An Assessment of QuikSCAT Ku-Band Scatterometer Data for Soil Moisture Sensitivity

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***Abstract*—The QuikSCAT enhanced (2.225-km) backscattering product is investigated for sensitivity to changes in soil moisture and its potential for spatial disaggregation of Advanced Microwave Scanning Radiometer (AMSR-E) soil moisture. Specifically, an active–passive methodology based on temporal change detection is tested using data from the 2006 National Airborne Field Experiment data set. This campaign was carried out from October 29 to November 20, 2006 in a 60 km $\times$ 40 km area of the Murrumbidgee catchment, southeast Australia. Temporal change detection analysis and accuracy in terms of spatial pattern distribution throughout the domain were assessed using a passive microwave airborne product derived from the Polarimetric L-band Multibeam Radiometer at 1-km spatial resolution. QuikSCAT–AMSR-E intercomparisons indicated higher correlations when using C-band observations. The greatest sensitivity to soil moisture was observed when using V-polarized backscatter measurement. While backscattering data showed adequate temporal sensitivity to changes in soil moisture due to precipitation events, the spatial agreement was complicated by the presence of irrigation and standing water (rice fields). This resulted in low Cramer's Phi values (less than 0.06), which were used as a measure of spatial correspondence in terms of change in soil moisture and backscatter. In addition, the high QuikSCAT sensor frequency and existence of noise in the observed data contributed to the observed discrepancies.**

***Index Terms*—Advanced Microwave Scanning Radiometer (AMSR-E), National Airborne Field Experiment 2006 (NAFE'06), QuikSCAT, soil moisture, temporal change detection.**

I. Introduction

THE CURRENTLY available Advanced Microwave Scanning Radiometer (AMSR-E) and near-future [i.e., Soil Moisture and Ocean Salinity (SMOS)] missions for global soil moisture have limited application due to their low spatial resolution. Consequently, future missions have a specific focus on providing a higher resolution product, and due to technical constraints on the passive microwave radiometer design, there will be a reliance on disaggregation techniques for this purpose. There will be a continued reliance on passive microwave sensors due to their all weather capability and greater accuracy of soil moisture data from these measurements.

To date, most of the disaggregation techniques are based on utilizing supplementary ground information such as soil and topographic [1] or other higher resolution remote sensing data [2]–[5]. Consequently, approaches such as passive–active synergistic techniques are being developed [3], [4]. This approach is also the basis for NASA's next-generation soil moisture mission [i.e., Soil Moisture Active Passive (SMAP)]. The fact that the active sensor response is linked to the same basic soil dielectric properties as the passive measurement allows combining the complementary elements of radiometer and radar derived soil moisture and developing high-resolution soil moisture change estimates suitable for small-scale applications.

In order to prepare algorithms for SMAP, studies that explore and develop the capability for active–passive retrieval and downscaling are required. However, there are no suitable airborne data sets at present, and there are only a limited number of spaceborne active sensors available for such studies. Moreover, there is no active–passive sensor combination currently in space that provide L-band data. Consequently, in this letter, we use the Ku-band QuikSCAT scatterometer, which has been providing global daily sigma-0 (backscattering) observations since 1999 [6], together with the AMSR-E radiometer, which has been providing global radio brightness and derived soil moisture at C-band since 2002 [7]. Specifically, this letter makes an assessment of the QuikSCAT data for use in disaggregation studies. Spatial and temporal sigma-0 evaluation was performed with aircraft soil moisture derived at 1-km resolution from the National Airborne Field Experiment 2006 (NAFE'06) [8], long-term soil moisture station measurements from the OzNet monitoring network in southeastern Australia, and AMSR-E estimated.

