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FIRST ANALYSIS OF SMOS SEA SURFACE SALINITY

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ABSTRACT

SMOS (Soil Moisture and Ocean Salinity) is the first interferometric radiometer in orbit. In the first ground processing (Level 1), an image reconstruction algorithm is applied which yields measured brightness temperatures (TB). Preliminary studies have shown that this processing is critical and likely to introduce biases that affect subsequent processing. Therefore, a comparison of modelled to reconstructed TB is essential. Homogenous ocean surfaces far from land masses are ideal for this task as the TB variation with the satellite geometry (incidence angle) is relatively well known.

Extensive comparisons were conducted between SMOS Level 1c TB and TB simulated using the default forward model implemented in the ESA SMOS ocean salinity processing and using ECMWF (European Centre for Medium-Range Weather Forecast) forcings. They demonstrate that the North-South behavior of SMOS measurements over the ocean is amazingly consistent with the simulated L-band signal, that the noise of the measurements with respect to the model estimate depends on the measurement location in the field of view and is very close to the expected radiometric uncertainty. On another hand, systematic biases of several Kelvins are observed, that depend on the location of the measurement in the Field of View.

After these systematic biases are removed, SMOS sea surface salinity (SSS) are retrieved over 5 days in March 2010 at global scale. They match quite well the SSS climatology; SMOS anomalies with respect to the

climatology are finally compared to the ones deduced from in situ measurements

1. INTRODUCTION

Ocean salinity is a key parameter in oceanic and climate studies. Together with the ocean temperature, the salinity influences the density of the water masses and actively participates in their formation and circulation. In situ sea surface salinity (SSS) measurements, acquired by buoys and oceanographic or commercial ships, remain sparse and irregular.

The Soil Moisture and Ocean Salinity (SMOS) mission was selected by European Space Agency (ESA) as an Earth Explorer Opportunity Mission [1] within the ESA Living Planet Program; the SMOS spacecraft was successfully launched on 2nd November 2009. The SMOS payload, MIRAS (Microwave Imaging Radiometer using Aperture Synthesis), is a L-band radiometer; for the first time onboard a satellite, it uses interferometric technology to obtain high spatial resolution over a large swath. The MIRAS radiometer is dual polarized (with an optional fully polarimetric mode), and it has a multiangular imaging capability [2]. This capability can be exploited to reduce the impact of radiometric noise on salinity retrieval and also allows the retrieval of geophysical parameters, other than the SSS, such as wind speed.

The objectives of this paper are to give preliminary assessments of the characteristics of SMOS brightness

temperature (TB) measurements and to report initial analysis of sea surface Salinity (SSS) retrieved from SMOS measurements.

The methods and data used are described in Section 2 together with statistics of the TB differences between model and simulation. Results on retrieved salinity are presented in Section 3 and are discussed and summarized in Section 4.

2. DATA AND METHODS

A. Data

SMOS Level 1C Sea Science measurements products (L1c) are generated by the Data Processing Ground Station (DPGS) for each half-orbit. In L1c product, two-dimensional fields of SMOS TB are reconstructed in the antenna reference frame. The Stokes vector at the antenna level is linked to the Stokes vector at sea surface level by a linear matrix, that depends on the geometry of observation [3]. The sensor images a 2-D field of view (FOV) in which TB is acquired at various incidence angles and spatial resolutions. Therefore any given point on the Earth is observed several times in successive locations within the FOV as the satellite moves ahead, along “dwell lines” parallel to the sub-satellite track [4].

L1c TB of one ascending orbit in Dual mode passing over the eastern Pacific Ocean on 3rd of March, 2010, processed by L1 operation processor software (L1OP) of version 330 was used to estimate the residual misfit between averaged measured and modelled TB. Only TB measurements from 50°S to 20°N in latitude are used in order to avoid interference from North America.

L1c TB of one ascending orbit in Full mode passing over the eastern Pacific Ocean on 10th of March, 2010, processed by L1 prototype processor software (L1PP) of version 330 with baseline weight computed for sea implemented was used to analyze radiometric accuracy of the SMOS instrument.

