SMOS and Aquarius Radiometers: Inter-Comparison Over Selected Targets

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Abstract—Passive microwave remote sensing at L-band is considered to be the most suitable technique to measure soil moisture and ocean salinity. These two variables are needed as inputs of predictive models, to improve climate and weather forecast, and to increase our knowledge of the water cycle. Nowadays, there are two space missions providing frequent and global observations of moisture and salinity of the Earth's surface with L-band radiometers on-board. The first one is the ESA's SMOS satellite, launched on November 2, 2009, which carries a two-dimensional, multi-angular, and full-polarimetric synthetic aperture radiometer. The second one is the NASA/CONAE's Aquarius/SAC-D mission, launched on June 10, 2011, which includes three beam push-broom real aperture radiometers. The objective of this work is to compare SMOS and Aquarius brightness temperatures and verify the continuity and consistency of the data over the entire dynamic range of observations. This is paramount if data from both radiometers are used for any long term environmental, meteorological, hydrological, or climatological studies. The inter-comparison approach proposed is based on the study of 1 year of measurements over key target regions selected as representative of land, ice, and sea surfaces. The level of linearity, the correlation, and the differences between the observations of the two radiometers are analyzed. Results show a higher linear correlation between SMOS and Aquarius brightness temperatures over land than over sea. A seasonal effect and spatial inhomogeneities are observed over ice, at the Dome-C region. In all targets, better agreement is found in horizontal than in vertical polarization. Also, the correlation is higher at higher incidence angles. These differences indicate that there is a non-linear effect between the two instruments, not only a bias.

Index Terms—Aquarius/Satélite de Aplicaciones Científicas (SAC)-D mission, brightness temperature, inter-comparison, L-band radiometer, passive microwave remote sensing, Soil Moisture and Ocean Salinity (SMOS) mission.

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I. INTRODUCTION

A MICROWAVE radiometer is a passive sensor capable of measuring the power naturally emitted by bodies at a physical temperature above 0 K, which is proportional to the so-called brightness temperatures (T_B) [1].

The frequency band from 1.400 to 1.427 GHz is a protected band, reserved for radio-astronomy and passive remote sensing. At these frequencies, the amount of microwave thermal radiation naturally emitted by the Earth's surface decreases with increasing soil moisture over land [2], and increasing surface salinity in the oceans [3]. Also, this band is significantly less affected by rain and atmospheric effects than higher microwave frequencies. Not only the atmosphere is nearly transparent, but the microwave radiation emitted by the Earth's surface can also pass through the vegetation canopy (up to 5 kg/m² which corresponds to 70% of non-frozen land areas on Earth, excluding dense forest).

Currently, there are two satellite missions providing unprecedented observations of the Earth's surface using L-band radiometers: i) the Soil Moisture and Ocean Salinity (SMOS) mission [4], [5]; and ii) the Aquarius/Satélite de Aplicaciones Científicas (SAC)-D mission [6]. The European Space Agency (ESA) launched the SMOS satellite on November 2, 2009, to monitor surface soil moisture and ocean salinity at global scale. Its single payload is the two-dimensional Microwave Imaging Radiometer with Aperture Synthesis (MIRAS), a novel instrument based on interferometry which provides multi-angular and full-polarimetric observations [7]. The Aquarius/SAC-D satellite was launched on June 10, 2011, in a collaboration between the U.S. National Aeronautics and Space Administration (NASA), and the Argentinian *Comisión Nacional de Actividades Espaciales* (CONAE). It is devoted to monitor the Sea Surface Salinity (SSS) at global scale and includes three beam push-broom radiometers/scatterometers [8]. The NASA's Soil Moisture Active Passive (SMAP), planned to be launched on November 2014, will be the third passive L-band mission [9]. Its payloads will be a real aperture radiometer [10] and a synthetic aperture scatterometer to monitor global surface soil moisture and its freeze/thaw state.

The SMOS and Aquarius payloads operate at the same frequency band, centered at 1.413 GHz, but have important differences in both the architecture of their radiometers (e.g., number of receivers and incidence angles), as in their operation principles (e.g., interferometric vs. Dicke radiometer and Stokes parameters measured). Also, they have different swath coverage, spatial resolutions, and revisit times. The main distinctive features of SMOS and Aquarius are summarized in Table I.

