Wheat Canopy Structure and Surface Roughness Effects on Multiangle Observations at L-Band

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***Abstract*—The multiangle observation capability of the Soil Moisture and Ocean Salinity mission is expected to significantly improve the inversion of soil microwave emissions for soil moisture, by enabling the simultaneous retrieval of the vegetation optical depth and other surface parameters. Consequently, this paper investigates the relationship between soil moisture and brightness temperature at multiple incidence angles using airborne L-band data from the National Airborne Field Experiment in Australia in 2005. A forward radio brightness model was used to predict the passive microwave response at a range of incidence angles, given the following inputs: 1) ground-measured soil and vegetation properties and 2) default model parameters for vegetation and roughness characterization. Simulations were made across various dates and locations with wheat cover and evaluated against the available airborne observations. The comparison showed a significant underestimation of the measured brightness temperatures by the model. This discrepancy subsequently led to soil moisture retrieval errors of up to 0.3 m^3/m^3. Further analysis found the following: 1) The roughness value H_R was too low, which was then adjusted as a function of the soil moisture, and 2) the vegetation structure parameters tt_h and tt_v required optimization, yielding new values of $tt_h = 0.2$ and $tt_v = 1.4$ from calibration to a single flight. Testing the optimized parameterization for different moisture conditions and locations found that the root-mean-square simulation error between the forward model predictions and the airborne observations was improved from 31.3 K (26.5 K) to 2.3 K (5.3 K) for wet (dry) soil moisture condition.**

***Index Terms*—L-band Microwave Emission of the Biosphere (L-MEB), microwave radiometry, multiangle, National Airborne Field Experiment (NAFE), Soil Moisture and Ocean Salinity (SMOS).**

I. Introduction

The POTENTIAL of passive microwave systems to monitor surface soil moisture has been extensively studied during the past decades [1]–[7] and is considered as one of the most well-suited techniques. Microwave remote sensing is particularly suitable due to the following: 1) its high sensitivity to the dielectric properties of the soil–water medium, which can be directly related to the water content; 2) the reduced interference with the atmosphere and surface roughness; 3) the low attenuation effects of the vegetation layer; and 4) its all-weather capability. Moreover, at low frequencies, the sampling depth within the soil column is deeper compared to shorter wavelengths. Hence, the protected L-band (~1–2 GHz) with a sampling depth of typically ~5 cm and low sensitivity to canopy and surface roughness is preferred for the purpose of surface soil moisture remote sensing. Consequently, the strong scientific demand for large-scale L-band observations of surface soil moisture data, with a sufficient temporal resolution for application in hydrological, meteorological, and agronomical disciplines [8], has led to the first spaceborne mission specifically dedicated to the monitoring of surface soil moisture.

The Soil Moisture and Ocean Salinity (SMOS) satellite, launched in November 2009 by the European Space Agency, was designed to provide global maps of the surface surface soil moisture fields with an accuracy better than 0.04 m^3/m^3 for the nominal case of bare or low-vegetated soils (nonnominal cases include mountainous and urban areas, frozen or very dry soils, ice, and significant snow-covered surfaces) [9], [10]. Importantly, the satellite's new antenna concept utilizes a 2-D interferometric L-band radiometer to overcome the constraints given by the proportional relationship between the antenna diameter and the resulting spatial resolution, achieving a pixel size of less than 50 km. Moreover, one of the innovative features of SMOS is its capability of multi-incidence-angle observations, which are obtained by the along-track movement of the satellite and the corresponding quasi-simultaneous acquisition of a series of brightness temperatures for a range of incidence angles over the same location on Earth. Previous studies [11]–[13] have shown that there are significant angular signatures on the measured radiometer signal associated with various land surface features and that, in some cases, it is difficult to separate the contribution of the vegetation from the actual soil emission based on single-angle measurements. Thus, by understanding these angular dependences, it has been suggested that model parameters such as vegetation attenuation and surface roughness may be simultaneously estimated, resulting in an enhanced and presumably more accurate surface soil moisture retrieval [14]. Due to the absence of comparable spaceborne observations regarding the novel SMOS configuration, retrieval algorithms such as L-band Microwave Emission of the Biosphere (L-MEB) [15] have been primarily developed and tested prelaunch using