And, two sets of L1c TB data are used for analysis of SMOS sea surface Salinity:

- 1) One ascending orbit in December of 2009 in dual polarization mode, processed by L1PP of version 321.
- 2) 5 days ascending orbits in March of 2010 in dual polarization mode, processed by L1 operation processor software of version 330.

B. Forward model in L2OS processor

The default forward model implemented in the ESA L2 Ocean Salinity processor (L2OS) [5] simulates emission by a rough sea surface, atmospheric emission and absorption, scattering of celestial and atmospheric radiation by the rough ocean surface, and rough sea surface emission. The L2OS processor calculates the sum of all modelled contributions at the sea surface, and then applies a transformation matrix of the Stokes vectors to the satellite instrument, including geometric and Faraday rotation [3]. So, TB can be compared to actual measurements in the SMOS antenna reference frame. Here, the Two-Scale model [6] developed by LOCEAN (Laboratoire d’Océanographie et du Climat-Expérimentation et Approches numériques) is used for simulating ocean roughness.

An algorithm based on the Levenberg and Marquardt iterative retrieval method [7] is used for salinity retrieval. It optimizes the geophysical parameters so as to minimize the difference between the TB measurements and the TB simulated by the forward model along dwell line [8]. The iterative method is initialized with salinity of World Ocean Atlas 2005 (WOA05) with a constraint of 100ps, that is practically no constraint, WS (with a constraint of 1.5m/s on each component) and SST (with a constraint of 1°C) as predicted by ECMWF (European Centre for Medium-Range Weather Forecast) and TEC (Total Electron Content) as predicted at the Center for Orbit Determination in Europe.

C. SMOS TB characteristics

The SMOS synthetic antenna consists of 69 antenna elements distributed along three equally spaced arms, resulting in a planar Y-shaped structure. The L1c

product provides 2-D fields of TB reconstructed in the antenna reference frame and corrected for the directional gain patterns of antenna elements.

When comparing L1c TB along some open ocean orbits in the eastern Pacific Ocean, under relatively moderate surface roughness conditions and far from continental areas, a residual misfit (OTT) is observed between averaged measured and modelled TB over 100 snapshots in the antenna cosinus-director frame, even after L1c data are fully calibrated using a flat target response (open sky image). The persistent spatial pattern of this bias in FOV, as shown by Fig. 1, is probably due to instrumental and image reconstruction imperfections, still under investigation.

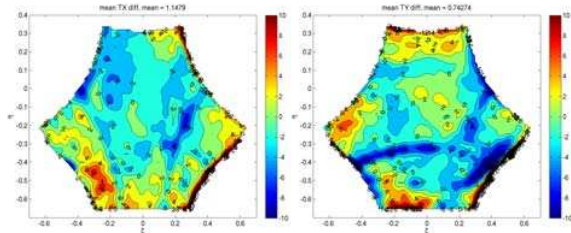
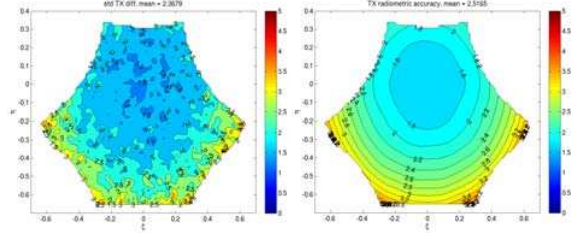
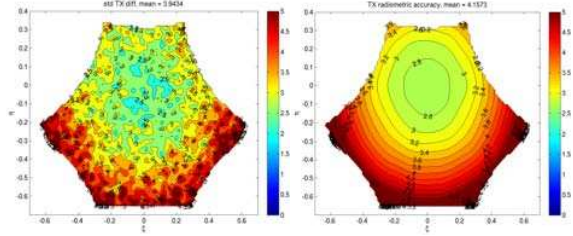


Figure 1. OTT for horizontal (left) and vertical (right) polarization from an ascending orbit over the eastern Pacific Ocean on 3rd of March, 2010, processed by LIOP v330

The SMOS instrument is now working in full polarization mode. This mode, producing only first two Stokes parameters in long-integration snapshots (about 1.2s) and all the four Stokes parameters in short-integration snapshots (about 0.4s), provides additional polarimetric information to be used in further processing improvements, e.g. better estimation of the Faraday rotation effect. By checking standard deviation of differences between measured and modelled TB computed over 50 snapshots along some open ocean orbits in the eastern Pacific Ocean, it is found that observed noise compares well with its theoretical value, as shown in Fig. 2.



