E-AIMS
Euro-Argo Improvements for the GMES Marine Service

Sea Surface Salinity: Synthesis of past studies and plan for E-AIMS
D4.442

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1. **Introduction**

1.1. **General presentation**

This document presents the synthesis of previous and current studies concerning the use of the Argo system for the calibration and validation (Cal/Val) of remote sensed sea surface salinity estimates. The information presented here is based on the validation activities being carried out by the SMOS and the Aquarius science teams.

This is the deliverable D4.442 (E-AIMS WP4 Task 4.4) identified in the description of work [AD-1], in the table WT 2, page 4, which is due by the end of September 2013.

1.2. **Applicable documents**

AD-1: Annex 1 to the grant agreement N0 312642: “Description of work”, date 24 April 2012.


1.3. **Remote observations of Sea Surface Salinity**

The remote measurement of ocean salinity is possible because the radiation emitted by matter at low frequencies, and captured by a passive radiometer looking at it, is related to its physical temperature through a proportionality coefficient, the emissivity. The latter is linked to the dielectric properties of the emitting body that, in the case of the ocean surface, depends on the seawater conductivity that in turn is a function of ocean salinity [AD-2]. The sensitivity of the emitted radiation to salinity is largest around 0.6–0.7 GHz (microwave P-band), but several factors (e.g. large Faraday rotation effects, high galactic noise and lower spatial resolution) render this band not well suited for remote sensing. Close to it, a narrow frequency band (1.400–1.427 GHz, L-band) is better suited for soil moisture and ocean salinity measurement as it is devoted to passive observations and hence legally protected from artificial emissions. Figure 1 shows the sensitivity of the brightness temperature as a function of ambient temperature and salinity. It is clear that at this band, the weakest salinity sensitivity correspond to the coldest water
temperature. Then, it should be expected that the quality of the remote sensed salinity retrievals diminishes at high latitudes.

On the other hand, it is well known that any electromagnetic wave will penetrate a limited depth into a conducting material. The penetration depth depends on the frequency of the electromagnetic wave and on the conductivity of the medium. In the microwave band, and for a salinity of about 35, the penetration depth is about 1 cm. As the water becomes fresher, the conductivity is reduced, and the penetration depth increases until a value of about 10 cm for pure water.

The first estimates of SSS from space started with the S-194 1.4 GHz microwave radiometer onboard SKYLAB. However, in the 1970s there were not enough in-situ salinity measurements to set a robust ground-truth for a proper validation of the retrieved information. Forty years after, the existence of the Argo automatic profilers and a better understanding of the required signal corrections do make possible to better correlate the remotely sensed signal with the surface salinity, and to validate the retrieved values.

The first operational satellite missions actually designed to provide global maps of the ocean salinity are SMOS (launched on November 2, 2009) and SAC-D/Aquarius (launched on June 10, 2011) by ESA and NASA-CONAE respectively. Although both satellites measure the ocean brightness temperature at the L-band, they differ on the choice made to solve the technical problems of making accurate measurements at these microwave frequencies. The satellite SMOS carries a single passive instrument, the radiometer MIRAS, designed to reconstruct brightness temperature images from a synthetic aperture antenna combining a collection of 69 receivers.
distributed in three telescopic arms (allowing the increase of the spatial resolution of the pixel while maintaining a reasonable antenna size). The satellite SAC-D carries seven active and passive instruments including Aquarius, a set of a 25 m reflector, three L-band radiometers, and a scatterometer to estimate the surface roughness.

![Illustrations of satellites SMOS (left) and SAC-D (right).](image)

The satellite products being validated here are:

**Level 2:** Scientific data (i.e. sea surface salinity) along the swath (Aquarius) or in a 2D image (SMOS). The sea surface salinity information is obtained from the measurements of the microwave brightness temperature with the help of an inversion algorithm. The inversion algorithm may also use of auxiliary data as the sea surface temperature value and a prior information about the value of the sea surface salinity (e.g., salinity climatology).