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synthetic simulations [16] and small-scale field experiments (e.g., Surface Monitoring Of the Soil Reservoir EXperiment (SMOSREX) [17], Mediterranean Ecosystem L-band characterisation EXperiment [18], and European campaign with the Salinity Temperature and Roughness Remote Scanner (EuroSTARRS) [19]), with the modeling of incidence angle relationships based on only a subset of the possible land cover types. Consequently, the derived relationships and the model interactions between land surface variables and observed brightness temperature response need to be verified at larger spatial scales and extended for a wider range of land surface conditions.

The objective of this paper is to compare multiangle L-band data from airborne observations with simulated brightness temperatures using the L-MEB model and ground truth data as input. Subsequently, the performance of the forward model parameterization is evaluated based on different surface soil moisture conditions and locations. Alternative parameterizations are also tested, including the following: 1) modifications of the modeled roughness and 2) vegetation structure characterization.

II. Experimental Data Set

The multi-incidence-angle airborne data used in this paper were acquired in November 2005 during the National Airborne Field Experiment (NAFE'05) in southeast Australia. The campaign was conducted over a period of four weeks including a combination of airborne observations and ground measurements. A complete description of the experiment and the data collection strategy is provided in [20], so only the pertinent details are summarized here.

A. Study Area

The field experiment concentrated on the northern part of the Goulburn River catchment (32° S, 150° E) located in New South Wales, Australia. The 40 km $\times$ 40 km study region had been subdivided into two main focus areas: the Merriwa River and Krui River catchments. Across each of these two focus areas, several smaller sites had been selected for intensive airborne and ground operations at farm scale. The multi-incidence-angle flights, which are the emphasis of this study, covered only three out of a total of eight focus farms, being Midlothian, Merriwa Park, and Cullingral (Fig. 1). The observed terrain is fairly flat, with soil types ranging from clay loams to sandy soils [21]. The regional climate can be described as subhumid to temperate with an average annual rainfall of 700 mm and mean maximum annual temperatures of 30 °C in summer and 16 °C in winter. During the campaign period, the focus farms were dominated by grazing lands with native grass cover and cropping land use (mainly wheat, barley, and lucerne).

B. Airborne Multiangle Data

The primary airborne instrument used in the NAFE'05 campaign was the Polarimetric L-band Multibeam Radiometer (PLMR), which operates at a frequency of 1.413 GHz with a bandwidth of 24 MHz. During the field experiment, the L-band radiometer was typically used to measure dual-polarized brightness temperatures in pushbroom mode at six across-track viewing angles $(\pm 7°, \pm 21.5°, \text{and} \pm 38.5°)$. However, for the multiangle data collection used in this study, PLMR was mounted on the aircraft in an along-track configuration, i.e., the instrument was rotated by 90° around its vertical axis, resulting in six along-track viewing angles, three PLMR beams pointing forward and three backward with respect to the flight direction of the aircraft. Consequently, as the aircraft moved along its flight path, this setup provided a minimum of six quasi-simultaneous multi-incidence-angle observations of the same location on Earth with an $\sim 15°$ (3-dB) antenna beamwidth. Due to an aircraft pitch of about 4°, the resulting angles of the six PLMR beams were approximately 3°, 11°, 17°, 26°, 34°, and 43° along track. The nominal flight altitude was about 750 m which corresponds to a spatial resolution of approximately 250 m. In general, an area of 1.5 km $\times$ 6 km was covered by four to five parallel south–north-oriented flight lines at each of the three farms. Dual-polarized multiangle data were acquired in the early afternoon between 12:00 P.M. and 3:00 P.M. on four days (once a week) at Merriwa Park and one day each for Midlothian and Cullingral. Additionally, specific dive flights (i.e., successive steep ascents/descents) were conducted immediately following the multiangle flights over the focus farms in order to provide observations with an even wider range of incidence angles ($\sim 3° - 60°$).