TABLE I
MAIN FEATURES OF SMOS AND AQUARIUS RADIOMETERS

Features	SMOS	Aquarius
Topology	Synthetic aperture Y-shape array with a diameter of 8 m	Real aperture
Antenna type	69 patch antennas (0.165 m spaced 0.875λ)	2.5 m reflector and 3 horns
Radiometer units	72 receivers	3 receivers
Stokes parameters	4 Stokes	3 Stokes (T_H , T_V , and T_3)
Operation principle	Interferometric radiometer	Dicke radiometer
Incidence angles	From 0° to 65°(multi-angular)	29.36°(inner), 38.49°(middle), 46.29°(outer)
Swath	~1000 km	~390 km
Spatial resolution	~40 km	~100 km
Revisit time	3 days	7 days
Calibration performance	Internal (noise diode and reference load) and external (cold sky views)	Internal (noise diode and reference load), model references (ocean, Antarctica and Amazon rainforest) and external (cold sky views)

TABLE II
CORRECTIONS APPLIED TO SMOS AND AQUARIUS RADIOMETERS

Correction type	SMOS	Aquarius
Direct galaxy	Yes	Yes
Reflected galaxy	No	Yes
Direct Sun	Yes	Yes
Reflected Sun	No	Yes
Direct Moon	Yes	Yes
Reflected Moon	No	Yes

Both instruments are calibrated to obtain their T_B products within the mission requirements using different calibration procedures (see Table I). In SMOS, there are two types of calibration: the internal and the external. The internal calibration is based on the injection of uncorrelated noise, which compensates for offset terms, and correlated noise at two known levels, which compensates for amplitude and phase terms. The external calibration uses cold sky maneuvers to calibrate the injected noise level [11]. Likewise, Aquarius has an internal calibration (injecting correlated and uncorrelated noise) and uses the cold sky as external calibration. Additionally, a vicarious calibration is performed using models over the ocean, Antarctica, and Amazon rainforest [12].

After calibration, some corrections are applied to SMOS and Aquarius T_B to obtain the signal from the Earth's surface and to filter signal contributions from celestial bodies (galaxy, Sun, and Moon). The main differences in the corrections applied are summarized in Table II. SMOS Level 1 (L1) data contain flags indicating the Sun and Moon corrections/detections in presence of direct/reflected radiations, respectively. Galaxy corrections are applied at SMOS Level 2 (L2) before retrieving the geophysical parameters. In Aquarius, T_B are already corrected for galaxy, Sun, and Moon signal contributions.

Direct comparison of SMOS and Aquarius observations is challenging, since both are Sun-synchronous Low Earth Orbits (LEO) satellites at similar heights (~758 km and ~675 km, respectively), but they have opposite equatorial ascending crossing times: 6 A.M. for SMOS, 6 P.M. for Aquarius. Due to this, cross-overs only occur near the equator and at the poles.

Previous studies have shown an increased interest in comparing SMOS and Aquarius T_B . Anterrieu *et al.* [13] proposed a resampling and multi-windowing method to obtain SMOS T_B at the incidence angles and ground resolution of Aquarius. Bindlish *et al.*

[14] used colocated overpasses (with at least 20 SMOS grid points inside the Aquarius footprint) and a 30-min time criteria to eliminate the effect of physical temperature drifts. This approach limits the observations to low latitudes between [20°S, 40°N]. Cabot *et al.* [15] used simultaneous observations over the same place (with a distance less than 2.5°) resampling SMOS data at the resolution and incidence angles of Aquarius and also obtaining a limited number of colocated (~750 overpasses in 500 days).

In this work, an alternative approach which does not require simultaneous cross-overs is proposed to compare SMOS and Aquarius T_B over different targets, without latitudinal/temporal limitations. The objective is to evaluate the consistency between SMOS and Aquarius data and detect possible differences and/or biases. Key target regions over land, ice, and sea are selected to cover the entire dynamic range of T_B .

In Section II, data selection procedures as well as the inter-comparison strategy are presented. Results of the analysis and evaluation of the SMOS-Aquarius inter-comparison are shown in Section III. Finally, the main conclusion and significant contributions of this study are outlined in Section IV.

II. DATA AND METHODS

A. SMOS Data

The SMOS T_B at the antenna reference plane are obtained from the L1C V5.05 products, provided by the European Space Astronomy Centre (ESAC), Madrid. These T_B have been first screened out for all the Radio-Frequency Interferences (RFI) detected (strong, point source, and tails), and also for the Sun (glint area, aliases, and tails), and Moon (aliases) contamination, using the corresponding flags. Later, geometric and Faraday corrections are applied to obtain T_B at the top of the atmosphere (TOA):

$$\begin{pmatrix} T_{B_H} \\ T_{B_V} \end{pmatrix} = \frac{1}{\cos^2(\varphi) - \sin^2(\varphi)} \begin{pmatrix} \cos^2(\varphi) & -\sin^2(\varphi) \\ -\sin^2(\varphi) & \cos^2(\varphi) \end{pmatrix} \begin{pmatrix} T_{B_X} \\ T_{B_Y} \end{pmatrix} \quad (1)$$

where φ is the rotation angle (geometric + Faraday), T_{B_X} and T_{B_Y} are the T_B at the antenna plane according to X and Y axis, and T_{B_H} and T_{B_V} correspond to the T_B at TOA for horizontal and vertical polarizations, respectively.

All SMOS T_B in an incidence angle range of $\theta \pm 5^\circ$ are linearly interpolated to obtain them at the Aquarius incidence angles (θ). Finally, T_B from the Icosahedral Snyder Equal Area (ISEA 4H9) grid [16] are interpolated to a 0.25° regular latitude-longitude grid, which is easier to manipulate.