II. Data and Watershed Description

The NAFE'06 was undertaken between October 29 and November 30, 2006 in the Murrumbidgee catchment located in southeast Australia. *In situ* soil moisture and aircraft brightness temperature (T_B) data were collected over three areas within the Murrumbidgee catchment: Yanco (3600 km^2), Kyeamba (600 km^2), and Yenda (0.26 km^2); however, based on the availability of aircraft derived soil moisture, the size of each study area relative to our objectives, and the number of repeat flights, only the Yanco area is considered here.

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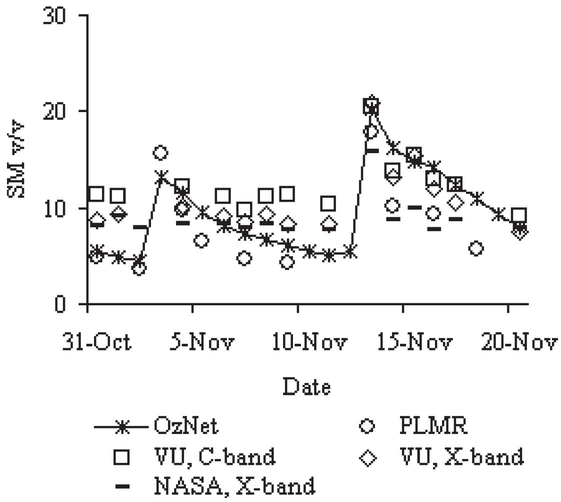

Fig. 1. Spatially averaged AMSR-E, PLMR, and OzNet station soil moisture time series for the duration of the NAFE'06 campaign over the 60 km × 40 km Yanco sampling domain.

The NAFE'06 experiment was specially designed to address important problems in soil moisture remote sensing, such as the development of downscaling techniques for disaggregation of satellite soil moisture estimates, and evaluation of currently available soil moisture retrieval algorithms under the conditions of standing water (rice fields) and extensive irrigation. One-third of the Yanco domain is occupied by the Coleambally Irrigation Area (see [8, Fig. 1]), where the main vegetation types include the following: rice, dry and irrigated wheat and pasture, fallow, and agricultural croplands. The rest of the Yanco area is predominantly covered by rangelands. The irrigation period typically lasts from October until mid-March.

Ground sampling and aircraft mapping were carried out at two different scales over six focus farms in the Yanco area. The Polarimetric L-band Multibeam Radiometer (PLMR) was flown during the campaign [8]. For the soil moisture product used here, PLMR data were acquired in the across-track configuration, measuring T_B data in both H- and V-polarizations with incidence angles of $\pm 7^\circ$, $\pm 21.5^\circ$, and $\pm 38.5^\circ$ across track. We utilized the 1-km PLMR-derived soil moisture product[1] here. Evaluation results are presented and discussed in detail in [8] and [9]. These studies where it is demonstrated that an accuracy of better than 4%v/v was achieved. A complete description of the NAFE'06 experiment and resultant data sets can be found in [8].

Traditionally, *in situ* monitoring, either by means of permanent network stations or controlled soil moisture field campaigns, involves elaborate sampling schemes. The ground conditions (i.e., vegetation, surface roughness, etc.) at the sampling point together with human factors (location accessibility and safety) can result in biased soil moisture values that may not be representative of the study domain. Considering that accuracy assessment is typically carried out using point measured soil moisture, the availability of the PLMR derived soil moisture product allows us to expand the validation over a much larger region, meaning that we can better examine the QuikSCAT ability to capture the soil moisture pattern distribution throughout the domain.

[1]The PLMR product is available via the University of Melbourne at http://www.nafe.unimelb.edu.au/.