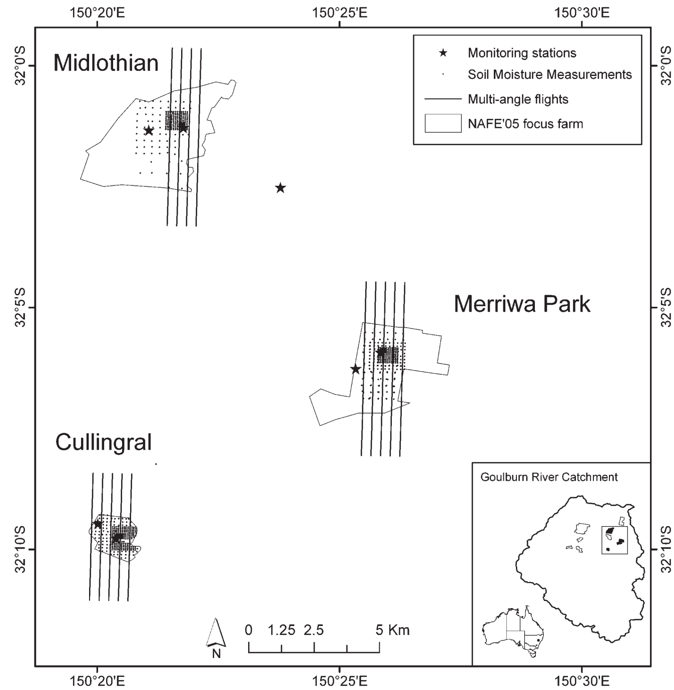

Fig. 1. Locations of the three focus farms covered by multiangle L-band observations in NAFE'05. Overlaid are the flight lines of the aircraft, the location of nearby monitoring stations, and the grid of HDAS surface soil moisture measurements. The high-resolution spatial sampling area of near-surface surface soil moisture (6.25–125 m) is displayed by a cluster of points in contrast to the coarser sampling scale (250–500 m), where each individual sampling location is marked. (Inset) Distribution of all NAFE'05 focus farms within the Goulburn River catchment, located in New South Wales, Australia.

Calibration of the PLMR instrument was carried out on a daily basis before and after the flight using both the sky (cold calibration) and a blackbody box (warm calibration) as target. Supplementary in-flight calibration checks were made through flights over a large water body that was continuously monitored

TABLE I
CHARACTERISTICS OF SELECTED NAFE'05 FOCUS FARMS WITH MULTI-INCIDENCE-ANGLE OBSERVATIONS

SITE	OBSERVATIONS DAYS	LAND COVER	TOPOGRAPHY	SOIL TYPE	SAND CONTENT [%]	CLAY CONTENT [%]	VEGETATION WATER CONTENT[a] MIN-MAX [kg/m^2]	SOIL MOISTURE[a] MIN-MAX [m^3/m^3]
Merriwa Park	4	Native grass + agriculture (wheat)	Gently sloping	Silty clay loam	21	30	0.70 - 3.00	0.10 – 0.50
Cullingral	1	Native grass + agriculture (wheat/barley)	Flat	Silty loam	36	26	0.14 – 0.47	0.03 – 0.09

[a]for area with wheat cover

in terms of surface water temperature and salinity. A detailed description of the complete calibration procedures can be found in [20]. Considering the range of brightness temperature measurements over land during the campaign (150–300 K), the PLMR accuracy was estimated in [20] to be higher than 0.7 K for H-polarization and 2 K for V-polarization. The calibrated radiometer observations have been further processed to provide local incidence angle and effective footprint size information, taking into account ground topography, aircraft position, and attitude. Finally, the data were filtered to eliminate large aircraft yaw and roll angles due to turbulence and strong crosswinds. As a result, sun glint effects in the external beams were also reduced.

