CALIBRATION EFFORTS FOR MWR ON-BOARD SAC-D/AQUARIUS MISSION

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ABSTRACT

The Microwave Radiometer (MWR) on board the SAC-D/Aquarius mission, launched on June 2011, is a Dicke radiometer operating at 23.8 GHz (H-Pol) and 36.5 GHz (H/V/+45/-45-Pol). MWR channels are useful to provide ancillary data for the various retrievals to be performed with Aquarius regarding ocean and land applications. In this study we report the calibration results obtained by a land cross-calibration between Windsat and MWR. Results were generated for the 2011-2012 period and using the version V5.0S of the MWR data. Radiometer inter-comparison over selected homogeneous targets is widely used for calibration assessment and data quality evaluation. The methodology lays on the temporal stability of the selected targets and their homogeneity in terms of brightness temperature (Tb), so that radiometers with similar characteristics (frequency, polarization, incidence angle) should observe the same Tb when passing over the target within a short temporal window. Differences on observed Tbs are associated to a poor calibration of the instrument under study. The cross-calibration is an adjustment of the Tb data of the radiometer under study to match the Tb data of the already calibrated radiometer. In this study, linear adjustments are applied for each MWR beams of its three channels to match Windsat observations. In order to examine the entire dynamic range of land observations, 19 homogeneous targets were selected for cross-calibration. These targets have been previously selected for quality assessment of AMSR-E data [1]. Targets include tropical and boreal forests, desert, grassland and Sahel. Overall, it was found that the instrument compares favorably to Windsat over land targets. Nevertheless, certain issues to be resolved are identified and corrections are proposed.

Index Terms— MWR; Windsat; cross calibration; colocation

1. INTRODUCTION

The Microwave Radiometer (MWR) on board the SAC-D satellite was launched in June 2011 [2]. The SAC-D/Aquarius is a cooperative international mission between CONAE (Comisión Nacional de Actividades Espaciales), Argentina, and NASA, USA. The mission primary goal is to provide weekly global measurements of sea surface salinity (SSS) useful to help understand of both climate change and the global water cycle [3]. Over land, Aquarius provides observations for soil moisture estimation. Soil moisture product developed by USDA [4] is currently available at NASA's web-page [*http://nsidc.org/data/aquarius/*]. The MWR is a push-broom Dicke radiometer operating at 23.8 GHz (H-Pol) and 36.5 GHz (V- & H-Pol) developed by CONAE, on board the SAC-D. It provides simultaneous spatially collocated measurements with Aquarius observations with the objective of supplying ancillary parameters for Aquarius algorithms. MWR channel 36.5 GHz V-Pol observations over land are useful to estimate canopy temperature [5].

Data products quality are highly related to the radiometric accuracy of the system. In general, biases on retrieved geophysical products can be avoided with accurate calibration of radiometric observations. One technique used in previous satellite missions [6], [7], [8], [9] for on-orbit calibration of microwave radiometers is the cross calibration between two similar instruments over homogeneous extended targets. Cross calibration allows to identify, quantify and correct calibration offsets that are stable in both space and time, provided that the instrument used as reference is well calibrated. In this work, MWR cross calibration is performed exploiting the currently on-orbit well-calibrated radiometer Windsat, a Naval Research Laboratory's multi-frequency polarimetric microwave radiometer on board the Coriolis satellite [10]. Coriolis and Aquarius/SAC-D similar orbital and instrument characteristics (see Table 1) simplify the inter-calibration between MWR and Windsat. Moreover, it allows collocation elapse of 90 minutes in the majority of the cases.

Previous cross calibration of both radiometers has been performed by [11]. However, the analysis was particularly focused on ocean targets, and therefore in the lowest part of the dynamic range of the radiometer observations ($Tb < 200K$). Furthermore, ocean targets are not as stable as land targets, hence longer temporal windows can be used when calibrating over land sites. In particular, highly stable land targets were found over the world for their use in cross calibration [1]. Such targets include tropical forests, deserts and land ice. Examination of the brightness temperature (Tb) over these sites and inter-comparison of MWR and Windsat observations in a

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short period of time makes possible the adjustment of MWR Tb to Windsat Tb.

