An assessment of SMOS version 6.20 products through Triple and Quadruple Collocation techniques considering ASCAT, ERA/Interim LAND, ISMN and SMAP soil moisture data

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***Abstract*— In this work, two remotely sensed soil moisture data sets, derived by the Advaced SCATterometer (ASCAT) and the Soil Moisture Ocean Salinity (SMOS), have been compared with the soil moisture provided by the ERA/Interim Land data sets and measured by the in situ probes belonging to the International Soil Moisture Network (ISMN). The Triple Collocation (*TC*) represents a very useful tool for validating remotely sensed products; in this work, since four sources have been considered, a Quadruple Collocation (*QC*) approach has been also applied in order to jointly estimate the error standard deviation of the four sources making reference to a common scale as for its magnitude. Both Europe and North Africa were considered during a period starting from June, 2010 to May, 2014. Moreover, the preliminary results of a TC analysis between SMOS, ASCAT and SMAP (Soil Moisture Active/Passive) soil moisture products are shown for the same region of interest considering a period between April and December, 2015 .**

Keywords—soil moisture, triple/quadruple collocation, SMOS, SMAP

I. INTRODUCTION

The role of soil moisture as a key variable for the characterization of the global climate is widely recognized within the international scientific community. Its knowledge is essential for several applications, such as drought and flood predictions, meteorology, agronomy and climatology. Volumetric soil moisture content (*SMC*) data can be directly measured by in situ probes, but soil moisture ground stations are generally very sparse, so that the spatial variation cannot be retrieved. Satellite remote sensing represents a very useful tool to monitor soil moisture at different spatial and temporal scales, presenting a direct sensitivity to *SMC* at microwave bands. In this spectral range, soil moisture directly influences the soil dielectric permittivity and the atmosphere can be considered fairly transparent. Different algorithms exploiting electromagnetic models, such as change detection [1] or multitemporal approaches [2], are available in the literature. Microwave radiometers (passive sensors) and scatterometers (active sensors) can be used to monitor the surface emission and the radar backscattering, respectively. These quantities are sensitive to common parameters that include not only the soil permittivity, but also vegetation conditions and roughness, so that the soil moisture retrieval problem can be highly ill-posed [3]. Consequently, it is important to perform a validation of remotely sensed soil moisture products as well as an intercomparison between different products.

The satellite soil moisture data are derived from the ASCAT-Metop scatterometer (available through the Eumetsat H-SAF project), from the SMOS radiometer (available through an ESA Category 1 project) and from the SMAP radiometer (available through the NASA National and Ice Data Center Distributed Active Archive Center, NSIDC DAAC). The analysis covered both Northern Africa and the Europe territories from June 2010, until May, 2014; when SMAP data was considered, the period started from April, 2015 to December, 2015. The satellite retrievals were compared with independent dataset. The Triple Collocation (TC) [4] technique is a powerful statistical tool able to estimate the relative error variance of three independent data sets, whose errors are assumed statistically independent. As third dataset, the ERA Interim/Land modelled soil moisture, produced by the European Centre of Medium Range Weather Forecasts (ECMWF) has been chosen. Moreover, a Quadruple Collocation (QC) [5] has been also applied considering the ground measurements provided by the International Soil moisture Network (ISMN), as fourth dataset.

II. DATASETS AND METHODOLOGY

The MIRAS-SMOS interferometric radiometer measures the antenna brightness temperature [6] at 1.427 GHz (L-band) at different angles from a 758 km height orbit, with a repetition time of 3 days and a spatial resolution of 35 km. The reprocessed Level 2 (L2) products, obtained from the version 620 of the processor, provide the volumetric soil moisture content (*SMC*) in m^3/m^3, sampled over the ISEA4h9 grid, which has a spatial sampling around 15 km. As for ASCAT, the large scale surface soil moisture products (SM-OBS-1), available through the H-SAF project over Europe and North Africa, are produced from the C-band vertically polarized ASCAT scatterometer data by means of the TU-Wien algorithm [7]. Measurements are taken from a 817 km height orbit on both sides of the sub-satellite track over two 550 km wide swaths, resulting in a global coverage achieved in about 1.5 days over Europe. Each pixel represents a relative value (between 0% and 100%) of moisture with respect to the driest and the wettest conditions, that is the degree of saturation *SD* (i.e., the soil moisture content expressed in percent of porosity). Moreover, the soil moisture retrievals provided by the SMAP[8] radiometer were also used for a preliminary TC analysis with the other satellite products. The SMAP satellite orbit is a sun-syncronous orbit with an altitude of 685 km, providing an exact orbit repeat in eight days, while a global coverage is provided in two/three days. In this work, the SMAP passive L2 soil moisture products [9] were used, providing soil moisture retrievals during morning passages (half orbit product) with a resolution of 36 km.

