

Application of a Change Detection Soil Moisture Retrieval Algorithm to Combined, Semi-Concurrent Radiometer and Radar Observations

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Abstract—This paper extends the application of an existing change-detection-based, time-series soil moisture retrieval algorithm to non-concurrent active and passive measurements from WindSat/AMSR2 and the Soil Moisture Active Passive radar, which was active from late April until mid-July on 2015. A time-series of L-band radar backscatter observations was used to populate an under-determined matrix equation whose optimal solution was derived via a bounded linear least squares estimator, and whose bounds were derived from a time-series of radiometer-derived soil moisture estimates (taken by either WindSat or AMSR2). Surface soil moisture estimates are compared with *in-situ* measurement probes, which were treated as ground truth. Error statistics and time-series results for the validation sites are presented here and conclusions derived therefrom. The overall RMSE and un-biased RMSE for the retrieval algorithm, taken across all reference pixels considered in the study, were 0.070 m³/m³ and 0.067 m³/m³ respectively, when using WindSat to constrain the algorithm. When using AMSR2 to constrain the algorithm, the RMSE and un-biased RMSE were 0.093 m³/m³ and 0.090 m³/m³ respectively.

Index Terms—Change detection, data fusion, hydrology, radar, radiometer, remote sensing, retrieval algorithm, soil moisture, time-series.

I. INTRODUCTION

THERE exists a long precedent for using radiometer brightness temperature for surface soil moisture (SSM) remote sensing, particularly at L-band frequencies [1]–[4]. Radar backscatter has also become a popular tool for SSM retrieval algorithms, in part due to the comparatively higher spatial resolution that radar systems can achieve. This study expands on previous work in the domain of combined active/passive (radar/radiometer), approaches to retrieving SSM from vegetated surfaces using space-borne sensors [5]. In particular, this work demonstrates the utility in combining non-simultaneous, frequency-diverse measurements to provide stable, accurate, high-resolution SSM data products.

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In a previous study, it was shown that a radiometer-constrained radar change detection algorithm could be used to combine simultaneous time-series observations from an L-band radiometer and an L-band radar on-board the Soil Moisture Active Passive (SMAP) satellite to form accurate, high-resolution (3 km) SSM products [5] during the SMAP radar's operation from late April until mid-July of 2015. The strength of this algorithm, whose formulation is detailed in the next section, lies in its simplicity: the radar portion of the algorithm does not require any parameter/curve fitting or forward modeling, and the hybrid radar-radiometer algorithm does not require ancillary input data. The lack of forward modeling, curve fitting, or ancillary data requirements indeed differentiates this algorithm from many existing radar-based SSM retrieval techniques [6]–[8]. Accordingly, this study used the same change-detection-based approach to fuse data from the WindSat polarimetric radiometer and Advanced Microwave Scanning Radiometer 2 (AMSR2) sensor suites and the SMAP L-band radar (independent of the SMAP radiometer) to demonstrate that radar and radiometer observations need not be simultaneous in order for the algorithm to achieve accurate results. WindSat and AMSR2 were chosen to constrain the radar algorithm. Although WindSat and AMSR2 retrievals were somewhat less accurate than passive SMAP retrievals for the validation sites considered here, this study has shown that in most cases, WindSat or AMSR2 observations were still good enough to guide the radar retrieval algorithm.

The remainder of the paper is organized as follows. Section II describes the hybrid radar-radiometer SSM retrieval algorithm. Section III displays the error performance of the algorithm for four diverse validation sites, where retrieved SSM is compared with aggregates of *in-situ* probe measurements. Section IV presents the conclusions of this work.

II. ALGORITHM FORMULATION

This section describes the radar- and radiometer-based algorithm for SSM estimation. The radiometer algorithms remain independent of radar observations, and utilize the τ - ω approximation as a forward model to derive SSM from 1) the multi-frequency, polarimetric WindSat radiometer suite [9], [10] and 2) dual-polarized, single frequency measurements (h and v at 6.9 GHz) from the AMSR2 radiometer suite. The radar portion of the algorithm was a time-series change detection approach whose solution space was locally bounded by radiometer-derived lower and upper limits for the SSM.

