CAPÍTULO 3:

Validation of Aquarius soil moisture products over the northwest of Spain: a comparison with SMOS

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ABSTRACT

A validation of the new L2 and L3 soil moisture products from the Aquarius/SAC-D mission from August 2011 to June 2014 using two *in situ* networks in Spain was conducted. The first network, the Soil Moisture Measurement Stations Network of the University of Salamanca (REMEDHUS), is considered to be a dense network. The second network (Inforiego) could be considered a sparse or large-scale network. Comparisons of temporal series using different strategies were made. Similar analysis was performed for the same area and period with two Soil Moisture Ocean Salinity (SMOS) soil moisture products: SMOS L2 and SMOS Barcelona Expert Centre (BEC) L3. The aim of the study was to analyze the performance of the Aquarius soil moisture products and to compare with that of SMOS soil moisture.

Results from the area-averaged comparison show that Aquarius products have correlation coefficients (R) between 0.33 and 0.65, and root mean square difference (RMSD) and centered root mean square difference (cRMSD) between 0.046 and 0.111 m^3m^{-3}. A better match was found for the L2 ascending series than for the L2 descending and L3 series. A dry bias was found. SMOS products showed better accuracy (R>0.8, RMSD and cRMSD~0.06 m^3m^{-3}) than those of Aquarius. The comparison made at point-scale reflected that the size and density of the networks do not influence the validation results at the Aquarius resolution, but it is remarkable at the SMOS resolution. Despite the scale restrictions, the results of this study showed that Aquarius soil moisture products have reasonably good performance.

Keywords: Aquarius; SMOS; soil moisture; validation.

RESUMEN

Se presenta una validación de los nuevos productos de humedad del suelo L2 y L3 de la misión Aquarius/SAC-D para el periodo de estudio comprendido entre agosto de 2011 a junio de 2014, utilizando para ello dos redes de estaciones *in situ* de medición de humedad del suelo en España. La primera red, la Red de Estaciones de Medición de Humedad del Suelo de la Universidad de Salamanca (REMEDHUS), se considera una red densa y de escala local. La segunda (Inforiego) podría considerarse una red dispersa o de gran escala. Las comparaciones entre las series temporales se realizaron aplicando diferentes estrategias. Asimismo, se llevaron a cabo análisis similares para el mismo área y período con dos productos de humedad del suelo del satélite *Soil Moisture Ocean Salinity* (SMOS): SMOS L2 y SMOS *Barcelona Expert Center* (BEC) L3. El objetivo de este estudio fue analizar la fiabilidad de los productos de humedad del suelo de Aquarius y compararlos con los de SMOS.

Los resultados de la comparación a nivel de red muestran que los productos de Aquarius tienen coeficientes de correlación de Pearson (R) entre 0.33 y 0.65, y errores (RMSD y cRMSD) entre 0.046 y 0.111 m^3m^{-3}. Se encontró una mejor coincidencia para las series temporales de las órbitas ascendentes L2 que para las descendentes y las series del producto L3. También se observó la existencia de una cierta subestimación. Los productos SMOS mostraron una mejor precisión (R> 0.8, RMSD y cRMSD ~ 0.06 m^3m^{-3}) que los de Aquarius. La comparación realizada a escala puntual reflejó que el tamaño y la densidad de las redes no influyen en los resultados de validación para la resolución de Aquarius, pero sí para la resolución de SMOS. Aun así, los resultados de este estudio mostraron que los productos de humedad del suelo de éste tienen un comportamiento razonablemente bueno.