B. Spatial Bias Correction in SMOS Data Over Ocean

SMOS' synthetic imagery can be interpreted as obtained by an array of antennas located in each spatial frequency point [17]. The incidence angle, the spatial resolution, and the radiometric accuracy vary depending on the position of each pixel within the Field Of View (FOV). The differences between pixels that remain after calibration are the so-called pixel biases or spatial errors.

It is known that SMOS pixel biases are significantly affecting ocean observations, since they have an important impact in SSS retrievals. Several studies characterize these spatial errors and describe methods to mitigate their effects on the T_B images. Camps *et al.* [18] proposed an improved reconstruction algorithm that decomposes the visibility samples in ocean and land/iced sea. Torres *et al.* [19] demonstrated that SMOS pixel biases are not zero mean and produce visible artifacts along-track, which could be minimized over the ocean using a multiplicative mask. Gourrion *et al.* [20] distinguished the spatial errors by azimuth dependence/independence and computed an empirically fitted pattern that could be applied over ocean, ice, and land.

In this work, an Ocean Target Transformation (OTT), which models the instrumental spatial pattern of the FOV, has been applied to SMOS data over South Pacific region, as it is currently applied operationally in the L2 Ocean Salinity processor. As a result, the errors in the FOV become practically random, preserving the geophysical variation in the scene.

C. Aquarius Data

The Aquarius T_B used are L2 V2.0 products provided by the Physical Oceanography Distributed Active Archive Center, managed and located at NASA's Jet Propulsion Laboratory (JPL), California. They are directly T_B at TOA and have been masked out for RFI, reflected Sun, glint, and Moon contamination (moderate and severe flags), and also for direct Sun contamination (severe flag). No gridding is performed.

D. Inter-Comparison Methodology

The inter-comparison procedure involves identifying locations on Earth that could serve as target regions to assess the behavior of both SMOS and Aquarius instruments. The main goal is to evaluate the T_B acquired independently over several relatively stable and homogeneous targets at scales compatible with both sensors. They should have nearly constant observed T_B over time and cover, as much as possible, the whole dynamic range of T_B observations from the cold to the hot end (sea, ice, and land). Attending to these criteria, four locations have been selected: 1) the Amazon rainforest, 2) the Sahara desert, 3) the South Pacific Ocean, and 4) the Dome-C zone in Antarctica (Fig. 1). Specific locations, areas, and number of observations selected from each radiometer are included in Table III. Observations from cold sky views have not been used in this study since both radiometers have different antenna patterns and also

Fig. 1. World map showing location and extent of target regions: Amazon rainforest and Sahara desert (land), South Pacific Ocean (sea), and Dome-C in Antarctica (ice).

different scenes entering into the back lobes that could severely affect the T_B measurements from the main lobe ($\sim 3 - 10$ K).

The four target regions selected for the present study have different radiometric characteristics.

- 1) The Amazon tropical forest has a very stable temperature and its surface is covered by a heavily vegetated layer that provides a feasible approximation to a blackbody at L-band. However, its surface contains rivers and it rains almost the whole year.
- 2) The Sahara's surface is very dry, sandy, and without presence of vegetation. It is characterized by a dry atmosphere and high daily surface temperature variations. In the Sahara desert, the area has been selected to ensure total absence of precipitation during the study period. It was checked using the total precipitation in (mm/month) of the Global Precipitation Climatology Centre (GPCC) using a 1° regular grid product based on quality-controlled data from Earth's stations.
- 3) The South Pacific ocean is an ice-free region on the sea, with low or moderate Wind Speed ($WS < 12$ m/s), an almost constant Sea Surface Temperature (SST) of $\sim 26.5^\circ\text{C}$, and a SSS of ~ 35 psu.
- 4) The Dome-C in Antarctica is considered a very stable region on Earth. Also, Dome-C has been suggested as a reference target for several experimental campaigns [21], [22].

All SMOS and Aquarius radiometric observations measured over the selected target areas have been analyzed at the three Aquarius Earth incidence angles along the year 2012. For Aquarius, only the footprints which are entirely enclosed within the target areas' boundaries have been considered. In SMOS, the orbits covering at least 20% of the total number of ISEA 4H9 grid points within the region have been taken into account. Both ascending and descending orbits have been used. The use of ascending and descending separately has been checked not to affect the results.