(a) long-integration snapshots



(b) short-integration snapshots

Figure 2. (a) Standard deviation of differences between measured and modelled TB for long-integration snapshots (left) and its theoretical value (right); (b) same plots as (a) for short-integration snapshots

3. RESULTS

A. Spatial variability of SMOS TB related to geophysical variability

In order to check spatial variability of SMOS TB related to geophysical variability, TB measurements and simulations as a function of latitude (time) along an open ocean orbit in the eastern Pacific Ocean are compared. High northern latitude parts of the orbit appear very noisy and are removed; it is suspected that Radio Frequency Interferences (RFI) and/or land contamination are responsible for this large noise. Two kinds of comparisons are shown below:

- 1) Modelled and measured TB at boresight (1 point per snapshot), corresponding to an incidence angle close to 37°, versus time are given in Fig. 3. In order to reduce the noise, the running mean of measurements over 7 points (about 100km on ground) is also displayed, after median of the bias with respect to modelled TB over the half orbit is removed.
- 2) Modelled and measured TB averaged over the whole FOV, with median of the bias with respect to model

over the half orbit removed, versus latitude are shown in Fig. 4.

As shown by figures 3 and 4, in most cases, large scale features of the individual and averaged measurements are in good agreement with model predictions. Southern-Northern variations of Tbs (due to SSS, wind speed and SST variability) are consistent between measurements and model computations.

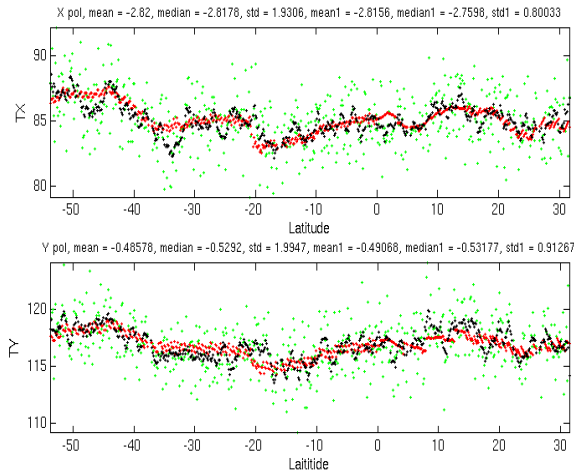


Figure 3. Latitudinal profiles of measured and modelled TB at boresight for X polarization (top) and Y polarization (bottom). Modelled TB are shown by red points, measured TB are shown by green points and 7-points-running-mean of measured TB are shown by black points

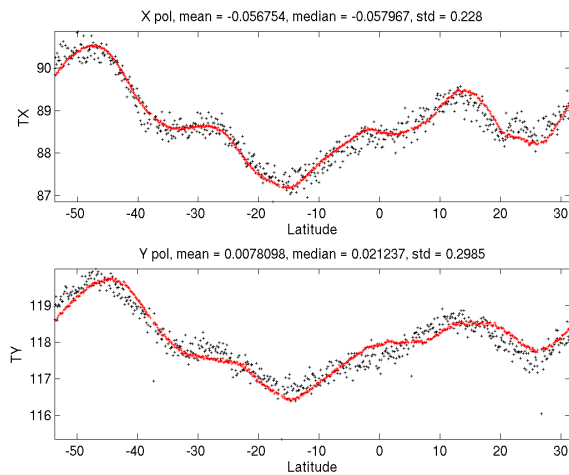


Figure 4. Latitudinal profiles of measured and modelled TB averaged in FOV for X polarization (top) and Y polarization (bottom). Modelled TB are shown by red points, measured TB are shown by black points

B. First test of salinity retrieval

Given the good behavior of measured TB compared with modelled TB, we attempted to retrieve SSS using the Levenberg & Marquardt retrieval method implemented in L2OS processor. The systematic biases in FOV described in Section 2C were removed before inversion

An orbit over the eastern Pacific Ocean on 11th December 2009 was first processed with preliminary calibration algorithms in L1OP processor, and used to retrieve SSS using all measurements in FOV. The maps of retrieved SSS and of the corresponding monthly climatological SSS from WOA05 is shown in Fig. 5. Even though the retrieved SSS of this orbit is noisy, it's clear that the low-high-low distribution of SSS of WOA05 from south to north is well captured by SMOS. In particular, the high SSS belt around 25°S is well located by the spacecraft.