Palabras clave: Aquarius; SMOS; Humedad del suelo; Validación

3.1. Introduction

Soil moisture is essential in most hydrologic and atmospheric processes, and it is very useful in agricultural, water resources and hydrological hazard management. Remotely sensed soil moisture monitoring has been investigated in recent decades (Ulaby *et al.*, 1983; Schmugge *et al.*, 1986). Since the 1970s, soil moisture was estimated from satellite instruments that were not specifically designed for sensing soil moisture, e.g., the European Remote Sensing (ERS) satellites designed to measure ocean surface temperature, wind fields and atmospheric ozone; the Advanced Microwave Scanning Radiometer-EOS (AMSR-E), which was designed to observe precipitation, sea surface temperature, atmospheric cloud water or water vapor; and the Advanced Scatterometer (ASCAT), designed to measure wind speed and direction over the oceans. The first satellite designed to make specific observations of soil moisture was the SMOS mission, which was launched by the European Space Agency (ESA) in November 2009. Another mission, the Soil Moisture Active Passive (SMAP), was launched in January 2015 by the National Aeronautics and Space Administration (NASA) to retrieve soil moisture and freeze/thaw state using an L-band radiometer and a synthetic aperture radar (Entekhabi *et al.*, 2010). However, satellites such as Aquarius, designed a priori to estimate other surface variables, are potentially useful for retrieving soil moisture.

Aquarius is an L-band radiometer and scatterometer instrument combination with the objective of mapping the ocean's surface salinity field (Le Vine *et al.*, 2007), but the National Snow & Ice Data Center (NSIDC) recently released the Aquarius L2 and L3 soil moisture products. Using the single channel algorithm (SCA) (Jackson, 1993) with L-band radiometer measurements, the Aquarius soil moisture retrieval algorithm is the same used by SMOS (Bindlish *et al.*, 2015). Aquarius was operative from the end of August 2011 to June 2015.

The advantage of remotely sensed soil moisture with respect to other soil moisture estimates is the coverage of large areas and the identification of large-scale events. The disadvantage is the aggregation of heterogeneities from local to regional scales, which renders validation difficult (Ochsner *et al.*, 2013). Large differences exist between point-scale measurements and remote sensing estimates. The establishment of credible ground validation approaches for soil moisture requires bridging the gap between the two resolutions (Crow *et al.*, 2012). Following the classification of Crow *et al.*, (2012), two types of *in situ* networks can be described: small scale networks (between 100 and 10000 km^2), which have the advantage of higher spatial densities that provide multiple measurements within a single footprint, and large-scale networks (>10000 km^2), which have the advantage of covering large areas and a larger range of land cover and soil types but typically lack in sampling densities that provide multiple measurements per footprint.

3.2. Data sets and Methods

3.2.1. *In situ* networks

Two networks located in the Duero basin (Spain) were used to validate the satellite soil moisture products (Fig. 3.1): REMEDHUS and the Inforiego networks.

REMEDHUS is located in the central part of the basin over an area of 1300 km^2. The climate is continental semi-arid Mediterranean, with a mean temperature of 12°C and an annual precipitation average of 385 mm (González-Zamora *et al.*, 2015). The main land use is agriculture, of which the main crops are cereals. REMEDHUS has been used in previous soil moisture validation works of remote sensing products (Wagner *et al.*, 2007b; Brocca *et al.*, 2011a; Sánchez *et al.*, 2012a; Sánchez *et al.*, 2012b) and is a member of the International Soil Moisture Network (ISMN) (Dorigo *et al.*, 2011). This network was selected as one of the SMAP cal/val core validation sites (Colliander *et al.*, 2015).