Temporal window averaging is needed to reduce the noise in the measurements. To select an appropriate length for this window, the Allan variance has been computed over each target region, both for SMOS and for Aquarius. Allan variance determines the stability and drifts of the measurement time series as a function of the integration time (in this study from 2 to 100 days). Plots of the Allan variance obtained for Aquarius (top) and

TABLE III
DESCRIPTION OF SELECTED TARGET AREAS

Location	Latitude	Longitude	Area (km ²)	Beam	SMOS / Aquarius (pixels)
Amazon	8°S, 1°N	75°W, 65°W	1113×10^3	Inner	294 697 / 22 618
				Middle	289 987 / 26 886
				Outer	335 133 / 23 001
Sahara	23.5°N, 27.5°N	18°E, 30°E	593×10^3	Inner	164 074 / 11 485
				Middle	162 554 / 11 216
				Outer	181 238 / 10 485
South Pacific	15°S, 0°N	135°W, 120°W	2782×10^3	Inner	712 923 / 66 141
				Middle	711 083 / 64 374
				Outer	793 666 / 62 707
South Pacific (with OTT applied to SMOS data)	15°S, 0°N	135°W, 120°W	2782×10^3	Inner	712 925 / 66 141
				Middle	706 166 / 64 374
				Outer	793 577 / 62 707
Dome-C	78°S, 72°S	116°E, 130°E	1039×10^3	Inner	1 450 060 / 30 994
				Middle	1 444 861 / 34 732
				Outer	1 737 110 / 38 305

Fig. 2. Aquarius (top) and SMOS (bottom) Allan variance for each target region: Amazon (green), Sahara (red), South Pacific (blue), and Dome-C (black) using only middle beam of the First Stokes ($I/2$). Other beams present similar behaviors.

SMOS (bottom) over all targets using the middle beam of the First Stokes parameter ($I/2 = (T_{BH} + T_{BV})/2$) are shown in Fig. 2. Other beams (not included) present similar behavior. It could be observed that Aquarius has a stability period of ~ 7 days over land and ice, in agreement with its revisit time. Over ocean, the stability period is not clear enough. SMOS has a stability period of ≈ 6 – 10 days over land, ≈ 3 – 7 days over ice, and ≈ 5 – 8 days over ocean. In view of these results, a 7-day averaging window has been selected in this study for all target regions and both instruments.

III. RESULTS OF SMOS-AQUARIUS INTER-COMPARISON

SMOS and Aquarius T_B have been compared at TOA for horizontal and vertical polarizations separately, at the three Aquarius incidence angles: $\sim 29.36^\circ$ (inner), $\sim 38.49^\circ$ (middle), and $\sim 46.29^\circ$ (outer) beams. First Stokes has also been analyzed to discard errors due to Faraday rotation.

Fig. 3. Aquarius T_B versus SMOS T_B over land ~ 250 – 300 K (Amazon rainforest and Sahara desert), over ice ~ 180 – 220 K (Dome-C in Antarctica), and over sea ~ 70 – 130 K (South Pacific ocean) for horizontal (top) and vertical polarizations (bottom). Different symbols represent inner (blue circles), middle (red squares), and outer (green triangles) beams.

A global view of the results over all the study areas (Amazon, Sahara, South Pacific, and Dome-C) is provided in Fig. 3. The yearly mean Aquarius T_B are presented as a function of the yearly mean SMOS T_B for each beam, polarization, and region. Each beam is depicted using a different color and symbol. Ideally, the yearly mean values within the dynamic range (70–310 K) should be on the 1:1 line (dashed line).

In South Pacific, Dome-C, and Sahara, higher incidence angles imply lower T_{BH} , and higher T_{BV} . However, in the Amazon, the T_B variation with incidence angle and polarization is not clear due to the vegetation scattering; the signal emitted by the Amazon's surface is highly affected by multiple reflections when it is traveling upward through the vegetation canopy, and coherent effects appear when the distance

between vegetation scatterers becomes comparable to the wavelength (~ 21 cm). As expected, there is a small difference between polarizations ($T_{B_V} - T_{B_H}$) for vegetation-covered soils.

To study the linearity between the two radiometers, representative scatter plots of Aquarius T_B versus SMOS T_B (7-day averaged) are presented for horizontal (Fig. 4) and vertical (Fig. 5) polarizations. Regions are sorted by rows and beams are assigned by columns. Dynamic ranges are fixed for each area to show full T_B variability with enough detail. The slope s is estimated through a robust linear fit [23].

Over land, the slopes are close to 1 (Amazon: $s \approx 0.94$ to 1.21, Sahara: $s \approx 0.86$ to 1.05). Over sea, slopes are low and only slightly increase after the pixel bias correction (South Pacific: before OTT $s \approx 0.08$ to 0.37, after OTT $s \approx 0.30$ to 0.42). It is evident from these results that there is a better agreement between SMOS and Aquarius T_B over land than over sea. In the case of Dome-C, the scatter plots show an unusual distribution and two slopes (opposite in sign) have been identified. The subset of points from the summer months (from December 21 to March 21) match with positive slopes (Dome-C Austral summer: $s \approx 0.30$ –1.66), whereas the other points match with negative slopes (Dome-C other seasons: $s \approx -0.11$ to -0.58). Note that some slopes over ice are non-significant ($p > 0.05$) for middle and outer beams. Focusing on a single target area and comparing the different polarizations, it can be noted that T_{B_H} slopes are higher than T_{B_V} slopes. Also, the slope values obtained at higher incidence angles are closer to 1 (ideal slope) than lower incidence angles in most cases.