The satellite data were compared to the ERA-Interim/Land modelled soil moisture and to in situ data available from the International Soil Moisture Network (ISMN). ERA-Interim Land, produced by the European Centre of Medium Range Weather Forecasts (ECMWF), is a global atmospheric reanalysis combined with an ocean and a land surface model available until 2014. Soil moisture is provided at four different time steps (at 00:00, 06:00, 12:00, 18:00) each day over a grid with a spatial resolution around 80 km [10]. ISMN is an international cooperation coordinated by the Global Energy and Water Exchanges Project (GEWEX), in cooperation with the Group of Earth Observation (GEO) and the Committee on Earth Observation Satellites (CEOS), with the task of maintaining a global in-situ soil moisture database [11]. In this study, all available data collected at a 0-5 cm depth from several European networks (Denmark, England, Finland, France, Germany, Italy, Poland and Spain) were used.

For each SMOS grid point, the closest ASCAT/H-SAF and SMAP grid points were searched for and the same nearest neighbor approach was adopted to collocate the model data. As for the ISMN, the measurements were up-scaled to the satellite resolution, i.e. the in-situ measurements within the satellite field of view was averaged. After the data colocation in space and time, the data points were filtered using the processing flag in the SMOS and ASCAT products. The collocated data with the following characteristics were disregarded: SMOS Data Quality Index (DQX) greater than 0.045; ASCAT values with more than 3 bad quality flags up.

Subsequently, the triple [4] and quadruple [5] collocation were used to estimate the error standard deviations of three and four systems, measuring the same target (in our case, soil moisture). Then, supposing three or four measurements, the following error model (1) was considered, where *SMC* represents the volumetric soil moisture content, *s* the gain of the system respect to the reference system, *b* the bias and *d* the error system variance:

$$
\begin{aligned}
x &= s_x\,(SMC + b_x + d_x)\\
y &= s_y\,(SMC + b_y + d_y)\\
z &= s_z\,(SMC + b_z + d_z)\\
w &= s_w\,(SMC + b_w + d_w) \qquad (1)
\end{aligned}
$$

The errors were considered statistical independent and independent on the true random variable *SMC*. Considering the satellite data, the TC was applied to each grid point as done in the literature [12]; for this kind of analysis, the ASCAT saturation degree can be considered, since only the correlation coefficients in each grid point have to be considered to produce the TC results. When the in situ probes were considered, a global QC [5] was performed, assuming a unique gain and bias of each system, which requires a comparison of the measurements in same units. For such purpose, the ASCAT SD retrievals were converted into volumetric moisture [m^3/m^3] using a soil porosity map available from the Global Land Data Assimilation System (GLDAS) website. For the global QC analysis, the seasonal variability of the soil moisture was considered as a temporal drift and removed, and assumed as part of the random variability and retained in the QC analysis.

III. ANALYSIS OF RESULTS

A. *SMOS, ASCAT, ERA-Interim LAND and ISMN*

After the collocation of the satellite and model data set in time and space (over the ISEA4h9 grid), the TC analysis was applied pointwise, i.e. independently for each grid point of the collocated maps; the analysis covered a period of four years, starting from June, 2010 to May, 2014.

Fig.1 reports the trend of the temporal correlation, which was evaluated in each point of the ISEA4h9 grid. Since the correlation coefficient is independent on a linear transformation, the ASCAT data were considered without any scaling.