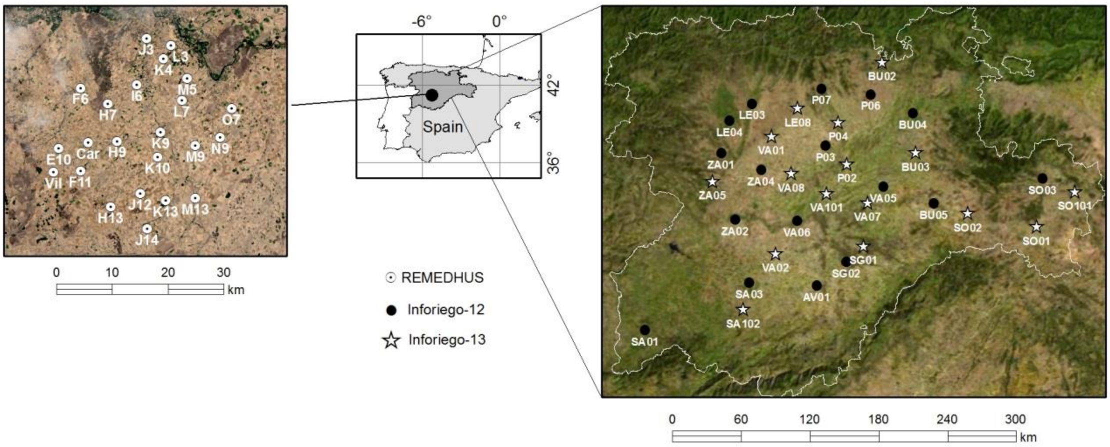

Figure 3.1. Location of the two networks used in the research.

Inforiego (Agriculture Technological Institute of Castilla y León, Spain) is spread over a topographically homogenous and fairly flat area of 65000 km^2, where climatic conditions are quite homogeneous in terms of temperature and precipitation distribution (Ceballos *et al.*, 2004; Ceballos *et al.*, 2013). The climate of the region is continental semi-arid Mediterranean, with a mean annual temperature of 11.7°C and an average annual precipitation of 525 mm, and the main land uses in the area are also agriculture (rainfed crops in winter and spring and irrigated crops in summer). The soil moisture network was installed within a meteorological network owned by the Government of the Castilla y León region.

Both networks are equipped with *Hydra probes*, which measure hourly surface (0-5 cm) soil moisture (*Stevens Water Monitoring Systems, Inc*.) at 23 stations in REMEDHUS and 33 stations in Inforiego (17 stations were measuring between July 2012 and July 2013, called Inforiego-2012, and 16 were measuring between August 2013 and August 2014, called Inforiego-2013). For the validation experiment, a daily-average of each station was made, with a total of 1041 observations in REMEDHUS, 363 in Inforiego-2012 and 334 in Inforiego-2013. This choice is based on previous validation experiments, where no differences were reported between the use of time-overpass values of *in situ* soil moisture or the use of daily averages for the comparison (Sánchez *et al.*, 2012a; Piles *et al.*, 2014; González-Zamora *et al.*, 2015).

3.2.2. Satellite products

Soil moisture products from Aquarius and SMOS were used. The first datasets of satellite soil moisture came from the international Aquarius/SAC-D mission (NASA and Argentina's Space Agency) (Lagerloef *et al.*, 2008). Aquarius is a sun synchronous satellite that uses an L-band radiometer to acquire measurements in three different spatial resolution beams: 76x94 km with an incidence angle of 29.36° (inner), 84x120 km with 38.49° (middle) and 96x156 km with 46.29° (outer). These beams provide coverage of a swath of approximately 390 km. The orbit is a 7-day exact repeat orbit, and, in contrast with SMOS, the orbit times are 6 PM for ascending orbits and 6 AM for descending orbits.

The Aquarius L2 Swath Single Orbit Soil Moisture (AQ2_SM) (Bindlish and Jackson, 2014a) and the Aquarius L3 Gridded 1-Degree Daily Soil Moisture (AQ3_DYSM) version 3 (Bindlish and Jackson, 2014b) products were validated in this work. For this research, the L2 single orbit was separated in ascending and descending orbits for a better comparison, whereas the L3 product is a daily composite. Both products are provided in HDF5 format. Aquarius Level-3 SM products are generated from physical measurements computed from the Aquarius Level-2 products. The gridded Level-3 processing of Aquarius satellite data takes measurements at the boresight locations of the three radiometer beams, which have already been converted into physical units of soil moisture, and maps these onto a 1° grid (Li *et al.*, 2015).