Fig. 6 shows scatter plots of Aquarius $I/2$ versus SMOS $I/2$. Results are in line with those obtained in Figs. 4 and 5. Scatter plots over land present a very linear trend (Amazon: $s \approx 0.96$ –1.20, Sahara: $s \approx 0.88$ –1.01). Slopes decrease over sea (South Pacific: before OTT $s \approx 0.15$ –0.27, after OTT $s \approx 0.37$ –0.40), and are far away from the 1:1 line. This may probably be due to the reduced dynamic range. Over Dome-C, the slopes are also in agreement with horizontal and vertical polarization (Dome-C Austral summer: $s \approx 1.19$ –1.56, other seasons: $s \approx -0.31$ to -0.77). Note that $I/2$ is independent of the Faraday rotation and results obtained with $I/2$ are consistent with those obtained with T_{B_H} and T_{B_V} . This confirms that differences in Faraday correction are not affecting the comparison.

Statistical scores, namely, the mean, the standard deviation (std), the root-mean-square difference (RMSD), the Spearman correlation (R), the T_B difference (Aquarius T_B minus SMOS T_B), and the slope (s) are displayed for horizontal, vertical polarization, and First Stokes in Tables IV–VI, respectively. Non-significant correlations or slopes ($p > 0.05$) are marked with an asterisk. Results are in agreement with the corresponding scatter plots in Figs. 4–6. Correlation is very strong over land ($R > 0.9$) and decreases over sea (before OTT: $R \approx 0.23$ –0.68, after OTT: $R \approx 0.63$ –0.80). Over ice, the correlations are $R \approx 0.74$ –0.96 in the Austral summer and $R \approx 0.24$ –0.65 during other seasons. Correlation and slope values are systematically higher at horizontal than at vertical polarization. This result reveals that there is a higher degree of linearity between SMOS and Aquarius at horizontal than at vertical polarizations.

Note that Aquarius T_B are warmer than SMOS T_B over all study areas. The difference is higher over warmer targets with ~ 5 K (~ 8 K) for horizontal (vertical) polarization over land. This difference decreases with colder targets being ~ 3 K (~ 5 K) for horizontal (vertical) polarization over ice and ~ 0.6 K (~ 2 K) for horizontal (vertical) polarization over sea. In the latter, the difference decreases significantly after applying the pixel bias correction down to ~ 0.3 K (~ 0.1 K) for horizontal (vertical) polarization. It has been checked that differences over sea are not due to different wind conditions, affecting SMOS and Aquarius during the 7-day period. Since the difference between SMOS and Aquarius T_B is found to be target dependent, it can be argued that there is a bias and also a non-linear effect between the two instruments.

The noise level of each instrument is calculated from the temporal standard deviation of the observations. In percent (std divided by mean), Aquarius noise varies from $\approx 0.2\%$ to 0.4% over sea, from $\approx 0.5\%$ to 1.5% over ice, and from $\approx 0.4\%$ to 1.4% over land. SMOS noise varies from $\approx 1.3\%$ to 2.5% over sea, from $\approx 1.5\%$ to 3% over ice, and from $\approx 1.7\%$ to 3.5% over land. This is consistent with the topology of the radiometers, since Aquarius is a real aperture Dicke radiometer and SMOS is a synthetic aperture radiometer, which involves T_B image reconstruction. Currently, the OTT reduces the image pixel biases within the FOV to a large extent. In this study, the application of the OTT results in an improvement of $\sim 30\%$ – 40% in South Pacific, obtaining a noise level from $\approx 0.8\%$ to 1.5% over sea.

Temporal evolution of SMOS and Aquarius T_B during year 2012 has also been analyzed. The T_B variations are displayed in Fig. 7. The corresponding yearly mean value has been subtracted ($\Delta T_{B_{pol}} = T_{B_{pol}} - \overline{T_{B_{pol}}}$, where the subscript *pol* indicates the polarization H or V for horizontal and vertical, respectively), in order to show the full variability with enough detail. Dynamic ranges are also fixed, being 6 K for Amazon, 20 K for Sahara, 3 K for South Pacific, and 2 K for Dome-C. Results show that SMOS T_B present higher temporal fluctuations than Aquarius ones over all regions due to the nature of the instrument.