A. Radar SSM Retrieval Algorithm

The algorithm used in this study is applied to a time-series of 3-km-resolution SMAP L-band radar backscatter observations, and is originally derived from the so-called ‘‘alpha approximation’’ [11]. The alpha approximation is based on the assumption that for a given observed scene, the ratio of consecutively-measured, co-polarized radar backscatter coefficients (measured at times t_1 and t_2) is equivalent to the squared ratio of corresponding alpha coefficients, such that

$$\frac{\sigma_{pp}^{0(t_2)}}{\sigma_{pp}^{0(t_1)}} \approx \left| \frac{\alpha_{pp}^{(t_2)}(\epsilon_s, \theta_i)}{\alpha_{pp}^{(t_1)}(\epsilon_s, \theta_i)} \right|^2, \quad (1)$$

where $\sigma_{pp}^{0(t_i)}$ is the pp -polarized radar backscatter coefficient (in linear units), and $\alpha_{pp}^{(t_i)}$ is the pp -polarized alpha coefficient for the observed scene at time t_i . The alpha coefficient is dependent on the soil permittivity ϵ_s and the incidence angle θ_i according to

$$\begin{aligned} \left| \alpha_{hh}^{(t_i)}(\epsilon_s^{(t_i)}, \theta_i) \right| &= \left| \frac{(\epsilon_s^{(t_i)} - 1)}{(\cos \theta_i + \sqrt{\epsilon_s^{(t_i)} - \sin^2 \theta_i})^2} \right| \\ \left| \alpha_{vv}^{(t_i)}(\epsilon_s^{(t_i)}, \theta_i) \right| &= \left| \frac{(\epsilon_s^{(t_i)} - 1)[\sin^2 \theta_i - \epsilon_s^{(t_i)}(1 + \sin^2 \theta_i)]}{(\epsilon_s^{(t_i)} \cos \theta_i + \sqrt{\epsilon_s^{(t_i)} - \sin^2 \theta_i})^2} \right|. \end{aligned} \quad (2)$$

Note that for a fixed, known incidence angle, the soil permittivity can be directly inverted from (2). In turn, the SSM content for the observed scene can be derived from the soil permittivity via a dielectric mixing model (DMM). The DMM used in this study is the Peplinski-Ulaby-Dobson model [12]. Given a revisit time on the order of days, (1) approximates the surface roughness and vegetation biomass in the observed scene to be the same for times t_1 and t_2 , and further approximates the vegetation contribution as only a multiplicative contribution to the signal scattered from the soil surface [5]. In addition, soil surface roughness contribution is also assumed to be strictly multiplicative, as is the case in first-order analytical rough surface scattering theories such as the Small Perturbation Method and the first-order Small Slope Approximation [13]. Therefore, under the alpha approximation’s assumptions, changes in consecutive radar backscatter measurements at a particular incidence angle for a particular scene can be entirely attributed to changes in SSM content. The hh - and vv -polarized radar backscatter coefficients can be organized into a matrix equation to solve for the unknown alpha coefficients at each element of the time-series, such that

$$\begin{bmatrix} M_{hh} & M_0 \\ M_0 & M_{vv} \end{bmatrix} \begin{bmatrix} |\alpha_{hh}^{(t_1)}| \\ |\alpha_{hh}^{(t_2)}| \\ \vdots \\ |\alpha_{hh}^{(t_N)}| \\ |\alpha_{vv}^{(t_1)}| \\ |\alpha_{vv}^{(t_2)}| \\ \vdots \\ |\alpha_{vv}^{(t_N)}| \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad (3)$$

where M_0 is the zero matrix, N is the number of radar observations in the time-series, and

$$M_{pp} = \begin{bmatrix} 1 & -\sqrt{\frac{\sigma_{pp}^{0(t_1)}}{\sigma_{pp}^{0(t_2)}}} & 0 & \dots & 0 & 0 \\ 0 & 1 & -\sqrt{\frac{\sigma_{pp}^{0(t_2)}}{\sigma_{pp}^{0(t_3)}}} & \dots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 1 & -\sqrt{\frac{\sigma_{pp}^{0(N-1)}}{\sigma_{pp}^{0(N)}}} \end{bmatrix}. \quad (4)$$