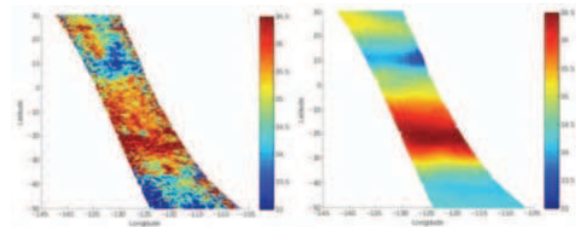


Figure 5. Retrieved SSS along an orbit in the east Pacific Ocean on 11th of December 2009 (left) and the corresponding monthly averaged SSS of December from WOA05 (right).

Next, the latitudinal variations of SSS from south to north of this orbit are considered quantitatively. SSS of WOA05 and ARGO/ISAS (in situ analysis system) are taken as references. ISAS uses estimation theory to combine information from previous knowledge of the

ocean with all synoptic SSS measurements, taking advantage of the relatively dense Argo coverage and of any other measurements, with high quality control [8]. In this paper, SSS of ISAS referred to 5m depth is taken for comparisons.

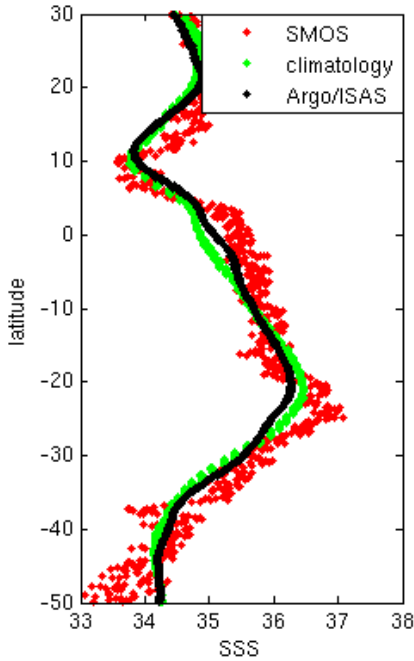


Figure 6. North-South SSS profile in the eastern Pacific Ocean, comparing SMOS, ISAS objective analysis and WOA5 SSS. The three curves are averaged in the same way, over 0.1 degree bin in latitude and across the SMOS swath

In Fig. 6, we plotted the latitudinal variations of SSS for the same orbit as Fig.5, deduced from WOA5 climatology, ISAS analysis and SMOS. Overall, the North-South gradient of SSS is well seen by SMOS although there are some discrepancies near the equator and around 20°S. There can be good reasons for the discrepancies as the WOA5 is a monthly climatology, ISAS analysis of in situ measurements is a monthly analysis whereas SMOS orbit gives an instantaneous view of the SSS. In addition, SMOS SSS is representative of the first centimeter depth whereas in situ measurements included in ISAS and WOA5 are taken at several meters depth.

Next, we try to assess the global performance of SMOS SSS over several days, retrieved with up to date algorithms in L1OP and L2OS processor. In order to use only measurements with smallest biases and noise, measurements outside the center of FOV (outside a square of 0.25 by 0.25 in the antenna cosinus-director frame (see Fig. 1)) were discarded. Then SSS retrieved from Tbs along dwell lines are spread over a 600km swath width.

A map of 5 days averaged SMOS SSS from 17 to 21 of March 2010 is shown in the top of Fig. 7. Only ascending orbits are used because descending orbits present too large SSS in the Southern hemisphere near Antarctica, the origin of which remains unknown. The monthly averaged SSS climatology of March, 2010 deduced from WOA5 is shown in the bottom map of Fig.7. As shown in Fig.7, in open ocean, far away from land, the global pattern of SMOS SSS is consistent with WOA5 climatology.