Satellite data from the NAFE'06 campaign period include AMSR-E and QuikSCAT. QuikSCAT is a Ku-band scatterometer acquiring sigma-0 measurements at two constant incidence angles (46°, H-pol. and 54.1°, V-pol.) twice a day (0600 and 1800) since 1999. The original QuikSCAT spatial resolution is 22.5 km, but an enhanced resolution product (2.225 km) has been developed by combining multiple orbit passes [10], [11]. AMSR-E is a six-band (6.9–89-GHz) dual-polarization radiometer providing global coverage at 0130 and 1330 local solar time; however, only the lowest two AMSR-E frequencies (with ∼56-km and ∼38-km spatial resolutions at C- and X-bands, respectively) have been shown to contain useful soil moisture information [12]. QuikSCAT sensitivity analysis was conducted using two different AMSR-E soil moisture products (25 km): the official NASA (X-band) product and an alternative product described in [13]. Since no radio frequency interference has been reported over southeast Australia [14], VU offers soil moisture products from both C- and X- AMSR-E bands.

The three remote sensing systems employed in this letter operate at different frequencies ranging from 1.4 to 13.4 GHz, with stronger vegetation impact as frequency increases. In addition, the approximately 6-h overpass difference between AMSR-E and QuikSCAT may result in near-surface soil moisture variations. This time difference will be very important factor in case of a rainfall event. While this was not a problem for this study, a possible solution in the case of operational application is the use of QuikSCAT overpass data that are on the same side of the rainfall event (example both before or both after) as the PLMR/AMSR-E observations. In addition, rainfall occurrence during the imaging period may cause inconsistency in the backscatter measurements which are combined in the resolution enhancement. In order to avoid any uncertainties, the data are used only if the rainfall event is outside the imaging interval. It is important to note that since all the data used for processing the estimated backscatter at one point were from within 5 min of each other, sigma-0 does not exhibit strong variability over the imaging period. This was confirmed by the standard deviation of the averaged counts (available on per pixel basis) which was on average within 1 and 0.95 dB for H- and V-polarizations, respectively. Moreover, the enhanced product is strongly correlated with the original QuikSCAT data (avr. $R > 0.95$), and it exhibits remarkable relative (mean ±0.05) and absolute (mean ±0.1) accuracy. In addition, at constant sensor observation geometry, backscatter variations will be caused by changes in vegetation and/or soil moisture. The temporal change detection approach that we examine here assumes that any change in sigma-0 is primarily due to changes in soil moisture content, as vegetation changes typically occur at much longer time scales.

III. Results and Discussion

Soil moisture analysis will be interpreted here in the context of rainfall and land features present in the area. There were two main dry-down periods as a result of the precipitation events on November 3 (6 mm) and 13 (11 mm). Soil moisture

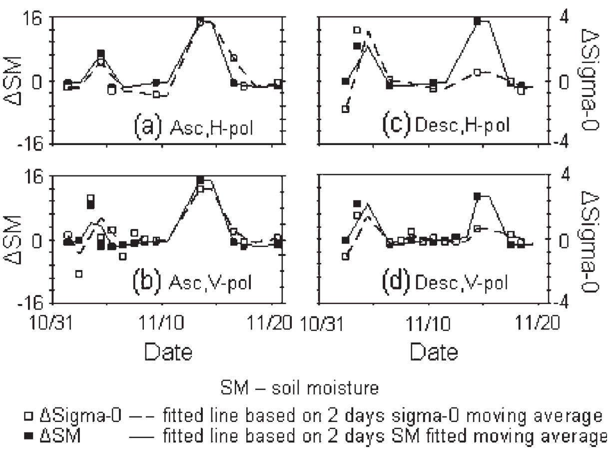

Fig. 2. Time series of the QuikSCAT enhanced Sigma-0 and station soil moisture temporal change detection analyses. The station data were used because of its higher temporal frequency as compared the to AMSR-E and PLMR products. This allowed achieving the maximum number of coincident observations with QuickSCAT overpasses.