The other satellite dataset used came from SMOS. This satellite uses an L-Band Y-shaped two-dimensional interferometric radiometer, with multi-angular and full-polarimetric capabilities to provide global measurements of the Earth's brightness temperature with a spatial resolution of 43 km (Kerr *et al.*, 2010). The SMOS Soil Moisture Level 2 User Data Product (SMUDP2) version 5.51 was used in this study. This product is provided by ESA over an Icosahedral Snyder Equal Area Earth (ISEA-4H9) grid with equally spaced nodes at ~15 km, known as the Discrete Global Grid (DGG). The other product used from SMOS was the SMOS Barcelona Expert Center (BEC) L3, which was developed from the operational SMUDP2 product and is provided over a 25 km EASE-ML regular grid in NetCDF format (González-Zamora *et al.*, 2015). The series from both products were filtered using the Data Quality Index (DQX) and Radio Frequency Interference flag (RFI) threshold suggested by González-Zamora *et al.*, (2015) for the best-quality retrievals.

3.2.3. Validation Strategy

The L2 and L3 datasets from both satellites were compared with *in situ* measurements provided by the two soil moisture station networks. The time series from the satellite were compared with *in situ* measurements that were previously collocated in time with satellite products. Four comparisons were made for both networks: area averaged, soil texture averaged, land use averaged and point-scale measurements at each station with its collocated beam (Aquarius L2), DGG (SMOS L2) or pixel (SMOS and Aquarius L3 products). To analyze the effects of soil characteristics and land use, the stations were clustered in four texture categories (fine, including silty clay loam, clay loam, clay and loam stations; medium, including sandy loam and sandy clay loam stations; coarse, including loamy sand stations; and very coarse, including sand stations) and four land use categories (irrigated, forest-pasture, rainfed cereals and vineyard).

The statistical metrics chosen to assess the results were the Pearson correlation coefficient (R), RMSD, cRMSD and the bias.

3.3. Results and discussion

The comparison of the Aquarius soil moisture series with the *in situ* soil moisture from REMEDHUS (Fig. 3.2) shows a dual behavior during the period of study. The Aquarius soil moisture estimates were higher during the winter months and lower during summer, with L2 product values lower than L3. L2 soil moisture values were very low during the wet period (October to May). For the dry periods, Aquarius estimates values close to 0.02 m^3m^{-3} for L2 ascending and 0.03 m^3m^{-3} for L2 descending and L3 (Fig. 3.2). In general, L3 shows higher values than L2. Similar results are obtained for the Inforiego network (not shown).

The comparison between area-averages for Aquarius L2 products (Table 3.1) shows better correlations for ascending than for descending series, but with very similar errors. Errors associated with REMEDHUS are lower than for Inforiego. Regarding the L3 product, slightly worse results than L2 were obtained, with lower correlations and higher errors in both networks. A positive bias indicates dry bias for three products. The bias observed is consistent with other research with microwave passive sensors, where positive bias was found worldwide with AMSR-E (Sahoo *et al.*, 2008; Draper *et al.*, 2009), SMOS (Dall'Amico *et al.*, 2012; Sánchez *et al.*, 2012a) or Aquarius (Champagne *et al.*, 2014; Bindlish *et al.*, 2015; Li *et al.*, 2015).

		R	RMSD	cRMSD	Bias
REMEDHUS	L2 Ascending	0.61	0.085	0.046	0.072
	L2 Descending	0.49	0.072	0.051	0.052
	L3	0.55	0.112	0.111	-0.016
Inforiego-2012	L2 Ascending	0.64	0.114	0.077	0.084
	L2 Descending	0.51	0.133	0.090	0.098
	L3	0.50	0.128	0.098	0.082
Inforiego-2013	L2 Ascending	0.52	0.108	0.071	0.081
	L2 Descending	0.33	0.138	0.078	0.114
	L3	0.37	0.125	0.100	0.074

Table 3.1. Comparison between the spatially averaged series of soil moisture for all networks and the time series of different Aquarius products (RMSD and cRMSD units: m^3m^{-3})

The first year of data from Aquarius has a lower dynamic range than the other years of the research. It is interesting to note that this year was the driest during the study period. If this year is omitted for the calculations, the correlations improved (0.75 for L2 ascending, 0.58 for L2 descending and 0.68 for L3).

The results are worse than those obtained in other studies performed in more humid climate areas (Champagne *et al.*, 2014; Bindlish *et al.*, 2015), where the rainfall and the soil moisture values are usually higher than in this part of Spain. These results probably suggest that Aquarius has low sensitivity to very low soil moisture values and that it has high sensitivity to changes in soil moisture linked to rainfall events.