Over land, SMOS and Aquarius T_B have a similar seasonal behavior. In the Amazon, lower T_B are obtained with the two radiometers during the first half of the year, coincident with the rainy season, than in the second half of the year, corresponding to the not-so-rainy season. In the Sahara, higher T_B are observed both in SMOS and Aquarius from April to November due to the very high temperatures at that time of the year. Over sea, SMOS T_B show higher seasonal variability than over land. In the South Pacific, SMOS T_B have a lower variability after applying the pixel bias correction, particularly at vertical polarization. In Dome-C, both radiometers show a more stable T_B at vertical than at horizontal polarization, which may be due to Sun scattering contributions, since the reflection coefficient is larger at horizontal than at vertical polarization. A seasonal phenomenon is also observed. The SMOS and Aquarius T_B vary in phase along time during the Austral summer. In contrast, SMOS and Aquarius T_B vary in opposite phase in the other seasons. One reason for this may be that Sun zenith angle variations are affecting SMOS and Aquarius observations in a different way, depending on the period of the year. Also, the upper 10 m

Fig. 4. Scatter plots of Aquarius T_{BH} versus SMOS T_{BH} over target areas sorted by rows: Amazon rainforest, Sahara desert, South Pacific Ocean without OTT applied to SMOS data (third row), South Pacific ocean with OTT applied to SMOS data (fourth row), and Dome-C in Antarctica. Different incidence angles are placed by columns: inner $\sim 29.36^\circ$ (left), middle $\sim 38.49^\circ$ (center), and outer $\sim 46.29^\circ$ (right) beams. Dynamic ranges are fixed, being 6 K for Amazon, 20 K for Sahara, 3 K for South Pacific, and 2 K for Dome-C. Over Dome-C, the Austral summer (in blue) is distinguished from the rest of the seasons (in red). The solid line represents the robust linear regression. Slope values s from the linear fit are shown in the plots. Non-significant slopes ($p > 0.05$) are marked with an asterisk.

Fig. 5. Same as for Fig. 4, but at vertical polarization (T_{B_v}).

experience seasonal temperature changes in the order of 30°C [24]. We assume that these temperature variations could affect the ice crystal size and shape, modifying the microwave emission of the ice surface in scales resolved by SMOS and

not by Aquarius. Spatial inhomogeneities over the Dome-C area were found in a recent airborne campaign using the EMIRAD-2 L-band radiometer [25]. Expected high values of T_B appeared in the Northern side, while other unexpected

Fig. 6. Same as for Fig. 4, but for First Stokes ($I/2$).

inhomogeneities were observed around Concordia station and the Western side.

Theoretically, the L-band penetration depth of ice and snow is of hundreds of meters. As ice and snow at Dome-C are very dry,

we thought that L-band penetration in this area could be more than hundreds of meters. In view of the results presented in this paper, we hypothesize the penetration depth may be significantly higher and T_B observations are being influenced by geophysical

TABLE IV
STATISTICS FOR HORIZONTAL POLARIZATION (T_{B_H})

Target region	Beam	Aquarius	SMOS	Aquarius-SMOS			Slope s
		mean $\pm$ std (K)	mean $\pm$ std (K)	RMSD (K)	R	Difference (K)	
Amazon	Inner	281.46 $\pm$ 2.49	273.41 $\pm$ 6.48	8.07	0.94	8.05	0.95
	Middle	278.93 $\pm$ 3.76	273.88 $\pm$ 5.69	5.09	0.94	5.05	1.21
	Outer	278.18 $\pm$ 3.17	273.12 $\pm$ 6.52	5.08	0.93	5.05	1.03
Sahara	Inner	273.15 $\pm$ 1.20	268.38 $\pm$ 7.31	4.95	0.97	4.77	0.90
	Middle	267.05 $\pm$ 1.17	261.89 $\pm$ 6.97	5.25	0.98	5.16	1.05
	Outer	256.05 $\pm$ 1.98	252.22 $\pm$ 8.96	3.94	0.98	3.83	0.94
South Pacific	Inner	89.04 $\pm$ 0.29	88.08 $\pm$ 1.88	1.06	0.48	0.96	0.23
	Middle	82.95 $\pm$ 0.29	82.39 $\pm$ 2.16	0.69	0.56	0.56	0.26
	Outer	76.70 $\pm$ 0.32	76.40 $\pm$ 1.88	0.49	0.68	0.30	0.37
South Pacific (with OTT applied to SMOS data)	Inner	89.04 $\pm$ 0.29	88.85 $\pm$ 1.06	0.35	0.76	0.19	0.41
	Middle	82.95 $\pm$ 0.29	82.67 $\pm$ 1.04	0.42	0.78	0.28	0.42
	Outer	76.70 $\pm$ 0.32	76.20 $\pm$ 1.13	0.63	0.80	0.50	0.41
Dome-C (Austral summer)	Inner	197.45 $\pm$ 3.07	194.04 $\pm$ 4.80	3.42	0.96	3.41	1.66
	Middle	193.93 $\pm$ 2.81	190.74 $\pm$ 4.78	3.19	0.95	3.19	1.15
	Outer	188.32 $\pm$ 2.67	187.12 $\pm$ 5.50	1.21	0.91	1.20	1.16
Dome-C (other seasons)	Inner	197.18 $\pm$ 2.78	193.78 $\pm$ 4.86	3.41	0.65	3.40	-0.58
	Middle	193.72 $\pm$ 2.64	190.21 $\pm$ 4.81	3.52	0.33	3.51	-0.29
	Outer	188.38 $\pm$ 2.40	186.64 $\pm$ 5.47	1.77	0.07*	1.74	0.20*

*Non-significant values of correlations or slopes ($p > 0.05$).

