Global Soil Moisture From the Aquarius/SAC-D Satellite: Description and Initial Assessment

Rajat Bindlish, Thomas Jackson, Michael Cosh, Tianjie Zhao, and Peggy O'Neill

***Abstract*—Aquarius satellite observations over land offer a new resource for measuring soil moisture from space. Although Aquarius was designed for ocean salinity mapping, our objective in this investigation is to exploit the large amount of land observations that Aquarius acquires and extend the mission scope to include the retrieval of surface soil moisture. The soil moisture retrieval algorithm development focused on using only the radiometer data because of the extensive heritage of passive microwave retrieval of soil moisture. The single channel algorithm (SCA) was implemented using the Aquarius observations to estimate surface soil moisture. Aquarius radiometer observations from three beams (after bias/gain modification) along with the National Centers for Environmental Prediction model forecast surface temperatures were then used to retrieve soil moisture. Ancillary data inputs required for using the SCA are vegetation water content, land surface temperature, and several soil and vegetation parameters based on land cover classes. The resulting global spatial patterns of soil moisture were consistent with the precipitation climatology and with soil moisture from other satellite missions (Advanced Microwave Scanning Radiometer for the Earth Observing System and Soil Moisture Ocean Salinity). Initial assessments were performed using *in situ* observations from the U.S. Department of Agriculture Little Washita and Little River watershed soil moisture networks. Results showed good performance by the algorithm for these land surface conditions for the period of August 2011–June 2013 (rmse $= 0.031\ \mathrm{m^3/m^3}$, Bias $= -0.007\ \mathrm{m^3/m^3}$, and $R = 0.855$). This radiometer-only soil moisture product will serve as a baseline for continuing research on both active and combined passive–active soil moisture algorithms. The products are routinely available through the National Aeronautics and Space Administration data archive at the National Snow and Ice Data Center.**

***Index Terms*—Aquarius, Microwave radiometer, Soil Moisture.**

I. Introduction

Aquarius is an L-band radiometer and scatterometer instrument combination designed to map ocean surface salinity from space [1]. The primary science objective of the Aquarius mission is to monitor the seasonal and interannual variation of the large-scale features of the surface salinity field in the open ocean. In order to achieve its objective, Aquarius sensors must provide very high accuracy salinity estimates, which, in turn, require the highest quality brightness temperatures and backscatter coefficients. This led to an instrument design with a relatively coarse spatial resolution and temporal frequency. This does not meet the primary soil moisture science requirements (10-km soil moisture estimate with a temporal frequency of two to three days) [2].

The Aquarius instrument operates continuously over both land and ocean, and it is well known that L-band sensors can also measure surface soil moisture. The spatial and temporal features of Aquarius (seven-day revisit, ∼100-km resolution) impose some limitations on the range of applications for use of the data; however, producing a soil moisture product will increase the value and impact of the Aquarius mission by including a broader scientific and application community.

The soil moisture retrieval algorithm development focused on using the radiometer data because of the extensive heritage of passive microwave retrieval of soil moisture. The single channel algorithm (SCA) [3] has been applied to observations from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) [4] and Soil Moisture Ocean Salinity (SMOS) [5] data and is also the current baseline approach for the upcoming Soil Moisture Active Passive (SMAP) mission [6].

An initial assessment of the soil moisture product retrieved from Aquarius was done using well-characterized *in situ* observations from two different watershed scale soil moisture networks as well as global soil moisture patterns. The validated radiometer soil moisture product, which is provided through the National Aeronautics and Space Administration (NASA) Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC), will serve as a baseline for continuing research on both active and combined passive–active soil moisture algorithms in addition to its usefulness in a variety of applications as a soil moisture product in its own right.

This research and the new soil moisture product increase the value and impact of the Aquarius mission by including a broader scientific community (land as well as ocean) and will contribute to a better understanding of the Earth's climate and water cycle. In addition, the use of Aquarius observations will contribute to establishing a longer term climate data record of L-band brightness temperature and soil moisture when combined with SMAP [6] and SMOS [7].