The SMOS datasets follow the temporal dynamics of the *in situ* measurements well (Fig. 3.3), although some underestimation can be observed, particularly in dry periods. SMOS exhibits a quicker reactivity to rainfall events. When comparing the evolution of Aquarius and

REMEDHUS in Fig. 3.2 and 3.3, it seems clear that SMOS has superior performance and higher stability. For the same areas and period, SMOS has better results than Aquarius (Table 3.1), with R>0.80, RMSD<0.093 m^3m^{-3}, and cRMSD<0.053 m^3m^{-3} in both networks (Table 3.2). This different performance is in contrast with the results obtained in other areas with wetter climates (e.g., Canada) (Champagne *et al.*, 2014), where Aquarius achieved better results than SMOS. Additionally, owing to the fact that the soil moisture retrieval algorithm is the same for both Aquarius and SMOS, the superior performance of Aquarius may be attributed to two potential causes. First, to a higher Aquarius signal-to-noise ratio compared with SMOS under highly dynamic soil moisture regimes. Second, even though the inputs and ancillary data sets considered in both retrieval algorithms are the same, the attribution of types (e.g. categories of land cover or soil texture) would be different in each retrieval. Nevertheless, the need for further research on this issue should be highlighted again.

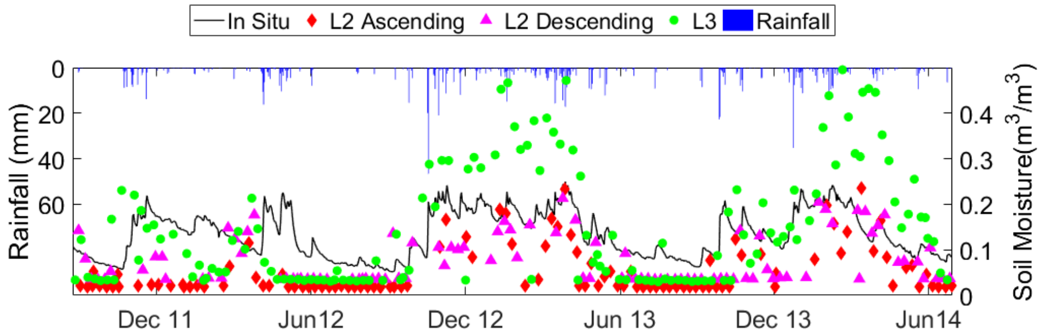

Figure 3.2. Soil moisture evolution of the *in situ* measurements (average of stations) and Aquarius products, along with rainfall during the study period, for the REMEDHUS network.

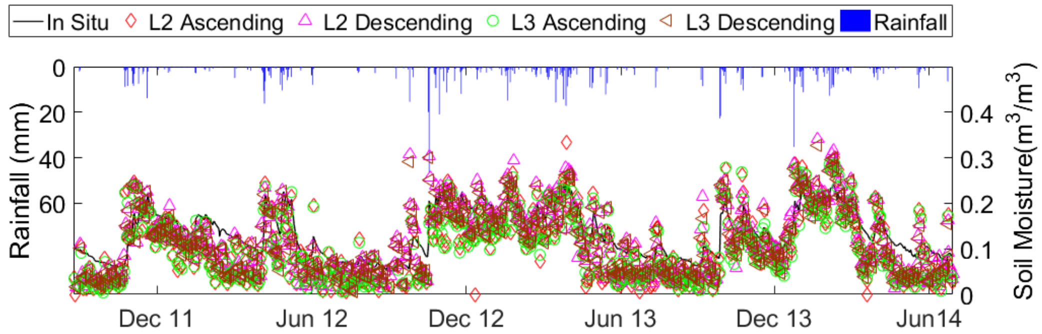

Figure 3.3. Soil moisture evolution of the *in situ* measurements (average of stations) and SMOS products, along with rainfall, during the study period for the REMEDHUS network.

