS than the future L-band missions, monthly and bi-monthly surface salinity can be retrieved with a relative accuracy that is in line with the future dedicated
mission objectives. The method we developed can be readily applied in all tropical ocean regions both to derive new satellite-based SSS climatologies and to characterize seasonal cycles and interannual variability in the large-scale surface salinity structures of the tropical oceans largest river plumes. And while AMSR-E can be used to begin the new era of global monitoring of surface salinity over the oceans, it may also prove useful to incorporate its independent estimates into the coming L-band SMOS and Aquarius SSS retrieval algorithms in the tropics.

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**References**


**Figure Legend**

**Figure 1.** Wind speed bin-averaged surface brightness temperatures at 6.9 and 10.7 GHz as function of wind speed for the year 2003. Wind speed bins are 1 m.s$^{-1}$.

**Figure 2.** (a) Monthly averaged difference $<\Delta T^V_b>$ in estimated flat sea surface brightness temperature between 6.9 and 10.7 GHz frequencies in vertical polarization, and for the month of July 2003. The black line illustrates the location of the transect shown in (c) and (d). (b) Corresponding monthly averaged AVHRR-AMSR OI 0.25° sea surface temperatures. (d) Sea surface temperature from AVHRR-AMSR (red curve) and salinity from the monthly climatology of the tropical Atlantic (blue curve) along the transect shown in (a). (d) Corresponding $<\Delta T^V_b>$ along the transect measured from AMSR-E (black) and estimated using Klein and Swift’s dielectric constant model applied to AVHRR-AMSR SST and (i) to a constant salinity of 36 psu (red) or (ii) to the surface salinity from the climatology (blue).

**Figure 3.** (a) Monthly composite map of $a_{cdom}$ obtained with the GSM model and the SeaWiFS and MODIS sensors for July 2003. (b) Monthly averaged sea surface salinity retrieved from AMSR-E. The thick black line shows the July 2003 transect of the ship MN/Colibri, equipped with an underway thermosalinograph. Thin black curves in both figures represent contours of $a_{cdom}$ at 0.005, 0.01, 0.025, 0.05 and 0.1 m$^{-1}$.

**Figure 4.** (a) Sea surface salinity measured by the MN/Colibri TSG (black dots), 15-days averaged retrievals from AMSR-E $\Delta T^V_b$ (blue dots) and July climatology (red dots) interpolated along the ship transect. (b) Comparison between co-localized AMSR-E SSS retrievals and in situ measurements over the year 2003. Root mean square difference is about 1.5 psu.