II. Description of the Aquarius Instrument

Aquarius is a NASA instrument aboard the Argentine Satelite de Aplicaciones Cientificas-D (SAC-D) spacecraft [1].

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R. Bindlish, T. Jackson, M. Cosh, and T. Zhao are with the Hydrology and Remote Sensing Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, MD 20705 USA.

P. O'Neill is with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

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TABLE I
CHARACTERISTICS OF THE AQUARIUS SATELLITE

Frequencies	1.413 GHz (radiometer), 1.26 GHz (scatterometer)
Polarization	Polarimetric
Sun synchronous orbit	6 PM ascending
Global coverage	7 days
Swath	390 km
Local incidence angles	29.36°, 38.49°, and 46.29°
Spatial resolutions	76 x 94, 84 x 120 and 96 x 156 km
Radiometric calibration (NeDT)	0.06 K (5.76 sec)
Footprint integration time	1.44 sec

Aquarius/SAC-D was placed in a sun-synchronous orbit at an altitude of 657 km on June 10, 2011. Aquarius is a combined L-band radiometer (1.413 GHz) and scatterometer (1.26 GHz). The instrument consists of a 2.5-m reflector antenna with three feedhorns corresponding to three separate beams. The antenna and the feed for each beam are shared by both the radiometer and scatterometer. The local incidence angles of the three beams are 29.36°, 38.49°, and 46.29° with spatial resolutions of 76 × 94, 84 × 120, and 96 × 156 km. These spatial resolutions are a bit coarser than the 40–50 km of other current satellite products (AMSR-E, SMOS, and AMSR2). It has an equatorial overpass time of 6 A.M. (descending orbit) and 6 P.M. (ascending orbit). Aquarius provides global coverage and has an exact repeat cycle of seven days, which is longer than the typical three-day repeat of satellites focused on land surface hydrology. Aquarius started collecting science data on August 25, 2011. A detailed description of the instrument characteristics is provided in Table I. A detailed description about the calibration of the radiometers is available in [8]. Aquarius data version 2.0 from podaac.jpl.nasa.gov was used in this research.

III. EVALUATION OF THE CALIBRATION OF THE AQUARIUS RADIOMETERS OVER LAND

Since Aquarius was designed to measure sea surface salinity, its calibration initially focused on the water brightness temperature (TB) range; we are concerned with the responses over land. It is a challenge to validate TB over land (as opposed to oceans) using models because there are more factors that contribute to the TB signal and the footprints are more heterogeneous. The SMOS mission which has been in operation since 2009 has done considerable work in calibrating their radiometer over water and land. Our approach to this problem is to exploit the availability of L-band TB from the SMOS satellite as part of the strategy for calibrating Aquarius radiometer data over land. This is accomplished by reprocessing concurrent SMOS data to match the incidence angles and sizes of the three Aquarius radiometer footprints. Aquarius and SMOS observations were matched in both space and time (±30 min between overpass times).

Fig. 1 shows the density plot of the comparison between Aquarius (version 2.0) and SMOS (version 5.05) h-polarization (pol) observations at an incidence angle of 38.49° (middle beam) for the period of August 25, 2011–January 31, 2012. Only the alias free portions of the SMOS orbit were used in the comparison. The alias free portions of the orbit provide brightness temperatures with the lowest NeΔT [9]. In addition, we also extracted the equivalent data sets over oceans, which are also plotted in Fig. 1. These combined results provide strong evidence of inconsistencies in the relative calibrations of Aquarius and SMOS over a wide range of targets. The Aquarius brightness temperatures compared well with SMOS observations over oceans. The comparison between Aquarius and SMOS brightness temperatures shows a strong linear relationship, although there is a difference in the calibration of the two sensors for warmer targets. Based upon these results, we concluded that the Aquarius brightness temperatures are biased warmer than the SMOS observations over land. There are bias values of about 8 K for h-pol and 6 K for v-pol observations. This is a large difference that will result in a dry bias in the soil moisture retrievals of 0.04 m^3/m^3, which, when combined with other sources of error, would not meet the target accuracy of the soil moisture retrievals. Based upon these results, an empirical correction was developed for each channel and applied to the Aquarius data to make them match the SMOS responses. Table II shows the regression equations for the empirical correction for each Aquarius channel.