TABLE I

CORRELATION COEFFICIENTS (R) BETWEEN THE ENHANCED QUIKSCAT SIGMA-0 PRODUCT AND THREE DIFFERENT SOURCES OF SOIL MOISTURE (PLMR, AMSR-E, AND OZNET STATIONS)

Spearman Correlation	ΔPLMR		ΔOzNet		ΔAMSR-E					
					$NASA_{X\text{-band}}$		$VU_{X\text{-band}}$		$VU_{C\text{-band}}$	
	n	*R*	*n*	*R*	*n*	*R*	*n*	*R*	*n*	*R*
ΔQuikSCATah	3	0.89	10	0.78	7	0.30	7	0.41	7	0.44
ΔQuikSCATav	6	0.75	15	0.79	10	0.32	10	0.94	10	0.96
ΔQuikSCATdh	5	0.86	10	0.60	—		4	0.38	4	0.60
ΔQuikSCATdv	7	0.69	14	0.75	—		9	0.47	9	0.62

NOTE: The notation a, d, h, and v indicate overpass (ascending or descending) and polarization (vertical or horizontal). NASA and VU specify the National Aeronautics and Space Administration and Vrije Universiteit soil moisture products respectively. *n* indicates the number of coincident days of observations used in the analysis. No temporal change detection analyses were performed using the QuikSCAT Enhanced and NASA descending overpasses because the initial inter-comparisons indicated very poor agreement ($R < 0.05$, both polarizations) between the two systems.

rapidly increased during the two rainfall events from 5%v/v to 13.2%v/v and 20.35%v/v (the average measured by the permanent stations), respectively. The PLMR SM maps revealed a fairly uniform distribution of rainfall throughout the domain. The aircraft estimates showed high agreement with the *in situ* data with R^2 values ranging between 0.74 and 0.97, depending on land cover type. The accuracy of the PLMR product was strongly influenced by the irrigation conditions with an rmse of 0.03 v/v over nonirrigated areas as compared to rmse of 0.10 v/v over areas occupied predominantly by irrigated crops. A good agreement in the temporal variability of average soil moisture conditions across the Yanco area was found to exist between the station measurements, PLMR, and AMSR-E (Fig. 1). The NASA derived AMSR-E soil moisture showed the lowest sensitivity to soil moisture with a range of 8%v/v as compared to 15.6%v/v for the OzNet stations, 19%v/v for the VU derived AMSR-E product, and 14.09%v/v for the PLMR product.

AMSR-E NASA and VU soil moisture product accuracies have been extensively studied over Australia [12]; therefore, we will not include any detailed evaluation statistics in this letter. In summary, it was concluded by Draper *et al.* [12] that VU estimates reflect better the station soil moisture than the NASA product and a slightly better C-band performance than at X-band. However, Draper *et al.* [12] notes that the observed discrepancies in performance between VU and NASA products are not caused by the difference in frequency but rather are a result of the different retrieval algorithms (NASA—[7], VU—[15]).

Temporal QuikSCAT sensitivity to soil moisture was evaluated using AMSR-E, PLMR, and *in situ* SM data. A summary of the results using change detection analyses is presented in Fig. 2 and Table I. Because all soil moisture products follow similar wetting and drying trends and are very highly correlated, the OzNet was selected for Fig. 2; moreover, the permanent stations offer continuous data and provide the highest number of matching coincident days between sigma-0 and soil moisture. As can be seen from the time series, delta sigma-0 from both polarizations and orbits responds to the two rainfall events. This is clearly indicated by the significant soil moisture and sigma-0 increase in all four plots. The smaller peak for the descending overpass at the time of the second storm is caused by the observational frequency of the available data. Sigma-0 sensitivity was found to be linearly related to change in soil moisture. Backscatter agreement with the PLMR data was consistently higher than ~0.7. The VU C-band derived soil moisture was better correlated to QuikSCAT than the X-band. In addition, based on the R values listed in Table I, better agreement with change in soil moisture was achieved when using QuikSCAT V-polarized sigma-0 as compared to H-polarized. This is counterintuitive considering that vegetation attenuation is known to be lower and the soil moisture signal is stronger in the H-polarized backscatter signal. The operational AMSR-E product was poorly correlated with the backscatter observations.