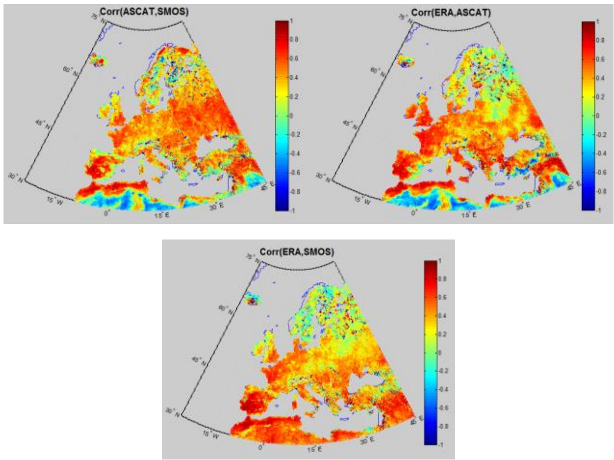


Fig. 1. Temporal correlation coefficients for each grid point between SMOS and ASCAT (upper-left), ASCAT and ERA-Interim/Land (upper-right) and SMOS and ERA-Interim/Land (lower-middle).

In general, the temporal correlation between ASCAT and the model is large in most of Central Europe with some exceptions. For example, ASCAT showed a negative temporal correlation respect to SMOS and ERA-Interim/Land data over desert areas. However, the differences into the behavior between SMOS and ASCAT over such kind of areas is already known in literature and it could be addressed to their different operating principle.

In the TC analysis, the ERA-Interim Land was chosen as reference, as done in [13]; then, referring to the error model reported in eq. (1), system x represents the model data with $s_x=1$ and $b_x=0$, while y and z stays for ASCAT and SMOS data, respectively. Fig. 2 shows the areas where each system performs worse (upper panel) and better (lower panel) than the others, through a RGB level slicing derived by the TC results.

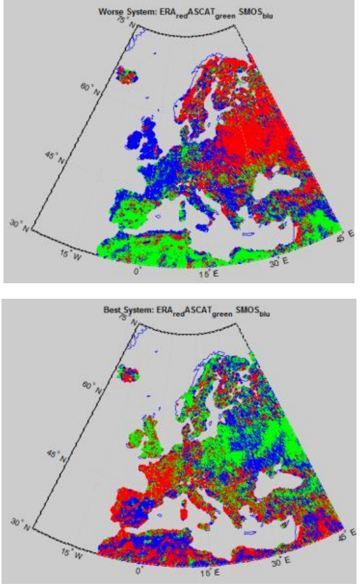


Fig. 2. RGB level slicing showing what system performs worse (upper map) and and better (lower map) than the others. Red: ERA-Inteirm/Land; green: ASCAT; blue: SMOS.

Generally, ERA-Interim Land was the system with best behavior over the most of considered areas, except for the Easternmost areas. SMOS presented the best behavior in the Mediterranean coast of Spain, but giving the worst performances in most of Central Europe. As for ASCAT, a least error was observed in Southernmost areas, with worse performances over the desert. However, the behavior over the desert areas is related to the negative correlation observed comparing ASCAT with the others two datasets.

Subsequently, the global QC analysis was applied to the model and satellite datasets, considering as a reference the ISMN in situ probes; Table I reports the QC results, which are expressed in percentage unit. The left column reports the results achieved by looking the temporal anomalies (i.e., estimating and removing the seasonal variability), while the right column represents the results obtained by retaining the seasonal variability into the data. The good performances of ERA-Interim/Land were confirmed, showing an error standard deviation of about 3%, considering either the entire dynamic range of the parameter or the anomaly. The in-situ data, which were up-scaled to the satellite resolution, were characterized by not very good performances, but such result is not really unexpected, since the capability of a pointwise measurements to represent the average soil moisture within an area equal to the field of view of the satellite was actually analyzed.