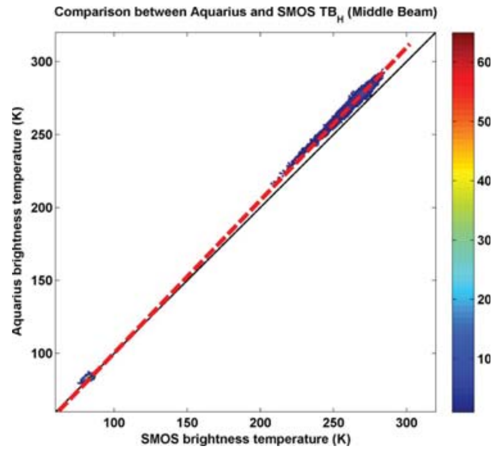

Fig. 1. Density plot of the comparison between Aquarius and SMOS brightness temperature observations for Aquarius middle-beam h-pol. The dashed red line is the regression fit between the Aquarius and SMOS observations and was used to recalibrate the Aquarius observations.

TABLE II
REGRESSION EQUATIONS DERIVED BASED ON THE INTERCOMPARISON BETWEEN AQUARIUS (VERSION 2.0) AND SMOS (VERSION 5.05) BRIGHTNESS TEMPERATURE OBSERVATIONS

Polarization	Beam (Local incidence angle)	Regression equation
H-polarization	Inner (29.36°)	$TB_{Aq} = 1.0436 * TB_{SMOS} - 3.3842$
	Middle (38.49°)	$TB_{Aq} = 1.0403 * TB_{SMOS} - 2.3361$
	Outer (46.29°)	$TB_{Aq} = 1.0391 * TB_{SMOS} - 2.2369$
V-polarization	Inner (29.36°)	$TB_{Aq} = 1.0244 * TB_{SMOS} - 0.6386$
	Middle (38.49°)	$TB_{Aq} = 1.0273 * TB_{SMOS} - 0.2334$
	Outer (46.29°)	$TB_{Aq} = 1.0246 * TB_{SMOS} - 0.6219$

IV. PASSIVE MICROWAVE SOIL MOISTURE ALGORITHM: THE SCA

There are a number of approaches that can be used to retrieve soil moisture from low-frequency passive microwave observations. Almost all of the soil moisture approaches are based on the same radiative transfer equation. Based upon our experiences with the operation and validation of the SCA, we have adopted the SCA as the baseline for Aquarius [10]. This is also the current baseline algorithm for the passive-only SMAP soil moisture product (L2_SM_P) [11].

The SCA is applied to individual Aquarius footprint brightness temperature observations (L2) to produce a swath-based time-order product [10]. A short description of the algorithm is provided hereinafter (more detailed description is provided in [3]). A detailed description of the algorithm, along with the ancillary data sets, is available in [11].

In the SCA approach, brightness temperatures are converted to emissivity using a surrogate for the effective physical temperature of the emitting layer. As implemented here, ancillary surface temperature data from the National Centers for Environmental Prediction (NCEP) Global Forecast System are used to correct for the effective physical temperature of the emitting medium. The derived emissivity is corrected for vegetation in order to estimate soil surface emissivity [10]. Two vegetation parameters are utilized: single scattering albedo and optical depth. A constant value of the single scattering albedo (ω) is used in the Aquarius formulation $(\omega = 0.05)$.