Note that the matrix in (3) is a rectangular, $2(N - 1) \times 2N$ matrix, i.e. the matrix equation is underdetermined. A bounded linear least squares regression was therefore applied to solve (3). Previous studies have shown that the alpha approximation algorithm performs poorly when bounded only by extremely dry and extremely wet soil conditions ($0.03 \text{ m}^3/\text{m}^3$ and $0.45 \text{ m}^3/\text{m}^3$ respectively) [5], [11]. Hard bounds for this linear least squares optimization were thus derived from coarser resolution (25 km) WindSat/AMSR2 SSM data products. Solving (4) via bounded linear least squares required the conversion of these minimum and maximum SSM bounds into alpha coefficient bounds. This conversion was performed by first inverting the Peplinski-Ulaby-Dobson DMM (with ancillary soil texture information) to derive relative soil permittivities from SSM values, then using those permittivities to derive alpha coefficients via (2).

B. Radiometer SSM Retrieval Algorithms

The WindSat and AMSR2 SSM retrieval algorithms have each been used to derive local minimum and maximum bounds for SSM over the 84-day time-series containing observations of SMAP L-band radar data. SMAP and WindSat sensor data have been collected from a polar orbit with an average revisit time of three days for the study regions considered here, but these observations seldom share a temporal overlap with each other. For AMSR2’s polar orbit, the average revisit time was two days. The discrepancy between radiometer and radar spatial resolutions was resolved by using the radiometer pixel which whose center point was closest to that of the radar pixel.

WindSat’s land surface algorithm simultaneously retrieves SSM, vegetation water content (VWC) and land surface temperature (T_s) by comparing multi-channel radiometer brightness temperature with a forward model. The AMSR2 algorithm works similarly, but uses a dual-polarized, single-frequency algorithm for each radiometer frequency band to simultaneously derive SSM and vegetation optical depth. The authors have chosen to use the lower C-band (6.9 GHz) channel due to its theoretical capacity to better penetrate foliage. The forward model used for both sensors was the τ - ω approximation, which assumes the surface brightness temperature for p -polarization T'_{Bp} (unmodified by atmospheric

attenuation or scattering) is given by

$$T'_{Bp} = T_s e_{sp} \exp(-\tau_c) + T_s(1 - \omega_p)(1 - \exp(-\tau_c))[1 + r_{sp} \exp(-\tau_c)], \quad (5)$$

where e_{sp} and $r_{sp} = 1 - e_{sp}$ are respectively the soil emissivity and soil reflectivity, ω_p is an empirically-derived parameter accounting for scattering and emission from vegetation, and τ_c is the slant optical depth of the vegetation canopy. The measured brightness temperature T_{Bp} is a modification of T'_{Bp} which accounts for atmospheric effects, such that

$$T_{Bp} = T_{Bu} + \exp(-\tau_a)(T'_{Bp} + r_{sp}T_{Bd}), \quad (6)$$

where T_{Bu} and T_{Bd} are the upwelling and downwelling atmospheric emission and τ_a is the slant atmospheric opacity. The WindSat SSM algorithm uses linear polarimetric data from WindSat's 10.7, 18.7, and 37 GHz channels [9], [10] while the AMSR2 algorithm uses dual-polarized (h and v) data at 6.9 GHz [14].