Spatially concurrent time series comparisons for Aquarius (each station with its corresponding beam or pixel) reveal a good agreement between satellite products and point-scale measurements (Table 3.3), with 37 out of 56 stations having significant results (p-value<0.05) for L2 ascending, 18 for L2 descending and 50 for L3. This good agreement, despite the very different scale of measurements, is in line with most of the remotely sensed soil moisture validation works, in which the temporal patterns of the soil moisture at coarse resolutions were better reproduced compared with the spatial patterns (Piles *et al.*, 2014; González-Zamora *et al.*, 2015). The validation of large temporal series of data, despite their different scale, afforded a generally reasonable fit. Moreover, the study area shows a considerable degree of temporal persistence for the spatial structure, as found in previous analysis of soil moisture temporal stability on it (Martínez-Fernández and Ceballos, 2003; Martinez-Fernandez and Ceballos, 2005; Sánchez *et al.*, 2012a; González-Zamora *et al.*, 2015).

From the obtained results (Table 3.3), in which there are no differences between the two networks at the Aquarius spatial resolution, it seemed irrelevant to use a dense network such as REMEDHUS or a sparse network such as Inforiego. The size and density of the *in situ* network is not a restricting factor for validating the Aquarius products, as suggested in a previous validation in the USA (Bindlish *et al.*, 2015). More validation activities of Aquarius should be conducted worldwide to corroborate this finding, as very different results were found in previous research (Champagne *et al.*, 2014; Bindlish *et al.*, 2015; Li *et al.*, 2015). Although the mission is now over, new versions of the products are still provided, which are available to be validated and analyzed under different climates, different networks worldwide or under different upscaling strategies. The validation of the current products of this satellite could be useful for future similar missions. Similar results are obtained for the Inforiego network for the comparison of land use and soil texture classes (not shown).

		R	RMSD	cRMSD	Bias
REMEDHUS	L2 Ascending	0.83	0.052	0.042	0.031
	L2 Descending	0.84	0.046	0.042	0.019
	L3 Ascending	0.83	0.052	0.039	0.034
	L3 Descending	0.83	0.045	0.039	0.022
Inforiego-2012	L2 Ascending	0.84	0.088	0.050	0.073
	L2 Descending	0.88	0.064	0.048	0.042
	L3 Ascending	0.84	0.093	0.050	0.078
	L3 Descending	0.87	0.069	0.050	0.047
Inforiego-2013	L2 Ascending	0.85	0.071	0.040	0.059
	L2 Descending	0.85	0.073	0.053	0.050
	L3 Ascending	0.87	0.073	0.038	0.063
	L3 Descending	0.80	0.061	0.047	0.038

Table 3.2. Comparison between the spatially averaged series of soil moisture for all networks with each SMOS product time series (RMSD and cRMSD units: m^3m^{-3})

The box plot representing the statistical distribution of R for each Aquarius product and network (Fig. 3.4) showed similar median correlations between networks, being the highest R for L2 ascending, which is in line with the results for the averages shown previously. Regarding the distribution, the L3 product has more variable correlations, despite the presence of outliers in L2 ascending in Inforiego.

In the comparison analysis of each station with the SMOS soil moisture products, better results were found at point-scale than for Aquarius products. All stations have significant results (p-value<0.05), with R ranging from 0.42 to 0.85, RMSD from 0.046 to 0.208 m^3m^{-3}, and cRMSD from 0.046 to 0.122 m^3m^{-3} for the REMEDHUS network. For Inforiego, R ranged from 0.39 to 0.91, RMSD ranged from 0.042 to 0.253 m^3m^{-3}, and cRMSD ranged from 0.042 to 0.148 m^3m^{-3}. These results are better than those of Aquarius (Table 3.3). No differences were found between L2 and L3 products or orbits, but better results were obtained on average for stations located in Inforiego. For SMOS, the higher variability of the sparse network improves the comparisons at the Inforiego scale, in which each SMOS cell is compared with a single *in situ* station measurement. In contrast, several stations in REMEDHUS are compared against a single DGG value. For the same reason (i.e., the coarse spatial resolution of the soil moisture products), Aquarius showed no differences between REMEDHUS and Inforiego. SMOS, with a resolution of 15 km, is clearly more appropriate for the point-scale comparison than Aquarius, which has a resolution of ~100 km.