Vegetation optical depth is dependent upon vegetation water content (VWC), a canopy structure coefficient (b), and incidence angle [10]. The baseline algorithm uses a default global constant value of $b = 0.08$ for all vegetation classes. VWC is estimated using a Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index climatology that was based on observations from 2001 to 2010 [12]. As optical depth increases, as a result of increasing VWC, we can expect that the ability to retrieve soil moisture will degrade (error increases). For Aquarius, an upper limit of VWC $= 5$ kg/m^2 is specified. Therefore, soil moisture retrievals are flagged if the estimated VWC exceeds this limit.

Roughness effects must be considered in order to determine the smooth surface soil emissivity. Here, the roughness effects are mitigated using a model described in [13] with a constant roughness parameter (h) of 0.1. The Fresnel equation is then used to determine the dielectric constant of the soil surface (soil–water mixture). This computation is also dependent on the incidence angle. Finally, a dielectric mixing model is used to relate the estimated dielectric constant to the amount of soil moisture (SM). The current formulation of the Aquarius algorithm uses the Wang and Schmugge dielectric mixing model [14].

V. Aquarius Soil Moisture Product and Initial Assessment

The soil moisture retrieval algorithm development focused on using only the radiometer data because of the extensive heritage of passive microwave retrieval of soil moisture. As noted earlier, the calibration of the Aquarius radiometer over the entire dynamic range is a key element for the successful implementation of the soil moisture algorithm. Based upon that analysis, we implemented a correction to the Aquarius brightness temperatures. This involves applying the gain and offsets (Table II) computed using the statistical analyses. The Aquarius brightness temperature observations over the oceans were used as a pivot point to compute the slope and the offset. This is an interim fix and will have to be re-evaluated for future versions of the Aquarius TB data set.

A new aspect to applying the SCA to Aquarius is the consideration of the varying incidence angles of the three beam positions. The SCA, as well as most retrieval algorithms, explicitly incorporates incidence angle in the Fresnel reflection, roughness correction, and the vegetation transmissivity equations. However, the SCA has been applied primarily to conically scanning fixed incidence angle observations. In our preliminary analyses, we evaluated whether or not the algorithm was effectively accounting for angle effects by looking at daily swath coverage for the presence of obvious striping between beam positions. Fig. 2 illustrates an example of this result with the composite soil moisture maps for several months during 2012. Soil moisture estimates from all three beams were used in Fig. 2. The soil moisture map does not show any striping features related to the individual beam positions. Our initial assessment of the performance of the algorithm is that it effectively accounts for angle effects.

Fig. 2 also illustrates the general performance of the SCA for soil moisture retrieval. Arid regions (northern Africa, Middle East, and central Australia) show low soil moisture values. The northern latitudes (northern Canada and northern Russia) show high soil moisture estimates. The effect of the onset of the Indian monsoon can also be seen in the figure. In Africa, a wide band of wet soils that matches the rain belt travels north of the equator in the Southern Hemisphere's winter and then moves south as summer progresses. High soil moisture estimates over central Africa are consistent with the precipitation climatology [15]. Soil moisture estimates are attempted over areas with dense vegetation (Northern Canada, Amazon, and Central Africa) but are flagged during the retrieval process. High soil moisture estimates are consistent with values expected in areas with high precipitation but have not been validated using *in situ* observations. The surface temperature and snow data from NCEP are also used to flag areas with frozen ground or snow on the ground where soil moisture retrievals are not attempted. The spatial patterns of the soil moisture estimates are also consistent with the other satellite missions (SMOS and AMSR-E).

The soil moisture estimates were compared with *in situ* observations from the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) research watersheds that have been used in previous validation campaigns [4], [5]. Validation of satellite-based soil moisture algorithms and products is particularly challenging due to the disparity of spatial scales between the satellite observations and conventional ground-based measurements of soil moisture. Due to the spatial resolution of the Aquarius footprint, only two (Little Washita (LW), OK, USA, and Little River (LR), GA, USA) out of the four USDA watersheds previously used in satellite validation are considered large enough for Aquarius soil moisture validation. A more detailed description of these watersheds is available in [4].