III. RESULTS AND DISCUSSION

Figures 1 and 2 show the algorithm performance at a representative 3 km reference pixel for each validation site used in this study, with Figure 1 corresponding to the WindSat-bounded algorithm and Figure 2 showing results using AMSR2. The four validation sites, in order of their appearance in Figures 1 and 2, are respectively located in Yanco, New South Wales, Australia [15], Walnut Gulch, Arizona, USA [16], Kenaston, Manitoba, Canada [17], and Fredricksburg, Texas, USA [18]. These validation sites were chosen for their high densities of hydra-probes, making comparisons with 3 km SSM products feasible and meaningful. Measurements for individual *in-situ* dielectric hydra-probes (represented by the thin, dotted-and-dashed curves in Figures 1 and 2) were linearly averaged to form a composite *in-situ* measurement for each 3 km pixel at each validation site (represented by the bold, solid green curves in Figures 1 and 2). This 3 km average provided the baseline against which the retrieval algorithm's SSM estimates (represented by the dark blue circles in Figures 1 and 2) were assessed.

The results in Figure 1 suggest the SMAP-WindSat retrieval algorithm was qualitatively and quantitatively effective over a broad range of observation conditions. Qualitatively, the retrieval algorithm appeared to effectively track day-to-day changes in SSM for each of the validation site reference pixels in Figure 1. The magnitude of the algorithm's bias for volumetric estimates was below $0.04 \text{ m}^3/\text{m}^3$ in each case. For each reference pixel, the RMSE ranges between $0.022 \text{ m}^3/\text{m}^3$ to $0.066 \text{ m}^3/\text{m}^3$ and the R -value (a measure of the correlation between retrieved and measured SSM) above 0.5 for every pixel except the one in Kenaston. Figure 2, which showcases results from the SMAP-AMSR2 algorithm, displays similar performance to the SMAP-WindSat case, but slightly worse results for the Kenaston site. This could be because the AMSR2 algorithm is a single-frequency-channel algorithm whose vegetation optical depth measurements are less reliable than those from a multi-frequency-channel algorithm.

For both WindSat- and AMSR2-derived constraints, the algorithm performance at the Kenaston site was noticeably worse than for the other validation sites, partly due to a number of precipitation events which were not captured by the hydra-probes due to their soil depth. Further discrepancies can be explained by the heterogeneity of the agricultural landscape and its effect on the orbit-to-orbit radar backscatter signal [17], [19]. Each of the instruments observed in this study was conically scanned, and strong scan-to-scan and/or orbit-to-orbit fluctuations due to heterogeneity would certainly introduce significant errors into a change-detection-based retrieval algorithm. The algorithm was shown to display less significant errors from airborne, side-looking SAR measurements taken in a similar environment during the SMAPVEX12 experimental field campaign [5].

Figure 3 shows the overall error performance for each validation site, computed over all 3 km reference pixels at each site. The RMSE for each site was reported within the figure. The overall RMSE for the SMAP-WindSat retrieval algorithm, taken across all reference pixels considered in the study, was $0.070 \text{ m}^3/\text{m}^3$, while the un-biased RMSE was $0.067 \text{ m}^3/\text{m}^3$. For the SMAP-AMSR2 algorithm, the overall RMSE was $0.093 \text{ m}^3/\text{m}^3$ and the un-biased RMSE was $0.090 \text{ m}^3/\text{m}^3$. Examining Figure 3, the larger RMSE for the SMAP-AMSR2 case seems to be driven by the relatively poor performance of the algorithm at the Kenaston site. The Kenaston site shows poorer error performance compared with the remaining validation sites for the aforementioned reasons, with the algorithm tending toward the lower- and upper-limits derived from both WindSat and AMSR2 radiometer estimates.