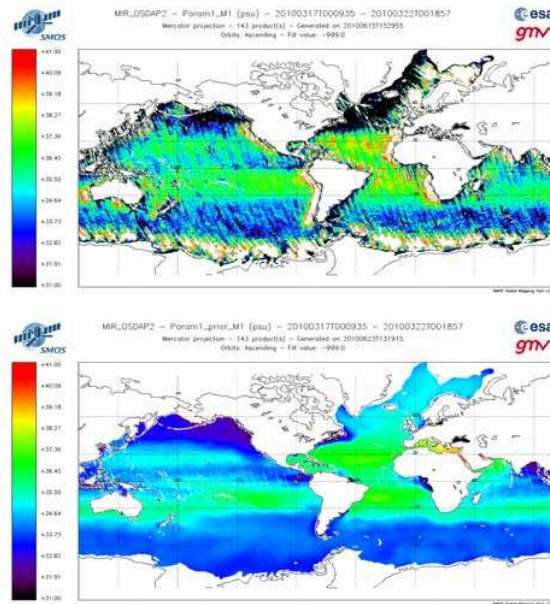


Figure 7. 5-day averaged global SSS of SMOS (top) with respect to WOA5 (bottom)

However, a serious problem observed in SMOS SSS is the land contamination from the continents when they

enter the SMOS very wide antenna FOV, as well as Radio Frequency Interference from island such as Hawaii. These effects may impacts strongly the quality of the SSS retrievals as soon as the distance to the coast becomes shorter than 1000 km..

C. Salinity anomaly

A detailed study of SMOS salinity with respect to WOA05 climatology and Argo/ISAS is performed over a large region in the Southern Pacific, in order to avoid land contamination.

In a box defined by [130°W 100°W] in longitude and [45°S 10°N] in latitude, 5 days averaged SMOS SSS from 17 to 21 March, 2010 follow quite well the geophysical patterns of ISAS salinity of March, 2010 (Fig. 8).

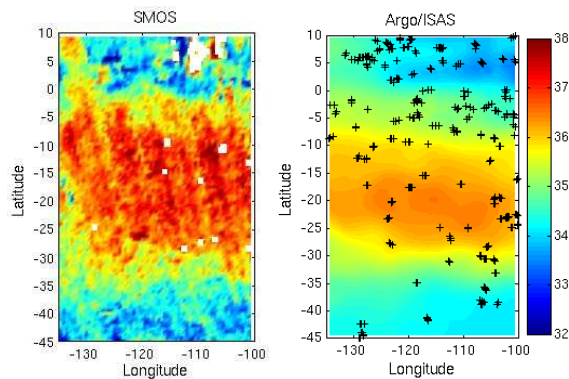


Figure 8. 5-day averaged global SSS of SMOS (left) with respect to ISAS salinity of March, 2010. “+” indicates position of Argo floats for that month

The advantage of SMOS is that, with only 5 days ascending passes and limited swath in a square (0.25 by 0.25 in the antenna cosine-director frame) in the center of FOV, SMOS SSS cover the global ocean, whereas some parts of the Pacific subtropics are not sampled by Argo floats in one month.

In this box, the spatial distribution of 5-day SMOS SSS anomalies with respect to WOA05 (Fig.9, left) is qualitatively close to the spatial distribution of ISAS monthly anomalies (Fig.9, right), with positive

anomalies around [120°W 30°S] and between 5°S and 15°S, and the fresh anomalies belt between 5°N and 0°N.

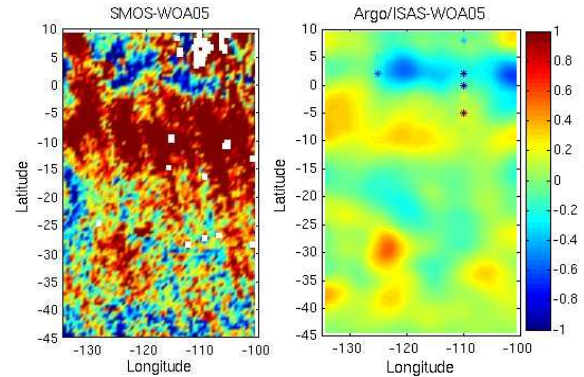


Figure 9. Salinity anomalies between SMOS SSS and WOA (left) and salinity differences between ISAS and WOA05 (right). Salinity differences between 5-day averaged TAO moorings from 16 to 20 of March, 2010 and WOA05 are shown by “*”

However, SMOS anomalies are stronger and noisier than ISAS. We then looked at SSS anomalies observed on the TAO (tropical atmosphere ocean project) moorings. The salinity differences between 5-day averaged TAO moorings from 16 to 20 of March, 2010 and WOA05 (“*” on right map of Fig. 9) also indicate stronger salinity anomalies than the ones of ISAS.