Due to the orbit characteristics, relative size of the Aquarius footprint ($\sim$100 km), and fixed locations of the validation sites, only one of the beams for either ascending/descending orbits will provide adequate coverage for comparison. Aquarius soil moisture estimates were averaged when the beam center passed over the watershed domain. The sampling box of size $0.5^\circ \times 0.5^\circ$ was used for both watersheds. The averaged values were compared to *in situ* observations. The *in situ* data used in this letter are the averages of the sensors located in

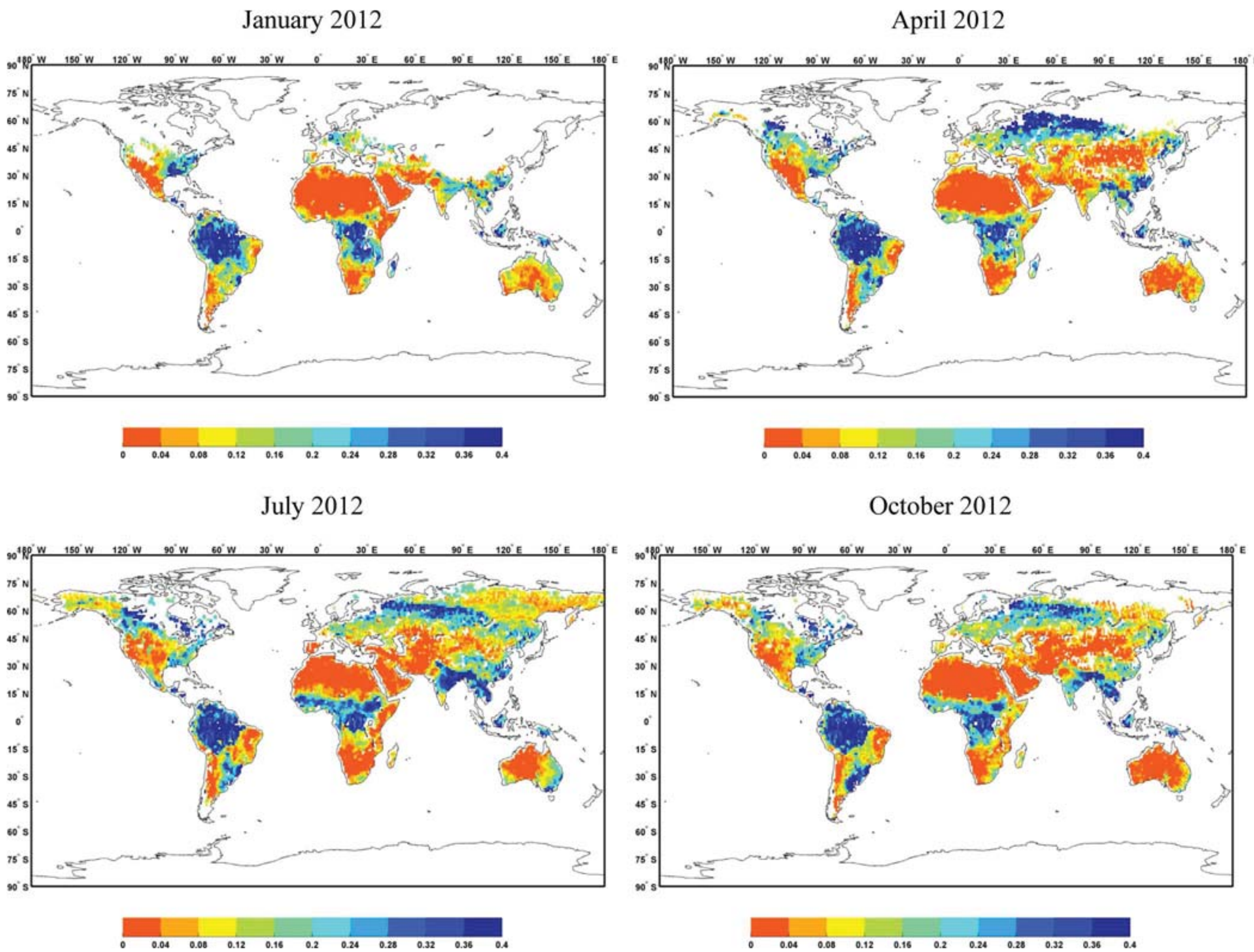

Fig. 2. Aquarius soil moisture estimates for January, April, July, and October months in 2012.