For reference, the 25 km passive WindSat SSM retrievals are shown as a function of 25 km *in-situ* probe averages in Figure 4 (top). Passive AMSR2 retrievals versus ground truth are shown in Figure 4 (bottom). Note that the TxSON and Yanco sites have proven especially problematic for the WindSat retrievals. Being that 10.7 GHz was the lowest radiometer frequency channel used for the WindSat soil moisture product, topographic effects and vegetation in these areas likely obscured upwelling radiation from the underlying soil surface. L-band microwave frequencies are less sensitive to these conditions, hence the higher sensitivity of SMAP active and passive observations to changes in surface soil moisture. AMSR2 tends to over-estimate soil moisture in both the TxSON and Kenaston study regions, likely due to issues arising from estimating vegetation optical depth using a single-frequency algorithm. Despite their shortcomings in the study regions, WindSat and AMSR2 observations seem generally sufficient to guide the alpha approximation retrieval algorithm toward a fairly accurate solution.

IV. CONCLUSION

This paper has presented an error analysis of a SSM retrieval algorithm that was designed to receive input data in the form of a time-series of polarimetric radar backscatter and radiometer brightness temperature observations. In this study, the algorithm used input data from the SMAP L-band synthetic aperture radar and derived constraints from either

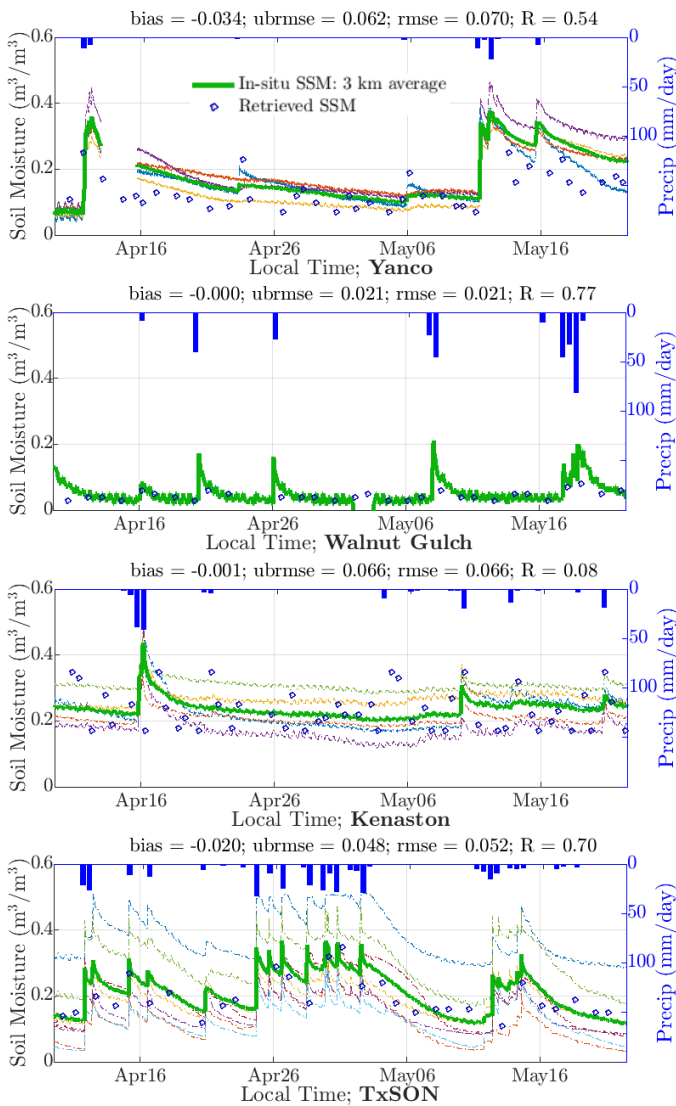


Fig. 1. Time-series data for a representative 3 km reference pixel within each of the four validation sites. Data for individual *in-situ* measurement hydra-probes are shown as thin, dotted-and-dashed lines in each plot. The linear average of probe measurements for each reference pixel is represented by the solid, dark green curves. SSM retrievals using the SMAP radar and WindSat radiometer are plotted as blue circles. The error bias (m^3/m^3), un-biased RMSE (m^3/m^3), RMSE (m^3/m^3), and R -value are reported at the top of each plot. Refer to Figure 4 (top) for information on the constraints derived from WindSat and applied to the SMAP radar data.