The following sections describe briefly both MWR and Windsat instrument and data. In Section 3, results of the cross calibration are presented and correction coefficients are provided. Finally, the results obtained are summarized and discussed.

2. DATA SETS AND METHODS

2.1. MWR

The MWR instrument consists of two Dicke push-broom radiometers on board the SAC-D satellite. MWR has aft- & fore-looking 8-horns radiometers operating at 23.8 GHz and 36.5 GHz respectively. The 23.8 GHz channel is only horizontally polarized, while the 36.5 GHz channel measures vertical, horizontal, and ± 45 polarized signals. Both radiometers resolution is around 40 km on ground. It has a 7 day revisit period and its primary goal is to provide ancillary information for Aquarius instrument, NASA's instrument on board SAC-D.

The MWR data set used is MWR L1B version 5.0 in both ascending and descending passes for the period from August 2011 to September 2012.

2.2. Windsat

Windsat is a conical scanning radiometer on board the Naval Research Laboratory satellite Coriolis, launched on January 6, 2003. Windsat instrument consists of an 11 feed-horn array operating at five frequencies: 6.8, 10.7, 18.7, 23.8 and 37 GHz. The 10.7, 18.7, and 37.0 GHz channels are fully polarimetric, and 6.8 and 23.8 GHz channels measure vertical and horizontal polarizations. Windsat has a 2-meter spinning reflector that creates fore and aft earth surface measurement swaths approximately 1025 km and 350 km across, respectively. The primary mission of Coriolis is to retrieve wind speed and direction.

The Windsat data set used is HiRes SDR in both ascending and descending passes aft- & fore-looking for the period from August 2011 to September 2012. Data set was provided by the United States Naval Research Laboratory.

2.3. Cross calibration of MWR and Windsat

MWR L1B brightness temperature at 23.8 GHz channel (Tb23H) and 36.5 GHz channel, V-pol (Tb37V) and H-pol (Tb37H), were compared with Windsat Tb at 23.8 GHz and 37 GHz. Each MWR channel was inter-compared with their corresponding Windsat channel in terms of frequency and polarization. Both instruments observations are contrasted only when measurements are collocated over the targets under study. Ideally, collocation between satellites occur when the instruments observe near-simultaneously the same target, with the same viewing geometry and the same spectral responses. Simultaneity is desired so that Tb of the target is precisely identical when both instruments make the measurements. However, these conditions are impossible to occur in reality mainly due to orbital constraints. Therefore, temporal thresholds are defined, e.g., a time tolerance for which target Tb should remain stable.

Table 1. MWR & Windsat Characteristics

	Windsat	**MWR**
Frequency	6.8, 23.8 GHz (VH) 10.7, 18.7, y 37.0 GHz (Polarimetric)	23.8 GHz (H) 36.5 GHz (Polarimetric)
Incidence angle	53°	52° & 58°
Orbit	Sun-synchronous height: 840 km 6 pm ascending time inclination: 98.7° eccentricity: 0.00134	Sun-synchronous height: 657 km 6 pm ascending time inclination: 98.01° eccentricity: 0.0012

Due to MWR and Windsat similar orbital characteristics, most of the collocations occurred within short time windows (less than 2 hours). Moreover, the land targets selected are extremely stable in terms of Tb. Therefore, given the stability of the targets selected and though most of the collocation are expected to occur within 90 minutes, a daily time window was used for operational proposes. Due to the instruments' relatively low spatial resolution and the necessity of calibrating with homogeneous targets, areas spanning hundreds of square kilometers were selected. Regarding corrections for incidence angle, none were applied to MWR nor Windsat Tbs owing to closeness of their incidence angles (52° and 58°; and 53° respectively). This is due to the fact that these small differences in observation angle should have a negligible effect on the measured Tb for most targets.

As a result of the Tbs inter-comparison, a linear adjustment is finally applied to MWR data, customized for each of MWR 8 beams, 3 channels, and for ascending and descending passes. The adjustment is of the form:

$$Tb_{new}^{MWR} = a * Tb_{old}^{MWR} + b \quad (1)$$

This correction of L1B MWR data intents to modify MWR Tb values to match Windsat Tbs.