TABLE V
STATISTICS FOR VERTICAL POLARIZATION (T_{B_V})

Target region	Beam	Aquarius	SMOS	Aquarius-SMOS			Slope s
		mean $\pm$ std (K)	mean $\pm$ std (K)	RMSD (K)	R	Difference (K)	
Amazon	Inner	282.55 $\pm$ 2.19	272.70 $\pm$ 5.63	9.86	0.91	9.85	0.94
	Middle	282.67 $\pm$ 3.31	274.92 $\pm$ 5.17	7.77	0.94	7.75	1.20
	Outer	281.84 $\pm$ 2.39	273.80 $\pm$ 4.57	8.05	0.92	8.03	0.97
Sahara	Inner	287.37 $\pm$ 1.17	278.50 $\pm$ 7.43	8.97	0.97	8.87	0.86
	Middle	292.88 $\pm$ 1.06	286.10 $\pm$ 7.89	6.86	0.98	6.78	0.98
	Outer	295.86 $\pm$ 1.76	289.27 $\pm$ 9.30	6.69	0.98	6.59	0.90
South Pacific	Inner	108.78 $\pm$ 0.29	105.52 $\pm$ 1.94	3.30	0.23	3.26	0.08
	Middle	117.87 $\pm$ 0.28	116.13 $\pm$ 2.01	1.80	0.38	1.74	0.14
	Outer	129.19 $\pm$ 0.27	128.31 $\pm$ 1.63	0.97	0.43	0.88	0.15
South Pacific (with OTT applied to SMOS data)	Inner	108.78 $\pm$ 0.29	108.74 $\pm$ 1.04	0.30	0.63	0.04	0.33
	Middle	117.87 $\pm$ 0.28	117.94 $\pm$ 1.02	0.27	0.69	-0.07	0.38
	Outer	129.19 $\pm$ 0.27	129.06 $\pm$ 1.09	0.31	0.67	0.13	0.30
Dome-C (Austral summer)	Inner	209.02 $\pm$ 2.22	203.15 $\pm$ 3.93	5.87	0.74	5.87	0.96
	Middle	213.20 $\pm$ 1.52	208.52 $\pm$ 3.65	4.68	0.09*	4.68	0.12*
	Outer	216.00 $\pm$ 1.18	211.68 $\pm$ 3.15	4.33	0.27	4.32	0.30
Dome-C (other seasons)	Inner	208.78 $\pm$ 2.03	202.99 $\pm$ 3.81	5.79	0.42	5.79	-0.20
	Middle	213.00 $\pm$ 1.45	208.36 $\pm$ 3.63	4.65	0.24	4.64	-0.11
	Outer	215.73 $\pm$ 1.17	211.52 $\pm$ 2.95	4.22	0.03*	4.21	0.02*

*Non-significant values of correlations or slopes ($p > 0.05$).

TABLE VI
STATISTICS FOR FIRST STOKES ($I/2$)

Target region	Beam	Aquarius	SMOS	Aquarius-SMOS			Slope s
		mean $\pm$ std (K)	mean $\pm$ std (K)	RMSD (K)	R	Difference (K)	
Amazon	Inner	282.00 $\pm$ 2.33	273.12 $\pm$ 5.19	8.90	0.93	8.88	0.96
	Middle	280.80 $\pm$ 3.54	274.44 $\pm$ 4.84	6.38	0.95	6.36	1.20
	Outer	280.00 $\pm$ 2.77	273.55 $\pm$ 4.31	6.46	0.94	6.45	1.05
Sahara	Inner	280.26 $\pm$ 1.15	273.42 $\pm$ 5.77	6.96	0.97	6.84	0.88
	Middle	279.97 $\pm$ 0.99	274.06 $\pm$ 5.91	5.97	0.99	5.91	1.01
	Outer	275.96 $\pm$ 1.76	270.73 $\pm$ 7.26	5.30	0.98	5.23	0.92
South Pacific	Inner	98.91 $\pm$ 0.27	96.80 $\pm$ 1.15	2.16	0.37	2.11	0.15
	Middle	100.41 $\pm$ 0.26	99.43 $\pm$ 1.13	1.07	0.52	0.98	0.23
	Outer	102.94 $\pm$ 0.27	102.34 $\pm$ 1.22	0.72	0.59	0.60	0.27
South Pacific (with OTT applied to SMOS data)	Inner	98.91 $\pm$ 0.27	98.79 $\pm$ 0.77	0.32	0.71	0.12	0.38
	Middle	100.41 $\pm$ 0.26	100.32 $\pm$ 0.77	0.31	0.75	0.09	0.40
	Outer	102.94 $\pm$ 0.27	102.63 $\pm$ 0.83	0.46	0.76	0.31	0.37
Dome-C (Austral summer)	Inner	203.23 $\pm$ 2.64	198.55 $\pm$ 3.68	4.68	0.93	4.68	1.53
	Middle	203.56 $\pm$ 2.14	199.61 $\pm$ 3.80	3.95	0.87	3.95	1.19
	Outer	203.16 $\pm$ 1.90	199.38 $\pm$ 3.63	2.79	0.85	2.78	1.25
Dome-C (other seasons)	Inner	202.98 $\pm$ 2.39	198.35 $\pm$ 3.61	4.63	0.63	4.63	-0.43
	Middle	203.35 $\pm$ 2.01	199.27 $\pm$ 3.74	4.09	0.47	4.08	-0.31
	Outer	202.06 $\pm$ 1.76	199.05 $\pm$ 3.57	3.03	0.55	3.01	-0.77