each watershed (with the weighting coefficients derived from a Thiessen polygon).

Fig. 3(a) shows the time series of the *in situ* soil moisture observations, the precipitation observations, and the Aquarius soil moisture estimates for the period of August 1, 2011–June 30, 2013, over the LW watershed. LW has a semihumid subtropical climate, and the vegetation is dominated by rangeland and agriculture (winter wheat). Only the Aquarius outer beam during ascending orbits provides coverage of this site. This results in soil moisture estimates with an exact repeat cycle of seven days. *In situ* observations have a higher temporal resolution and are able to capture the peak soil moisture conditions after precipitation events. Aquarius with a seven-day observation frequency often misses the peak soil moisture conditions immediately after precipitation events. The Aquarius soil moisture estimates are lower during summer and higher during the winter months, which is consistent with the *in situ* observations. In reviewing Fig. 3(a), we observed that the soil moisture estimates are lower than the *in situ* data during spring and fall 2012, which results in a small overall dry bias for the LW watershed (shown in Table III).

Fig. 3(b) shows the LR watershed soil moisture and precipitation time series for August 1, 2011–June 30, 2013. The LR

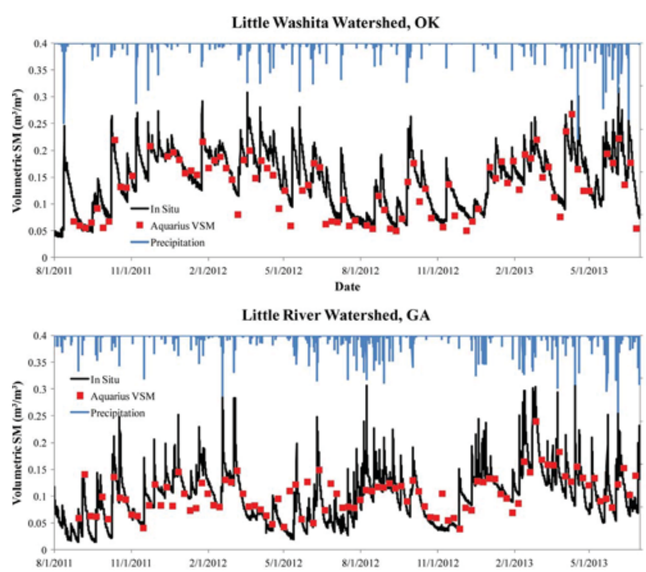

Fig. 3. Time series plots of *in situ* soil moisture observations, Aquarius soil moisture estimates, and observed precipitation for (a) LW and (b) LR watersheds. Only the outer-beam ascending observations pass over the LW watershed, and only the middle-beam descending orbits pass over the LR watershed. The Aquarius soil moisture estimates have a temporal frequency of seven days.

TABLE III
PERFORMANCE STATISTICS OF THE AQUARIUS SOIL MOISTURE ALGORITHM FOR THE LW AND LR WATERSHEDS

Watershed	Number of Days	Bias (m^3/m^3)	RMSE (m^3/m^3)	Correlation Coefficient (R)
Little Washita, Oklahoma (Outer beam, Ascending orbits)	86	-0.018	0.031	0.893
Little River, Georgia (Middle beam, Descending orbits)	96	0.002	0.030	0.823
Overall	**182**	**-0.007**	**0.031**	**0.855**