Spatial evaluation of the temporal change detection analysis was assessed at two different scales: point (at the network station locations using OzNet data) and regional (extent of Yanco domain using PLMR data). Point scale comparison revealed good agreement, with R values of 0.7 and 0.81 (ascending and descending, respectively) for vertical polarization. Regional spatial comparisons between changes in QuikSCAT sigma-0 and changes in PLMR SM at 2.225-km pixel resolution are shown in Fig. 3. Coincident PLMR–QuikSCAT observations were available for several days (seven to nine depending on polarization and overpass) during the NAFE'06 duration; however, a full QuikSCAT polarization–overpass combination set was available only for November 9 and 13. Fortuitously, the time span depicts a significant change in soil moisture due to the rainfall event on November 13. It is evident that there were no similarities in terms of spatial pattern distribution under the NAFE'06 ground conditions. The Cramer's Phi (ϕ_i) coefficient (same as Cramer's V statistics [16, eq. (8)]) as a measure of resemblance was used to quantify the spatial correspondence between the ΔPLMR SM and ΔQuikSCAT sigma-0. It determines the degree of similarity based on the contingency matrix and ranges between 0 and 1, where 0 indicates no categorical association. Cramer's values ($\phi_{i(\mathrm{asc,h})} = 0.043$, $\phi_{i(\mathrm{asc,v})} = 0.036$, $\phi_{i(\mathrm{desc,h})} = 0.047$, $\phi_{i(\mathrm{desc,v})} = 0.054$) demonstrated poor spatial agreement. It is likely that the lack of high spatial coherence is related to noise level present in the QuikSCAT data enhanced by the irrigation and presence of standing water.

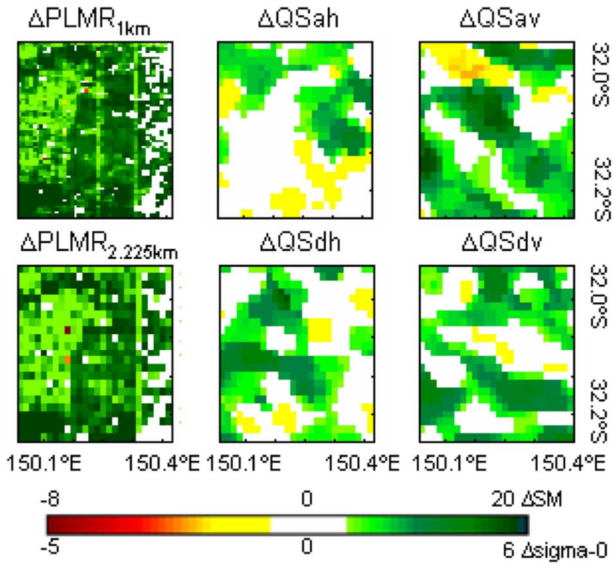

Fig. 3. Change analysis: Change in PLMR derived soil moisture and QuikSCAT sigma-0 from November 9 to 13 QS stands for QuikSCAT, a, d, h, and v indicate overpass (ascending or descending) and polarization (vertical or horizontal).

IV. Conclusion

QuikSCAT was evaluated for its sensitivity to soil moisture over an area characterized by a mix of dryland farming and irrigation agriculture (including standing water in rice fields), using satellite (AMSR-E), aircraft (PLMR), and *in situ* measured soil moisture. While QuikSCAT was found to be reasonably well correlated with the temporal soil moisture variation at regional scale (R values were better than 0.6 for most of the cases) as estimated by all three sources of spatial data, the spatial analysis indicated spatial scale dependence with a higher agreement at point scale (OzNet data set). Comparisons at the station locations produced correlation values greater than 0.7; however, the spatial correspondence across the 60 km $\times$ 40 km area at 2.225-km pixel resolution assessed using the PLMR data set produced Cramer's Phi values of less than 0.06, confirming the poor visual coherence. The high QuikSCAT observational frequency, existence of noise, overpass time difference, and ground conditions in the area contribute to the observed discrepancies.

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