**Level 3:** Spatial and temporal averages of Level 2 data over a regular grid. The most used grid is the 1 degree bin. The temporal average ranges from three days to one month. The spatial averages may use a filter algorithm to reduce noise and increase the spatial and temporal coherence of the data. In the case of Aquarius, a bilinear fit is used. In the case of SMOS, an Objective Analysis may also be used.

**Level 4:** A salinity map generated by combining low-level salinity data and information from another sensor (sea surface temperature, sea surface high, or ocean color). Alternatively, the output of a data assimilation experiment in which various data might be simultaneously assimilated in the model may also be considered Level 4.
2. Argo SSS data

2.1. Argo data

The first in-situ observing system able to provide systematic, global measurements of the ocean salinity in the first 1500 m of depth has been the Argo array of automatic floats. The first floats were launched in 1999, and the number of floats has stabilized since 2006. In its operation cycle, a float stays most of the time at a parking depth of about 1000 m. At a specified period of time, it dives to a depth of about 2000 m, to subsequently rise toward the surface while taking measurements (about 70) of temperature, conductivity and pressure, from which salinity is calculated.

The most used types of buoy have been PROVOR (built by NKE-INSTRUMENTATION), APEX (by Teledyne Webb Research), and SOLO (by Scripps Institution of Oceanography). Recently, two new float types are also being deployed: ARVOR (a new generation of the PROVOR) and SOLO-II (a new SOLO generation by MRV systems). The temperature/salinity sensor suites are SBE, and FSI. In 2004, after recalibration of three Argo floats, it was found that the temperature and conductivity sensors had little drift after being deployed four to nine months, and that their accuracies remained inside the Argo project requirements (0.005°C for temperature and 0.01 for salinity).

In order to validate remote sensing SSS it is customary to consider salinity data in the top 10 meters. It is assumed that, in general, the surface mixed layer extends beyond that depth, and that the buoy measures would be an accurate estimation of the 1 cm layer below the surface. However, Argo data too close to the surface (less than 0.5 m) are usually discarded because the presence of air bubbles may cause erroneous pressure measurements. On the other hand, for SOLO and PROVOR profilers, no salinity data shallower than 5 m should be used as these models stop pumping water at that depth to reduce the risk of fouling the conductivity sensor cell. In the works described below, some authors consider data between 3 and 5 m deep. Other authors use data between 0.5 and 10 m. Another option is to interpolate the value of the vertical profile at a given fixed depth, as for example 7.5 m (i.e. the center of the layer between 5 and 10 m). An advantage of the interpolation approach is that it allows an additional automatic quality control based on the comparison between different methods (linear, splines, etc.). If the difference between the various interpolation methods is not negligible (due to non-resolved vertical gradients, presence of outliers, etc.), the profile is rejected. In any case, there is a mismatch between the layer seen by the satellite (1-2 cm) and the one seen by Argo (about 10 m).

2.2. Method of comparison

Until now, both SMOS and Aquarius teams rely in the direct comparison between the satellite estimates and the in situ estimate derived from the upper part of the Argo profile. The difference between both estimates is often regarded as a salinity error. The central measure of these differences (average or median) is considered as an indicator of the presence of biases in the satellite processing chain. The accuracy of the satellite products is estimated through the calculation of dispersion (standard deviation or interquartile range, IQR).
The mission goal for the SMOS mission accuracy was set to be 0.1 for 100-200 km and 10-30 days. The mission goal for Aquarius accuracy was set to 0.2 for 150 km and 30 days.

3. Validation of SMOS salinity products

To avoid using a large antenna, an aperture synthesis radiometer would use a large number of small antennas. In the case of SMOS, the MIRAS instrument is formed by 69, 20-cm diameter antennas, deployed in three 4 m arms forming a Y shape. The raw measurements are the complex cross-correlations between the signals collected by all pairs of antennas. These correlations (together with the average brightness temperature measured at low spatial resolution by three dedicated radiometers) are equal to the two-dimensional Fourier transform of the brightness temperature image. Through an inverse Fourier transform, a full snapshot of the brightness temperature scene is obtained every 1.2 seconds [AD-3].