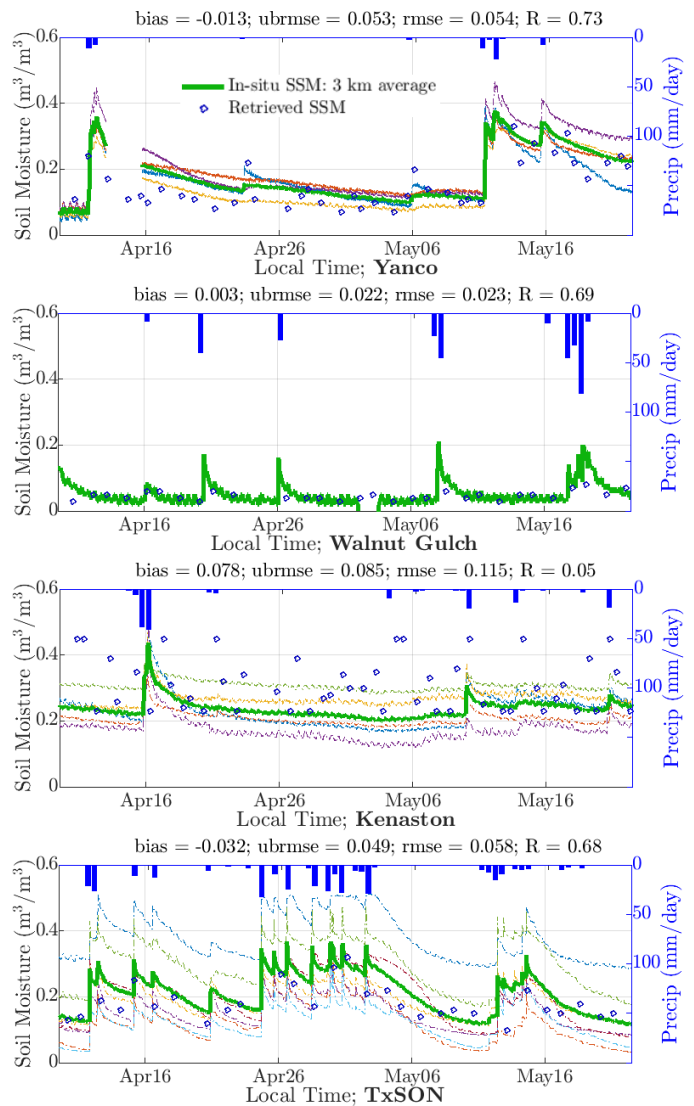


Fig. 2. Same as Figure 1, except the retrievals use the SMAP radar and AMSR2 radiometer, which are plotted as blue circles. The linear average of probe measurements for each reference pixel is represented by the solid, dark green curves. Data for individual *in-situ* measurement hydra-probes are shown as thin, dotted-and-dashed lines. The error bias (m^3/m^3), un-biased RMSE (m^3/m^3), RMSE (m^3/m^3), and R -value are reported at the top of each plot. Refer to Figure 4 (bottom) for information on the constraints derived from AMSR2 and applied to the SMAP radar data.

the WindSat multi-frequency polarimetric radiometer suite or the AMSR2 C-band (6.9 GHz) radiometer channel. The algorithm uses a time-series of ratios between consecutive radar backscatter measurements, cast as a matrix equation and constrained by radiometer-derived lower- and upper-limits to the retrieved SSM. The radiometer retrieval algorithms, which were used to derive these constraints, both utilized a zeroth-order approximation to the radiative transfer equation commonly known as the τ - ω model. The hybrid radar-radiometer retrieval algorithm's performance was assessed against four soil moisture validation sites, consisting of dense *in-situ* networks of hydra-probes. SMAP-WindSat algorithm error performance exhibited an RMSE of $0.070 \text{ m}^3/\text{m}^3$ and an un-biased RMSE of $0.067 \text{ m}^3/\text{m}^3$ across all validation sites.