watershed has a humid subtropical climate, and the vegetation is dominated by agricultural crops (cotton and peanuts) with some forest. For this site, the coverage is from the Aquarius middle beam during descending orbit passes. The very large footprint and a narrow swath width with a seven-day repeat cycle make it difficult to observe drydown cycles with Aquarius observations. The precipitation observations over these watersheds typically have a higher temporal frequency. However, there were two instances for the LR watershed when a large precipitation event was followed by an extended dry period of record. The LR watershed received very little precipitation during March–April 2012 and October–November 2012 periods, and the satellite observations were able to capture these extended drydowns (soil moisture decrease from 0.20 to 0.05 $\mathrm{m^3/m^3}$). Overall, the Aquarius soil moisture estimates were able to capture the precipitation events. The soil moisture estimates show a dynamic range with little bias consistent with the *in situ* observations. The *in situ* observations are made every 30 min.

Fig. 4 is a scatter plot that compares the Aquarius soil moisture estimates and the *in situ* observations from the two USDA ARS watershed for the period of August 2011–June 2013. Table III summarizes the performance statistics. The retrieved soil moisture compares well with the *in situ* observations for both of the watersheds. Results show good performance by the algorithm for these land surface conditions (rmse $= 0.031\ \mathrm{m^3/m^3}$, Bias $= -0.007\ \mathrm{m^3/m^3}$, and $R = 0.855$). Further validation will consist of using additional sites and longer periods of record as they become available.

VI. SUMMARY

The single channel soil moisture retrieval algorithm was implemented using Aquarius observations (version 2.0). The brightness temperatures were recalibrated using an empirical relationship derived from concurrent Aquarius and SMOS observations. The Aquarius team is expected to make changes and improve the warm end calibration. The calibration coefficients will have to be reassessed for future versions of the soil moisture product.

The estimated soil moisture is consistent with the expected climatology and other satellite products (AMSR-E and SMOS). It also compared well with *in situ* observations from the LW and LR watersheds for the period of August 2011–June 2013. The estimated soil moisture was able to capture the dynamic range and the drydown cycles over these watersheds. The soil moisture estimates have low rmse and high correlation

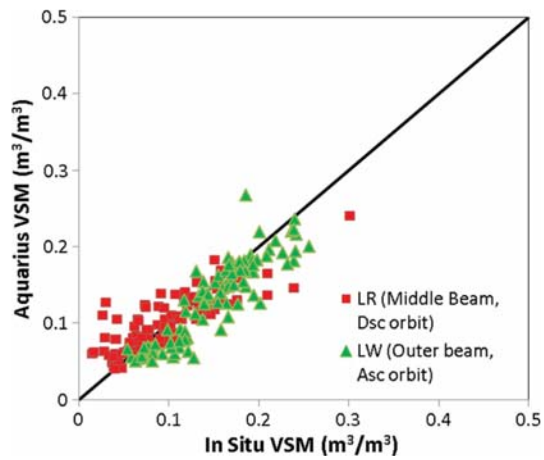

Fig. 4. Comparison between *in situ* observed and Aquarius estimated soil moisture (VSM) for the LR and LW USDA ARS watersheds for the period of August 2011–June 2013.

with *in situ* observations. We intend to expand these initial assessments as additional sites and a longer period of record become available.

We have adopted the same performance standards as the upcoming SMAP mission for Aquarius soil moisture retrievals: soil moisture estimated with an rmse less than 0.04 $\mathrm{m^3/m^3}$ for moderate vegetation canopies (VWC of $\leq 5\ \mathrm{kg/m^2}$). The validated radiometer soil moisture product will serve as a baseline for continuing research on both active and combined passive–active soil moisture algorithms. The Aquarius soil moisture product will add to the soil moisture products from other current (SMOS) and future (SMAP) L-band retrievals. The retrieved soil moisture can be used in studying the climate and water cycle and in a variety of applications of benefit to society. The Aquarius soil moisture products are available from the NASA DAAC at the NSIDC.

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