2.4. Calibration Targets

In order to analyze most of the dynamic range of the instruments, 19 diverse homogeneous sites were selected for the cross calibration. Sites have already been selected by [1] for the evaluation of the AMSR-E data calibration over land. Targets include tropical and boreal forest (dense vegetation), deserts and ice land (bare soil), grasslands and Sahel (low vegetation).

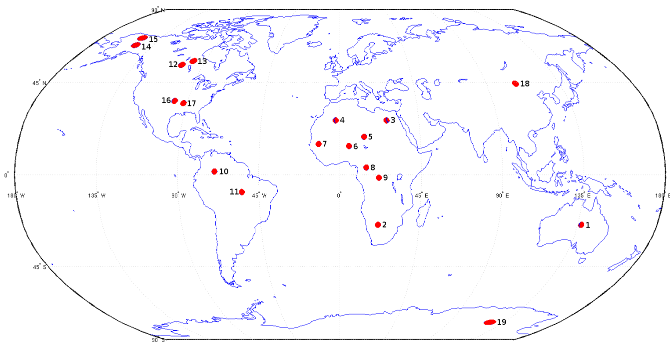


Fig. 1. Location of targets selected for cross calibration (numbers correspond to legend order in Figure 2)

Figure 1 shows a global map with the location of the selected targets and their extent marked in red. A detailed list of the selected targets center coordinates with the corresponding numbering can be found in [1]. In each site, daily mean and standard deviation of Tb23H, Tb37H and Tb37V were computed for each Windsat and MWR beam and channel, for ascending and descending passes separately.

3. RESULTS

3.1. MWR & Windsat Tb Inter-Comparison

In the following sections, results of the MWR and Windsat Tb inter-comparison over the 19 selected targets are presented. Moreover, a summary of all the derived linear coefficients is shown in Table 2.

3.1.1. Tb23H

Figure 2(a) shows mean Tb values observed by MWR and Windsat for ascending (ASC) and descending (DES) passes over the 19 homogeneous targets selected. Plots show that the analysis covers most of the system dynamic range likely to be encountered for land Tb (ranging from $\sim 150K$ to $\sim 290K$). In general, both instruments observations are consistent. Nevertheless, lower MWR Tb23H values exhibit a slightly negative bias. Furthermore, in some particular cases, discrepancies between MWR and Windsat Tb values are significant, specially in the ASC case (dots far from the 1:1 line in the plot). However, such observations presented a high standard deviation, most likely associated to rain events. As a result of previous analysis, a minor correction of MWR Tb23H data is expected, in order to increase Tb values of the lowest part of the MWR dynamic range over land and remove the bias found.

3.1.2. Tb37H

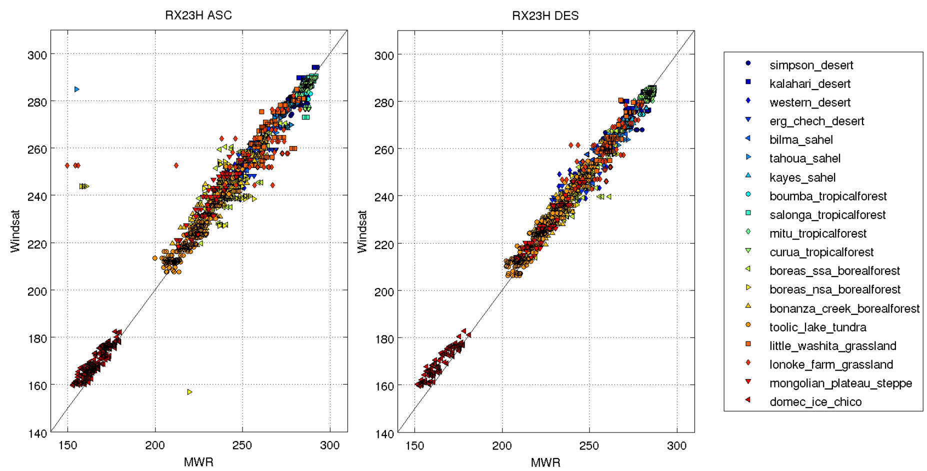
The same previous analysis was performed for Tb37H and results are shown in Figure 2(b). In this case, a significantly bias was found, that increases as Tb rises. The identified bias becomes appreciable for Tbs higher than $\sim 240K$, therefore making it not possible to be noticed on previous cross calibration performed by [11] with emphasis over ocean targets (Tbs between $\sim 130K$ and $\sim 200K$). As MWR Tb37H values are significantly lower than Windsat Tb, linear coefficient “a” on equation (1) for the Tb adjustment is expected to be greater than 1.