The latitudinal variations of SSS in the region defined by [130°W 100°W] in longitude and [45°S 10°N] in latitude are given in Fig.10. SSS are taken from SMOS, WOA05 climatology, ISAS analysis and TAO. The three curves of SMOS, WOA05 and ISAS SSS are averaged the same way, over 130°W-100°W in longitude and over 0.5 degree bin in latitude. The TAO SSS are averages from all moorings in the same latitudinal band.

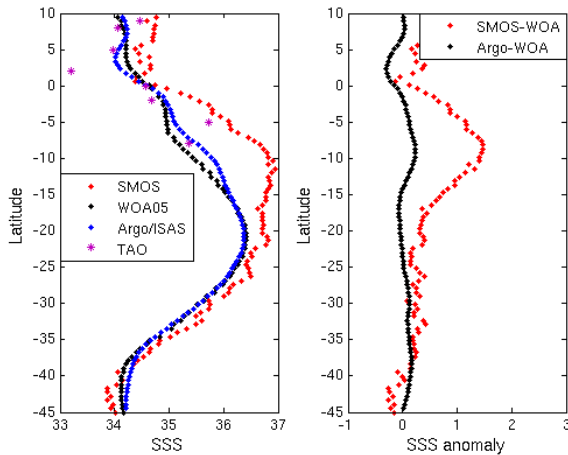


Figure 10. North-South SSS profiles in east Pacific Ocean, comparing SMOS, ISAS, TAO and WOA05 SSS information.

As shown by Fig. 10, the three SSS profiles for SMOS, WOA05 and ISAS follows each other well from 45°S to 25°S. SMOS began to find a higher SSS anomaly than ISAS compared to WOA05 from 25°S northwards. This anomaly reached a maximum around 10°S. It's difficult to decide whether SMOS SSS is more realistic than ISAS or not when taking TAO SSS into comparison. Sometimes TAO SSS is closer to SMOS, sometime it's closer to ISAS and sometimes it's even far away from SMOS and ISAS.

Possible reasons for discrepancies between these four sources of SSS could be:

- 1) While combined SMOS OS retrievals are close to uniform space averages, the ISAS analysis is based on much sparser data, although each individual measurement here is considerably less noisy.
- 2) Given the skin depth at L-band, SMOS SSS represent SSS at 1 cm depth, while WOA and Argo SSS are representative of SSS at about 5m depth.
- 3) The forward model used in the retrieval is the one defined before launch without any fitting to the SMOS measurements; future research on the modelling of L-band signal could reveal some imperfection of this model
- 4) The origin of the systematic biases observed within the FOV remains unclear so that the TB bias removal

strategy we adopted here (empirical OTT removal) may be not robust enough.

This study strengthens the importance of gathering a large set of in situ data taken as close as possible to the sea surface .

4. CONCLUSION

The North-South features of SMOS TB measurements (due to SSS, wind speed and SST) are at first order consistent with modelled TB. The quality of SMOS measurements seems to meet the expectations, except that a systematic bias dependent on the location in FOV is observed and needs to be removed before SSS retrievals. SSS obtained by L2OS processor with the algorithm defined previous to launch (without any fitting to SMOS measurements) shows good consistency with the climatology; even SSS anomalies with respect to climatology shows encouraging results. Nevertheless SMOS SSS exhibit stronger anomalies in the southern tropics than other products, for reasons still to investigate. More collocations between SMOS data and in situ measurements taken as close as possible to the sea surface are needed to discriminate between a geophysical signal and a flaw in SMOS data processing.

As SMOS L1c and L2OS processings are at their infancy, they are expected to improve , and we are very hopeful about the future quality of SMOS SSS.

5. ACKNOWLEDGEMENTS

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