![Figure 3. Schematic of the brightness temperature image reconstructed along a single satellite overpass and the exagonal antenna pattern (left).Level 2 salinity retrieval over an ascending orbit over the Pacific Ocean (right) [AD-3].](image)

Various assessments of the brightness temperature measured by MIRAS indicate that the instrument is performing accordingly to the specific requirements [AD-3]: Measured radiometric sensitivity over oceans agrees with theory, thermal noise is negligible after calibration, and the instrument appears to be stable over the length of the mission. However, corrections applied to the radiometer calibrations and some aspects of the image reconstruction algorithm still require further refinement to achieve the expected mission accuracy.
3.1. Level 2 image validation

In [AD-4] the SMOS Level 2 salinity data are validated using a combination of in-situ sources combining Argo, thermosalinographs, moorings and CTD data. From July to December 2010, the ensemble of in situ valid SSS measurements in the first 10 meters of the world ocean is about 300 observations per day when spatially-averaging the data over 0.25 degree bins (Figure 4).

![Figure 4. Spatial distribution of the ensemble of in situ qualified SSS data collected between July and December 2010 used for SMOS validation [AD-4].](image)

The in situ SSS data are co-localized with SMOS Level 2 data using proximity criteria: the distance between satellite and in situ data should be less than ±25 km and less than ±12 hours.

<table>
<thead>
<tr>
<th></th>
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<th>Global</th>
<th>Tropics</th>
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<td></td>
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<tr>
<td></td>
<td>Ascending</td>
<td>0.81</td>
<td>0.64</td>
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<tr>
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<td>Descending</td>
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<td>-0.19</td>
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<tr>
<td></td>
<td>Combined</td>
<td>0.52</td>
<td>0.27</td>
</tr>
<tr>
<td>STD</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Ascending</td>
<td>1.10</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>Descending</td>
<td>1.40</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>1.32</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*Table 1. SMOS Level 2 SSS - in situ. 95% percentile error statistics. Tropical region (lat<27.5°) [AD-4].*
Thus, global Level 2 data have been found to be too salty for both ascending and descending passes. In the tropics, descending passes are too fresh compared with the in situ data. Satellite retrievals are too salty in regions of fresh waters (SSS < 33). The standard deviation of the error is systematically lower for ascending orbits than for the descending ones.

In [AD-5], the comparison between SMOS and Argo is done for the period July 29 and September 5, 2010. When processing the Argo profiles, the closest value to the sea surface between 0.5 m and 10 m depth is used as the corresponding SSS. No measurements are considered if depth is lower than 0.5 m. For SOLO and PROVOR profilers types, data are considered only between 5 m and 10 m. Measurements must have flags of position, date, depth, temperature and salinity equal to 1 (good) or 0 (not checked because of real time transmission). The SMOS SSS is co-located with ARGO SSS using a distance of ±50 km and ±5 days. Only ascending orbits are used.

<table>
<thead>
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<tbody>
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<td>All</td>
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<td>All</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>3.2. Level 3 and Level 4 salinity maps validation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In [AD-6] various 0.25 degree, Level 3 and a Level 4 SSS products, created from the Level 2 ESA 2012 and 2013 Reprocessing campaigns are validated against Argo.

Surface salinity values are being estimated from Argo data by interpolating the salinity profiles at 7.5 m below the surface. To avoid extrapolation, only profiles with a valid value at least at 5.5 m depth are considered. Every ten days around 3200 profiles become available. Profilers included in the Global Argo Data Centers (GDAC) Grey list are not used here. About 700 profilers are also filtered out because no observation as shallow as 5.5 m depth is available. In the case of SOLO and PROVOR profilers only the data below 5 m are used as in [AD-5]. Finally, no data are used if the associated quality flag indicates bad or interpolated value. The whole profile is used in the
interpolation, with the exception of any observation above 0.5 m depth. Interpolation artefacts are reduced by using three different interpolation methods: Akima splines, cubic splines, and third-order polynomial fitting. The final interpolated value is obtained from the average of the three methods. Profiles are rejected if any of the three interpolation schemes differs more than 5% from the average. Every 10 days, about 15 profiles are filtered out due to this rejection criterion. Argo box-averaged products at 0.25 degrees for three-, nine- and 30- day are used for the validation of Level 3 SMOS salinity maps.