3.1.3. Tb37V

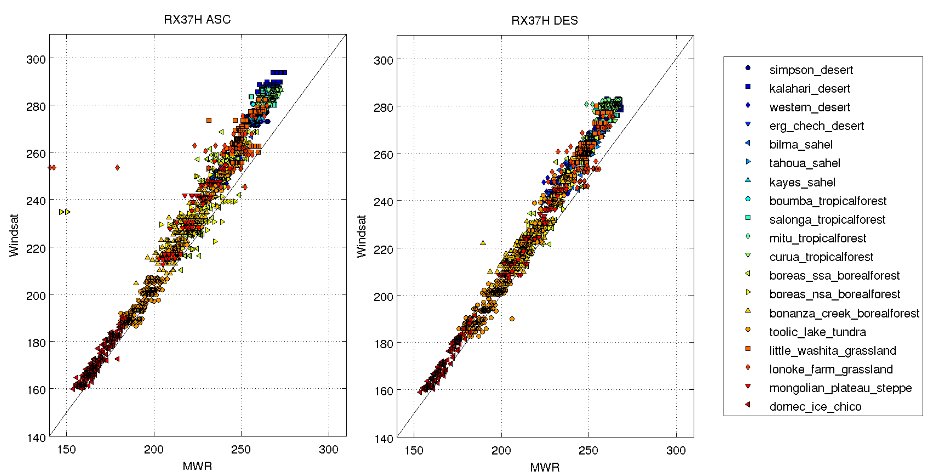
Figure 2(c) shows cross calibration results for Tb37V. MWR Tb exhibits a slight bias. In the cases of high Tb values, MWR observed colder Tb values than Windsat. On the other hand, for low Tb values, MWR overestimates Tb values with respect to Windsat, resulting in a positive bias. Therefore, as the Tb37H situation, “a” values are expected to be greater than 1.

3.2. Residues

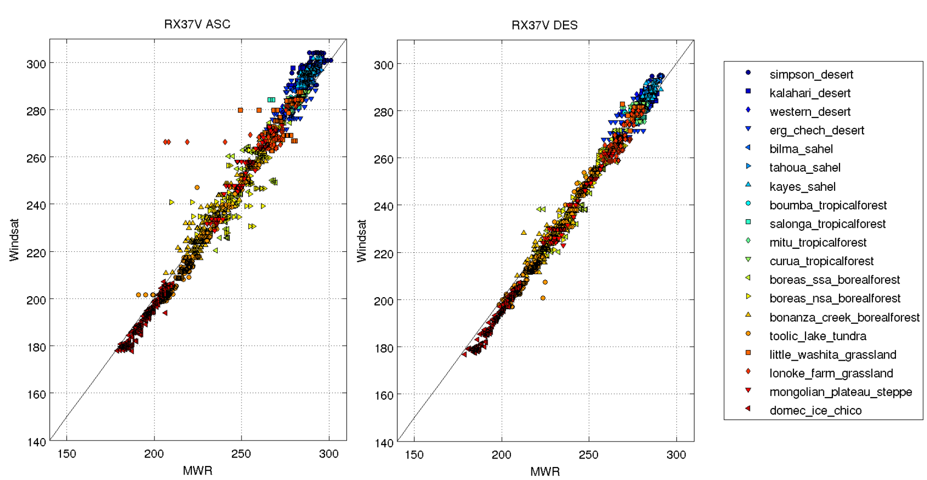
After applying the linear correction to MWR dataset, residues were obtained to check for possible error structure. Residues were calculated as MWR Tb after correction minus Windsat Tb. Results are shown in Figure 3. Density plots of Windsat Tb vs. residues are shown for the three channels and for ASC & DESC passes. Beam results were not isolated due to similar performance. Nevertheless, ascending and descending passes yielded different results. In general, ascending passes exhibit a strong nonlinear distribution (dependent on measured Tb), whereas descending passes do not display such pronounced behavior. Moreover, residues of descending passes have lower standard deviation. In particular, channels 37H & 37V in the ASC case display a negative residue for Windsat Tb higher than $\sim 275K$ and positive residue for lower Windsat Tb. On the other hand, 23H ASC exhibits a similar performance, though the residue sign changes at Windsat Tb $\sim 240K$.