Fig. 7. SMOS (bluish solid lines) and Aquarius (reddish dashed lines) T_B variations subtracting the corresponding yearly mean value ($\Delta T_{B_{pol}} = T_{B_{pol}} - \overline{T_{B_{pol}}}$, where the subscript pol indicates the polarization H or V for horizontal and vertical, respectively) over target areas sorted by rows: Amazon rainforest, Sahara desert, South Pacific ocean without OTT applied to SMOS data, South Pacific with OTT applied to SMOS data, and Dome-C in Antarctica. Polarizations are by columns: horizontal (left) and vertical (right). Different beams (inner, middle, and outer) are shown by colors on graduated shading.

elements greatly affecting emissivity, such as the bedrock surface [26] or the presence of subglacial lakes [27].

IV. DISCUSSION AND CONCLUSION

For the first time, there are two satellite missions in orbit with L-band radiometers on-board: SMOS and Aquarius. In this work, an inter-comparison of SMOS T_B versus Aquarius T_B has been performed over four selected targets: 1) the Amazon rainforest, 2) the Sahara desert, 3) the South Pacific Ocean, and 4) the Dome-C zone in Antarctica. Radiometric observations, acquired independently for each instrument, are therefore compared over land, ice, and sea areas, covering a large dynamic range.

This paper differs from the previous works on SMOS and Aquarius comparisons on the use of a 7-day window averaging. The proposed technique allows to do inter-comparison in any latitude and to collect a fair amount of data for robust statistics. The length of the window should be chosen to ensure that T_B

values are preserved when averaging. Both ascending and descending orbits are used. The comparison is based on the analysis of the level of linearity, the correlation, and the differences between SMOS and Aquarius T_B , using daily statistics along the whole year 2012.

Main conclusions of this work are as follows:

- 1) There is a high correlation over land ($R > 0.9$) and it decreases over sea ($R \approx 0.23\text{--}0.68$). Slope values obtained from a robust linear fit are close to 1 over land ($s \approx 0.86\text{--}1.21$) and lower over sea ($s \approx 0.08\text{--}0.37$). Slopes are systematically higher at horizontal than at vertical polarizations. Also, slopes are higher at high incidence angles.
- 2) The Aquarius L2 T_B product has been produced using an ocean model as a reference during its calibration. In this study, an OTT obtained from an ocean model has been applied to SMOS data to reduce the pixel bias existing in the FOV. Results show the inter-comparison is significantly improved over sea when applying the OTT, with

increasing correlation ($R \approx 0.63\text{--}0.80$) and slope values ($s \approx 0.30\text{--}0.42$).

- 3) Aquarius is systematically measuring warmer T_B than SMOS. There is a higher difference over land targets ($\sim 5\text{--}8$ K). This difference decreases over colder targets ($\sim 3\text{--}5$ K over ice, and $\sim 0.1\text{--}0.3$ K over sea, after OTT). This indicates there may be a non-linear effect between the two radiometers, and not only a bias.
- 4) SMOS and Aquarius T_B have similar seasonal cycles over land. Nevertheless, SMOS T_B show higher seasonal variability than Aquarius over sea.
- 5) A seasonal effect is observed in the Dome-C region. The correlation associated to the Austral summer is high ($R \approx 0.74\text{--}0.96$) and it decreases in the other three seasons ($R \approx 0.24\text{--}0.65$). Also, two different slopes are shown in opposite sign (Dome-C Austral summer: $s \approx 0.30\text{--}1.56$, other seasons: $s \approx -0.11$ to -0.77).
- 6) The East Antarctic Plateau, particularly the Dome-C area has been used as a test site for calibrating and validating data of satellite-borne microwave radiometers since the 1970 s [22], [28], [29]. However, the analysis performed in this work evidences some spatial inhomogeneities in this area that can be detected with L-band radiometers, in line with the conclusions achieved in a recent airborne experiment [25]. Consequently, some studies for having a better understanding of Dome-C emissivity at L-band are required before using this area as a calibration target.

Any study using a long term environmental data record that spans multiple L-band missions requires consistent input observations. Results presented on this work are a contribution to understand the differences between SMOS and Aquarius measurements. Also, they could help in deciding future target areas for a vicarious calibration or to validate in a better way the T_B products from both radiometers using *in-situ* measurements of a particular area. These results could also help the definition of the calibration and/or validation of the SMAP radiometer as well.

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