		L2 ascending		**L2 descending**		**L3**	
		REMEDUS	**Inforiego**	**REMEDUS**	**Inforiego**	**REMEDUS**	**Inforiego**
R	max	0.69	0.73	0.54	0.69	0.63	0.76
	min	0.21	0.36	0.42	0.33	0.21	0.27
RMSD	max	0.253	0.182	0.125	0.165	0.207	0.226
	min	0.042	0.063	0.069	0.058	0.108	0.064
cRMSD	max	0.148	0.121	0.065	0.103	0.165	0.128
	min	0.042	0.063	0.062	0.052	0.101	0.063
Bias	max	0.212	0.154	0.108	0.142	0.171	0.190
	min	-0.034	-0.107	0.026	-0.006	-0.125	-0.099

Table 3.3. Time series comparison between each station with each beam/pixel from Aquarius in both networks (RMSD and cRMSD units: m^3m^{-3})

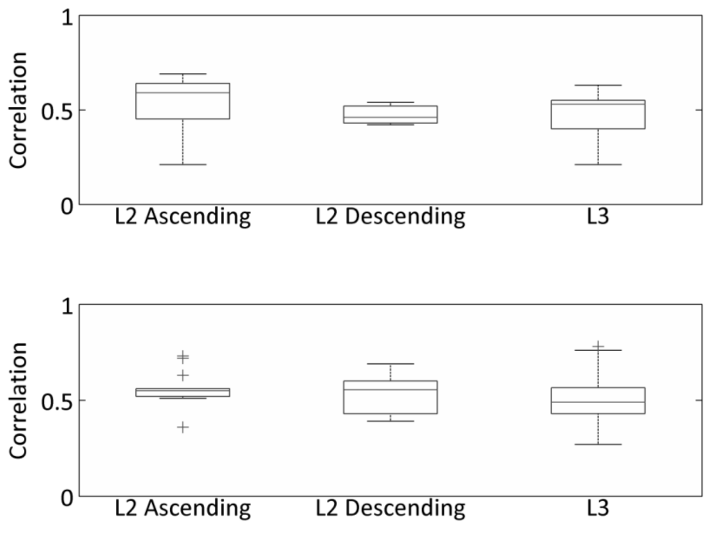

Figure 3.4. Box plot of the correlation coefficients of the point-scale measurement validation for all products in REMEDHUS (top) and Inforiego (bottom).

The results of the comparisons after the spatial disaggregation by land uses (Table 3.4) and soil texture classes (Table 3.5) for REMEDHUS did not reveal notable different correlations between categories for Aquarius. However, regarding the errors and bias, remarkably higher errors occurred for forest-pasture cover. The forest-pasture stations usually have much higher soil moisture than the rest of the land use types; consequently, they have higher errors, owing to the low Aquarius soil moisture values that were observed. Similar results were found in most of the previous validation experiments carried out in REMEDHUS (Sánchez *et al.*, 2012a; Piles *et al.*, 2014). In contrast, low errors and bias were found for vineyards. These results may be related to the fact that the soils of this type of land use are usually very sandy, and they thus have a very low water retention capacity. Accordingly, bias in coarse and very coarse soils types is negative, and errors are very small. These results were also found in other validation experiments (Jackson *et al.*, 2012; Wanders *et al.*, 2012). In contrast, for SMOS, there were differences between irrigated (R~0.5) and other land uses (R>0.8) and between very coarse soil texture (R~0.5) and the rest of the soil textures (R>0.8), which is in line with the results obtained in González-Zamora *et al.*, (2015) for the same area.