(a)



(b)



(c)

Fig. 2. Cross calibration of Tb23H (a), Tb37H (b) and Tb37V (c) for ascending (ASC) and descending (DES) passes.

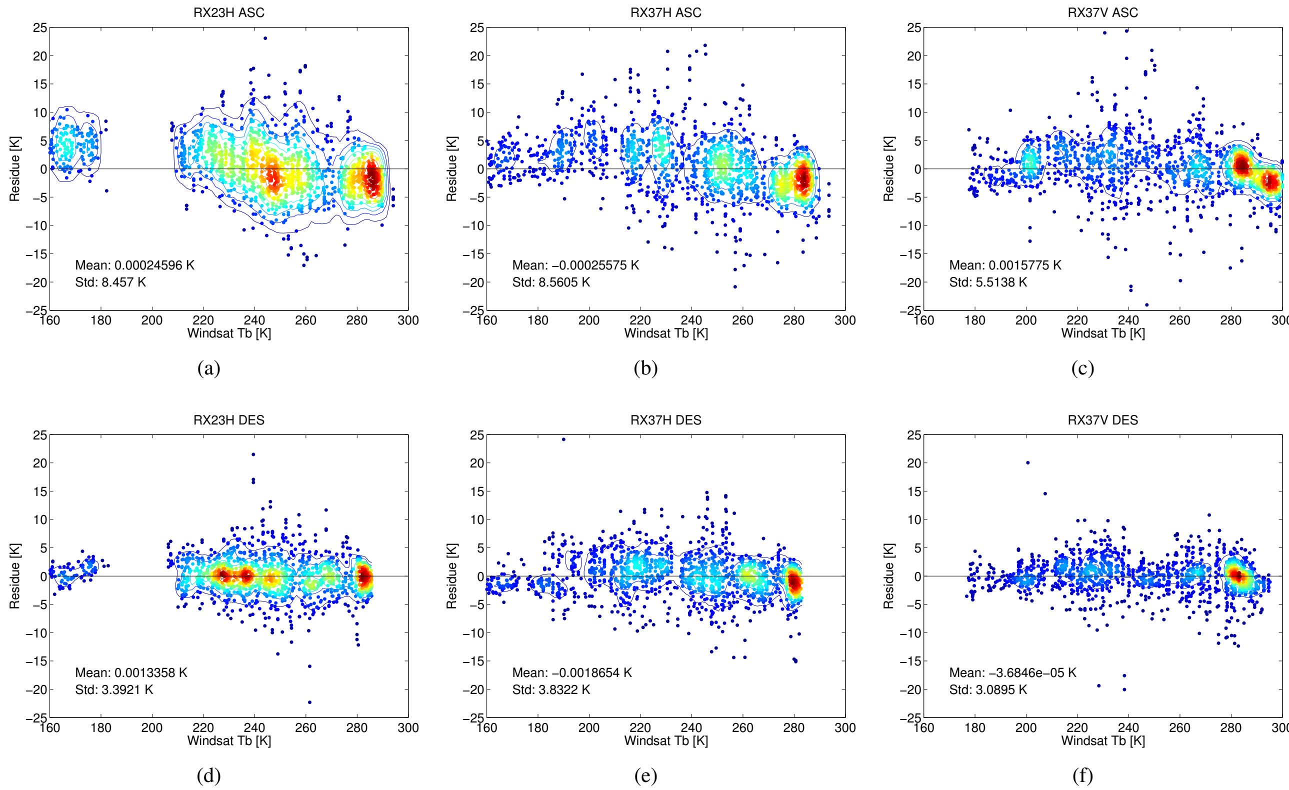


Fig. 3. Density plots of Windsat Tb vs. Residues (*Residue: corrected MWR Tb - Windsat Tb*) for all MWR three channels (RX23H, RX37H & RX37V) for ASC & DESC passes. Reddish (blueish) markers indicate higher (lower) density distribution of values. Contour lines are plotted in black.