Table 3 shows the central and dispersion measures for year 2010. Similar results are obtained for years 2011 and 2012 [AD-6]. These results indicate that although higher data processing is able to strongly reduce the standard deviation of the salinity product, it has little effect on biases (the bias slightly increases in various cases when higher processing level is used). As in [AD-5], ascending semi-orbits agree better with Argo than the descending ones.

4. Validation of Aquarius salinity products

4.1. Level 2 swath validation

In the context of the Aquarius project, the SSS products being generated are: Level 2 (salinity data in a swath coordinates) and Level 3 (gridded 1-degree daily, weekly and monthly salinity). For validation, in [AD-7] the shallowest value (in the 3-5 m below the surface) of an Argo data is considered as representative of the SSS.
Figure 5. Schematic of the Aquarius observation scheme. The sun is located on the left-hand-side of the satellite. That is, the satellite looks away from the sun to mitigate L-band solar flux from contaminating the observations.

The match-up between the Level 2 data with the Argo SSS estimate is done as follows. The Aquarius Level 2 swath data (see Figure 5) are compared with any buoy located inside a radius of 75 km and ±4.5 days. The Aquarius data are averaged over 11 samples (approx 100 km).

Figure 6 displays the pairs of in-situ versus Aquarius V2.0 SSS. The version 2.0 of the Science Data Processing SSS product does represent a major advancement over previous science data processing versions. In Figure 6, color represents the density of points. The distribution of points clearly approximates a right line. Most of the outliers are evident at low salinities, and they are
mostly located at high latitudes (i.e. cold water), where the sensitivity of the brightness temperature by respect salinity is low (See Figure 1).

Table 4 shows the median and the standard deviation of the Aquarius minus the in-situ estimates of SSS. These statistics are calculated by removing the cases in which SST < 5ºC, wind speed > 15 m/s, and the land or ice fraction > 0.0005.

<table>
<thead>
<tr>
<th></th>
<th>Beam 1</th>
<th>Beam 2</th>
<th>Beam 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>0.01</td>
<td>-0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>STD</td>
<td>0.50</td>
<td>0.50</td>
<td>0.49</td>
</tr>
</tbody>
</table>

*Table 4. Aquarius minus Argo SSS statistics as a function of the beam [AD-AA].*

In Aquarius, the surface emission for the forward model is derived from ancillary SST and SSS information. The SST ancillary data come from NOAA NCEP. The SSS ancillary data come from the US Navy Hybrid Coordinate Ocean Model (HYCOM) daily averaged data-assimilation analysis, and distributed by Florida State University. That is, HYCOM salinity is used as a global surface calibration target for the sensor.

The use of Argo data goes beyond the validation of the final SSS product. Another application of the Argo data is to validate the ancillary HYCOM SSS. In Figure 7, HYCOM data are evaluated against Argo measurements with the same matchup processing as the Aquarius Level 2 data. The Aquarius team has processed separately the ascending (northward) and descending (southward) halves of the orbit, and found that the reference salinity displays no significant difference between simulated ascending and descending passes. However, it is shown that there are regional long-term biases between HYCOM and Argo. The numerical simulation is significantly saltier than Argo buoys in the Circumpolar Current, tropics, and North Pacific. The model is slightly fresher than buoys at mid latitudes. The median of the global difference is 0.00.

This result is of interest because it shows, with the help of Argo data, that the methodology used to calibrate Level 2 Aquarius SSS does not introduce a spurious global bias, although it may introduce regional biases from the HYCOM salinity.
Finally, Argo data can also be used to verify the improvements obtained by the new versions of the science data processing. The daily median of the global differences between Aquarius and Argo is shown in Figure 8. The version V2.0 (on the right) is shown next to the previous version V1.3 (on the left). The new radiometer calibration removes the wiggles present in the previous processing. Although the wiggles have disappeared, the daily median of the differences show the persistence of low-frequency drifts, currently explained as the effect of errors in the geophysical corrections in the forward geophysical function.