SMAP-AMSR2 algorithm error performance was found to exhibit an RMSE of $0.093 \text{ m}^3/\text{m}^3$ and an un-biased RMSE of $0.090 \text{ m}^3/\text{m}^3$ across all validation sites. The SMAP-WindSat algorithm error performance is comparable to the SMAP active baseline algorithm in both RMSE and unbiased RMSE [19], though SMAP-AMSR2 is somewhat worse. The methodology described herein achieved reasonable results without the aid of ancillary information or the need for training data, and furthermore demonstrated synergy between disparate and non-simultaneous microwave remote sensing observations.

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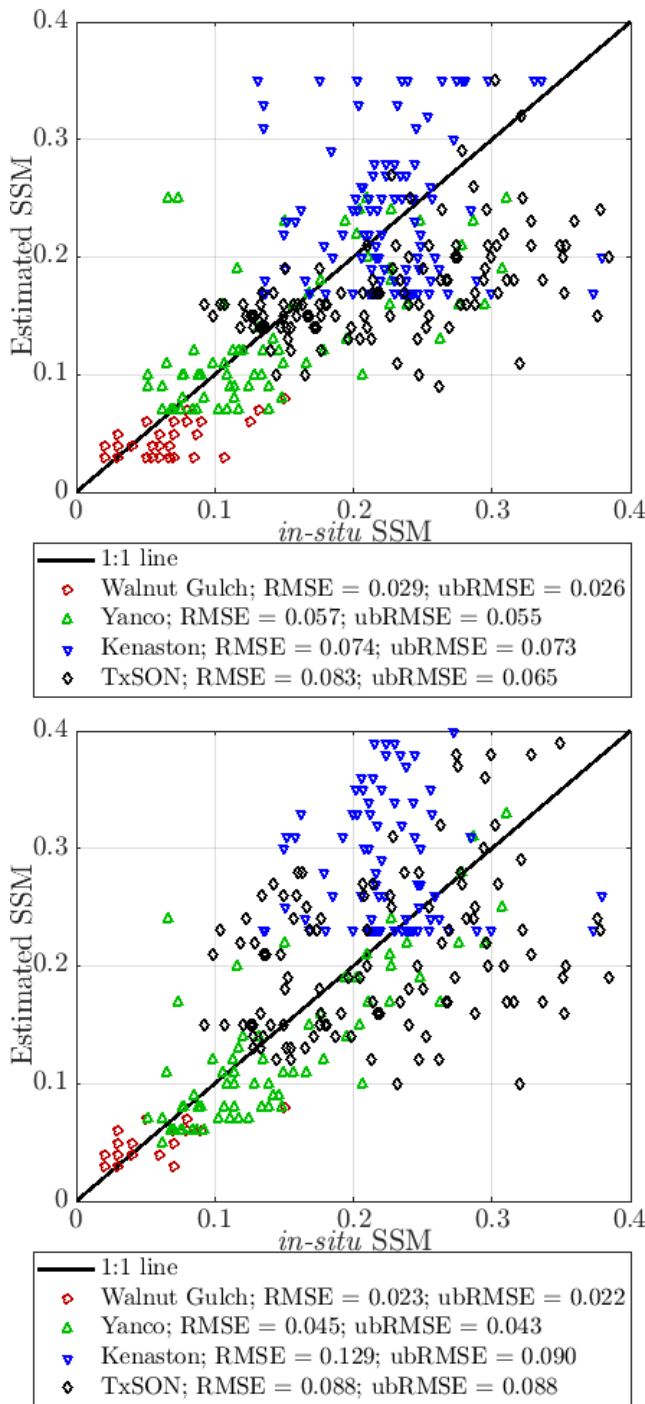


Fig. 3. Active/passive retrieved SSM versus *in-situ* measurements (3 km average) for every 3 km reference pixel within every validation site. RMSE and un-biased RMSE are reported for each site, across all its reference pixels. Top: SMAP/WindSat; bottom: SMAP/AMSR2.