4. DISCUSSION

Cross calibration methodology is a useful tool for post launch calibration to identify, quantify and remove relative biases between two instruments. It involves the inter-comparison of collocated observations of two on-orbit instruments. However, calibration accuracy of the monitored instrument depends on the calibration of the reference instrument. In this work, highly confident Windsat Tb [12] was used as a reference data set for calibrating the MWR, CONAE's radiometer on board the SAC-D spacecraft.

Due to selected site's emissivity features and Coriolis and SAC-D orbital characteristics a daily temporal window was used. For the cross calibration, 19 sites were selected as homogeneous stable targets. As seen in Figures 2(a), 2(b) and 2(c), scene Tbs covered most of the dynamic range for the three channels involved in the calibration. Cross calibration revealed and allowed to remove the following artifacts: (i) existence of a slight negative bias at low Tb23H values; (ii) a significant negative bias throughout the Tb37H dynamic range; (iii) a minor bias in Tb37V, positive at lower Tb values and negative at high ones. In all the cases analyzed (Tb23H, Tb37H and Tb37V), higher Tb values were observed for ascending passes compared to descending passes. As a result of the analysis, a linear adjustment of MWR Tb was proposed, and calibration coefficients derived to correct MWR Tbs.

Residues after the correction were analyzed. In general, residue of ASC passes exhibited twice the standard deviation than the one displayed by DESC passes.

Though differences in MWR and Windsat Tb were treated as biases and offsets on MWR radiometric measurements, causes of such biases were not addressed. If relative differences between MWR and Windsat observations are not due to MWR calibration errors, it could be argued that they are related to differences on both instruments spectral response, incidence angle and viewing geometry. In this case, differences arise from the collocation methodology itself, thereby introducing artifacts on the corrected data set. Nevertheless, this does not appear to be the case. First, instrument spectral response of both instruments are very similar. Second, although different, MWR incidence angles present a 1° and 5° difference (below and above Windsat 53°). Both experimental data and theoretical simulations show that this small difference should have a small effect on measured Tb. Third, due to acquisition strategies (conical scanning vs. push-broom) both instruments can present different viewing angles. However, azimuthal dependence of Tb is very low for these large, homogeneous targets. Finally, all targets and MWR beams

Table 2. Linear Correction Coefficients

Channel	Beam	Ascending		Descending	
		a	b	a	b
23H	1	0.98694	3.9108	0.97297	7.8392
	2	0.8565	39.4745	0.89511	27.123
	3	0.96909	8.2212	0.954	10.5932
	4	0.89756	27.5456	0.92963	19.1245
	5	0.90868	23.2777	1.0008	-0.82069
	6	0.86298	36.4253	0.91648	22.6145
	7	0.93469	16.1957	0.96616	8.1175
	8	0.91447	23.7059	0.93869	16.7805
37H	1	1.1219	-19.1177	1.1383	-24.0788
	2	1.1509	-22.7353	1.1039	-13.6748
	3	1.1286	-21.2954	1.1085	-18.5082
	4	1.0671	-1.9863	1.1053	-13.3515
	5	1.1095	-12.191	1.2475	-45.5736
	6	1.0265	6.0777	1.1215	-16.8013
	7	1.1037	-9.9243	1.1743	-26.4572
	8	1.1038	-11.9025	1.1104	-14.2161
37V	1	1.0591	-14.4051	1.0837	-21.1007
	2	1.1021	-26.5787	1.0795	-21.3856
	3	1.1316	-32.0848	1.0935	-23.8659
	4	1.1007	-24.8229	1.0558	-15.4049
	5	1.1273	-28.7053	1.1553	-37.8758
	6	1.0738	-17.9359	1.0727	-19.2004
	7	1.0318	-8.5096	1.0824	-21.367
	8	1.0638	-16.5852	1.0959	-25.1562

displayed consistent results in the linear fit, even for different incidence angles and viewing geometries. Therefore, no systematic bias can be explained only in terms of instrument differences.

5. ACKNOWLEDGMENT

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