Figure 7. Co-located salinity differences between HYCOM and buoys for ascending (top) and descending (bottom) passes [AD-7].

Figure 8. Daily global median Aquarius-Argo difference time series, V1.3 (left), and V2.0 (right) [AD-7].
4.2. Level 3 monthly salinity maps validation

The Level 3 1x1 degree salinity maps are generated from Level 2 salinity data without any adjustment for climatology, reference model output, or in situ data. An smoothing interpolation is applied by using a bi-linear fit within a specified (approx. 150 km) influence radius. The algorithm excludes data where land or ice fractions exceed 0.0005. The buoy matchups are compiled for each 1-degree bin, with an average of the buoys within 150 km radius, and using only buoys for which their measured SST > 5°C.

![Figure 9. Aquarius V2.0 monthly difference maps [AD-7]](image)

The monthly standard deviation of the monthly differences between Aquarius and Argo ranges from 0.30 to 0.35. The maps of differences show a distinct pattern between the first five months
and the next five months, which could indicate a seasonal source of error in the processing chain. The seasonal component is clear in the southern hemisphere, while a systematic fresh bias appears in the tropics.

<table>
<thead>
<tr>
<th></th>
<th>Sep 2011</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan 2012</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
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<td>0.07</td>
<td>0.07</td>
<td>0.05</td>
<td>0.06</td>
<td>0.02</td>
<td>-0.10</td>
<td>-0.13</td>
<td>-0.11</td>
<td>-0.07</td>
</tr>
<tr>
<td>STD</td>
<td>0.30</td>
<td>0.33</td>
<td>0.35</td>
<td>0.35</td>
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<td>0.37</td>
<td>0.33</td>
<td>0.31</td>
<td>0.31</td>
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</tr>
</tbody>
</table>

*Table 5. Aquarius V2.0 monthly differences by respect Argo. Matchup made for land and ice fraction < 0.0005 and buoy SST>5ºC, Influence radius 150 km. [AD-7]*

5. Summary and plan for E-AIMS

5.1. Summary

There is no doubt that the Argo array is the only component of the global climate observing system able to provide enough information to validate the various salinity products and its quality is good enough to help assess improvements in the processing chain.

However, three is a mismatch between the layer observed by the satellite (1-2 cm) and the vertical samples of the buoys (up to 10 m). On the other hand, the various validation teams use different approaches to obtain an SSS estimate from each Argo profile. However, it seems that most of the results are compatible and the standard deviation of the error of the two satellites is of the same order (i.e. of about 0.3).

The need of Argo data in the validation of remotely sensed SSS will continue as there still are sources of error in the data processing chains of SMOS and Aquarius pointed out by the different error structure between ascending and descending orbits, and the presence of seasonal modulation of the differences between satellite and in situ estimates of SSS. These errors may arise due to imperfect knowledge of the required corrections and/or imperfect reconstruction algorithms.

5.2. Plan for E-AIMS

The difficulty in the validation of the salinity products retrieved from satellite is double: In one hand, salinity is the most recent oceanographic variable being observed from space and it is the first to rely on the observation of the earth surface in the domain of the L-band microwaves. Thus, there is a significant amount of unknowns about the ambient corrections required for these frequencies. On the other hand, there is a mismatch between the representativeness of the satellite measure (1-2 cm) and the impossibility, at this moment, to monitor the conductivity of the ocean at these depths due to the current fouling of the conductivity sensor cells.

The studies proposed during this project are:
⇒ Use multi-scale techniques for data fusion and interpolation to help assess the representativeness of the Argo estimates of SSS from data from Argo and auxiliary, high-resolution observations of temperature and salinity near the surface as the ones provided by CTDs, surface drifters, moorings, etc. (CSIC).

⇒ Increase the reliability of the salinity product validation by taking into account the intensity of local wind, ambient sea surface temperature, viewing geometry (CATDS).

⇒ Develop a new generation of Level 4 SSS products by merging SMOS data with Argo (CSIC, CATDS).

⇒ Provide a set of recommendations for the evolution of Argo (CSIC, CATDS).