TABLE I. RESULTS OF THE QC APPLIED TO SATELLITE, MODEL AND IN-SITU DATA. LEFT COLUMN REFERS TO THE TEMPORAL ANOMALIES, WHILE THE RIGHT COLUMN TO THE DATA INCLUDING THE SEASONAL VARIABILITY

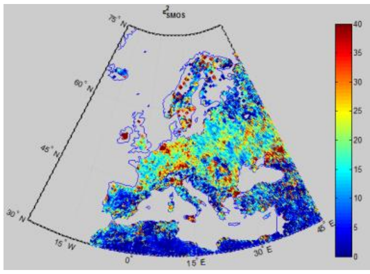
[%]	**ISMN ERA-Interim/Land ASCAT SMOS**	
	anomaly	***retaining season variability***
σ	4.78	5.07
s_{ASCAT}	2.17	1.74
s_{SMOS}	0.94	0.99
s_{ERA}	1.19	1.20
ε_{ISMN}	4.96	4.03
ε_{ASCAT}	4.07	5.98
ε_{SMOS}	5.82	5.32
ε_{ERA}	3.23	2.95

As for the satellite results, removing only the spatial pattern, SMOS outperformed ASCAT, whereas the opposite was observed when the temporal anomalies were considered. A possible explanation is that the SMOS retrieval algorithm is based on a forward model of surface emissivity, which reveals itself more suitable to account for other environmental variables involved in the seasonal cycle and then, to sense the whole dynamic range of moisture. On the other side, the ASCAT/H-SAF retrieval algorithm is based on a change detection approach, which relates directly the variations in radar backscatter to soil moisture changes, whatever the temporal scale is.

B. SMOS, ASCAT, SMAP

Subsequently, the TC analysis was performed considering the SMOS, ASCAT and SMAP data over the H-SAF region for a period starting from April, 2015 to December, 2015. Fig.3 reports the error variance of each system, where SMOS was chosen as a reference, i.e. the error variance are expressed in the scale of SMOS.

Generally, SMAP was the system with the best performances over the analysed area, while SMOS and ASCAT presented error variance pattern similar to the trend noticed in the TC comparison using ERA/Interim Land as third system.



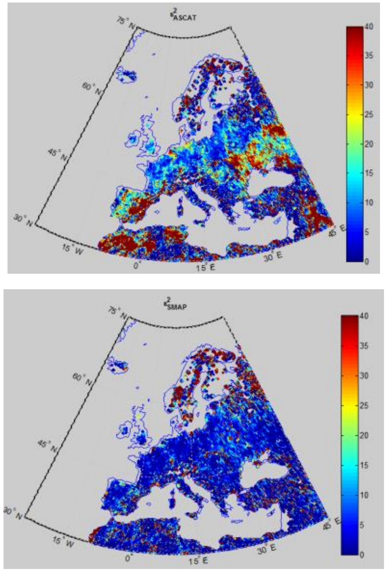


Fig. 3. Error variances derived from the pointwise TC analysis: SMOS (upper panel), ASCAT (middle panel) and SMAP (lower panel). The error variances are expressed in the scale of the system reference, i.e. SMOS.

However, it is worth to mention that such results were derived from a preliminary TC analysis, without taking into account several factors, like a possible error correlation between the SMOS and SMAP products. Such effects will be analysed and considered in the future comparison.

IV. CONCLUSIONS

In this work, the soil moisture products derived by satellite (SMOS, SMAP, ASCAT) model (ERA/Interim Land) and in situ measurements (ISMN) were compared through the *TC* and *QC* approaches. The analysis was carried out over both Europe and Northern Africa. Since the period availability, a first analysis was accomplished between SMOS, ASCAT, ERA/Interim Land and ISMN. In general, ERA/Interim Land was the system with the best performances, while the error behavior of the in-situ stations may suffer from the difficulty to represent the soil moisture within the satellite field of view. As for the satellite products, SMOS outperformed ASCAT when the data including the seasonal variability were considered, while the opposite was observed looking at the temporal anomalies. As a second step, the TC was applied to the SMOS, SMAP and ASCAT products. In this case, the SMOS and ASCAT spatial error variances showed pattern similar to the trends noticed in the TC analysis with the model data; generally, SMAP was the system with best performances. However, because of several issues, such as the presence of Radio Frequency Interference (RFI), strong orography and desert, in future work analysis filtering of the data will be strengthened considering also other flags, like the chi-square information provided by SMOS. Moreover, possible error correlation between SMOS and SMAP, such same measurement principle and band, should be taken into consideration in the TC analysis.

ACKNOWLEDGMENT

Authors acknowledge the EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management “(H-SAF)” and the Technology (TU Wien) Department of Geodesy and Geoinformation for providing the ASCAT soil moisture products.

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