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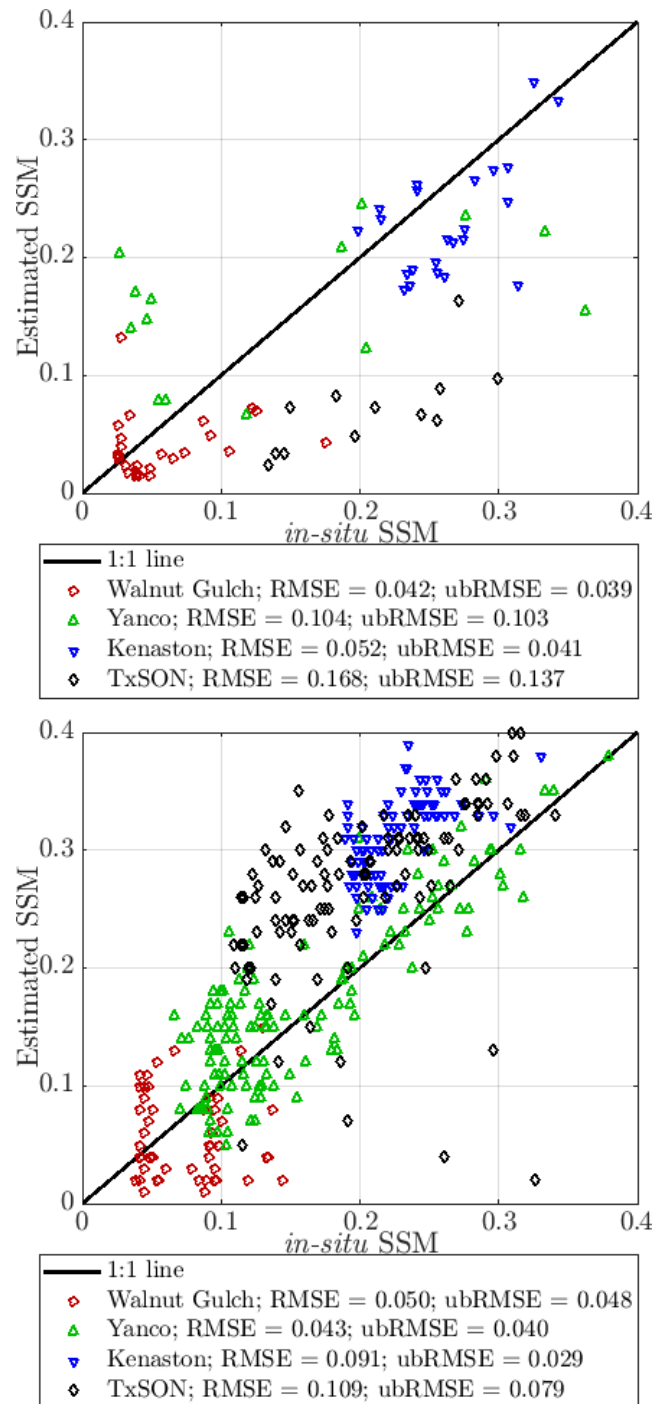


Fig. 4. Passive retrieved SSM versus *in-situ* measurements (25 km average) for every 25 km reference pixel within every validation site. RMSE and un-biased RMSE are reported for each site, across all its reference pixels. Top: WindSat; bottom: AMSR2. Note there are many more AMSR2 measurements than WindSat measurements due to AMSR2 having a slightly higher revisit time and fewer quality control flags.

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