		R	**RMSD**	**cRMSD**	**Bias**
Forest-Pasture	L2 ascending	0.55	0.235	0.124	0.199
	L2 descending	0.35	0.215	0.128	0.173
	L3	0.44	0.191	0.150	0.118
Irrigated	L2 ascending	0.60	0.132	0.059	0.118
	L2 descending	0.41	0.120	0.076	0.093
	L3	0.59	0.111	0.108	0.024
Vineyard	L2 ascending	0.63	0.043	0.041	0.013
	L2 descending	0.42	0.048	0.047	-0.009
	L3	0.51	0.143	0.118	-0.080
Rainfed	L2 ascending	0.60	0.097	0.048	0.085
	L2 descending	0.50	0.083	0.052	0.065
	L3	0.56	0.111	0.111	-0.004

Table 3.4. Comparison between the temporal series of the soil moisture of the REMEDHUS network and Aquarius after land use clustering (RMSD and cRMSD units: m^3m^{-3}).

A second validation strategy was attempted, the so-called spatial validation, which consists of an individual correlation for each day in which all of the spatially concurrent pairwise observations are compared. Unfortunately, for Aquarius products, only a few days in the period were available for this analysis, and the correlations were not significant in all cases. Moreover, the spatial correlation applied to the SMOS series led to very poor results, including both negative and positive correlations, as also found in González-Zamora *et al.*, (2015). Such spatial and instantaneous requirements seem inappropriate at the resolutions of the Aquarius and SMOS products, even though recent research applying the same analysis at higher resolution (1 km) showed results similar to those obtained at coarse resolution (Piles *et al.*, 2014). The performance of this strategy for remote soil moisture product validation is still an open issue.

		R	RMSD	cRMSD	BIAS
Fine	L2 ascending	0.63	0.193	0.101	0.165
	L2 descending	0.53	0.181	0.104	0.149
	L3	0.57	0.150	0.119	0.092
Medium	L2 ascending	0.63	0.114	0.047	0.104
	L2 descending	0.52	0.099	0.052	0.085
	L3	0.58	0.109	0.108	0.017
Coarse	L2 ascending	0.60	0.048	0.043	0.021
	L2 descending	0.42	0.049	0.049	0.000
	L3	0.50	0.135	0.116	-0.069
Very Coarse	L2 ascending	0.63	0.043	0.042	-0.011
	L2 descending	0.44	0.057	0.047	-0.033
	L3	0.55	0.158	0.119	-0.105

Table 3.5. Comparison between the temporal series of the soil moisture of the REMEDHUS network and Aquarius after soil type clustering (RMSD and cRMSD units: m^3m^{-3}).

3.4. Conclusions

This research conducted a validation of Aquarius soil moisture products under different spatial scenarios provided by two *in situ* networks in the northwest of Spain. To perform a deep analysis of the Aquarius data, the L2 retrieved soil moisture was separated in ascending and descending orbits and compared with the new L3 product. These products were compared with data collected in two dense/sparse networks in Spain and analyzed in light of the results obtained with SMOS L2 and L3 soil moisture products.

The analysis of correlation afforded a better agreement of the L2 ascending product with soil moisture measurements compared with L2 descending and L3. However, Aquarius estimates low soil moisture values, especially in dry periods, and it seemed to perform better in highly dynamic soil moisture areas. This fact should be attributed to a low sensitivity to low soil moisture, and it is in line with the underestimation found with other passive sensors.

The coarse resolution of Aquarius results in no differences between the two scales of validation based on a change from dense to broad networks and from local to regional scales. Regardless of the size and density of the networks used, the validation results seemed similar. Additionally, owing to the differences between *in situ* and remote sensing resolutions, the spatial validation yielded poor results, which is in line with other research about soil moisture measurement from passive satellites. Underpinning this reasoning, it was shown that SMOS reproduced the temporal patterns of the *in situ* soil moisture better than Aquarius, owing to its better temporal and spatial resolution.

The results of this study showed that the Aquarius soil moisture products have reasonably good performance. Moreover, for a comprehensive validation, more research in a wider range of environmental scenarios would be necessary. Despite the limited length of the series, the current Aquarius L2 soil moisture product, together with the newly reprocessed L3, will contribute to a deeper knowledge of the retrieval of soil moisture from passive remote sensing radiometers, widening the satellite soil moisture datasets and thus the field of applications.