C. Ground Data

Extensive ground sampling activities were conducted coincident with the airborne observations, focusing on an area of approximately 1.5 km $\times$ 3.0 km at each farm (see Fig. 1). The measurements of near-surface soil moisture (0–5 cm) were made using the Hydraprobe Data Acquisition System (HDAS) [22], which consists of a Hydraprobe surface soil moisture sensor, a Global Positioning System, and a handheld pocket personal computer that has a geographic information system installed to provide a visual output of the sampling location and the corresponding surface soil moisture observation. The HDAS measurements were typically collected between 9:00 A.M. and 1:30 P.M. over a spatial sampling grid with varying spacing from 6.25 m to 2 km, as shown in Fig. 1. The high-resolution sampling (6.25–12.5 m) was mainly concentrated on an area of 150 m $\times$ 150 m within the cropping fields at Merriwa Park and Cullingral and within a large patch of native grass at Midlothian. The surrounding areas were sampled at coarser spatial scales. The Hydraprobe surface soil moisture output was calibrated against both laboratory data and gravimetric soil samples from the field, resulting in an estimated accuracy of $\pm 0.033\ \mathrm{m}^3/\mathrm{m}^3$ [22]. The gravimetric samples were further analyzed in terms of soil texture and soil properties (Table I). Supplementary data, including land use, surface roughness, rock cover fraction, rock temperature, dew amount, vegetation biomass, and vegetation water content (VWC), were also recorded at each farm site. Long-term surface soil moisture (0–5, 0–30, 30–60, and 60–90 cm), soil temperature (0–5 and 0–30 cm), and rainfall data were available through an existing *in situ* monitoring network [21]. During the campaign, a few stations were temporarily upgraded with additional instrumentation, including thermal infrared sensors, surface soil-temperature profiles (1, 2.5, and 4 cm), and leaf wetness sensors, to determine the presence of dew. Midlothian, Merriwa Park, and Cullingral were each equipped with one permanent and one temporary monitoring station. The latter was always located within the high-resolution surface soil moisture sampling area of the focus farm.

This paper focuses on the use of multi-incidence-angle airborne observations and ground data collected across the cropping fields at Merriwa Park and Cullingral. Both sites were covered by mature wheat, whereas Midlothian was predominantly characterized by native grass and some lucerne. Consequently, data collected across the Midlothian site were not considered in this study. The PLMR observations used herein were selected in such a way that the following holds: 1) they fell in the high-resolution surface soil moisture sampling area, and 2) the individual PLMR footprints were located entirely within the wheat crop. This ensured that homogeneous surface conditions (vegetation type, vegetation state, and topography) were mapped by the different PLMR beams. Table I summarizes the main features of the Merriwa Park and Cullingral study sites, showing an overall dynamic surface soil moisture range of about 0.05–0.55 $\mathrm{m}^3/\mathrm{m}^3$ for Merriwa Park over the entire period. Moist soil conditions were generally observed at the start of the campaign in response to significant rainfall in the area, while toward the end of the field experiment, the topsoil showed substantial drying effects. However, the daily temporal near-surface surface soil moisture variability was found to be negligible within the time period of ground and airborne data acquisition. Cullingral was only covered once with multiangle flights and corresponding *in situ* surface soil moisture measurements during the campaign. The spatial surface soil moisture distribution across Cullingral ranged from 0.05 to 0.25 $\mathrm{m}^3/\mathrm{m}^3$ on the observation day.

III. RADIATIVE TRANSFER MODEL

The radiative transfer model used in this study is the L-MEB model [15], which is the core element of the operational surface soil moisture retrieval algorithm developed for SMOS [23]. A detailed description of the model structure and parameterization is presented in [15], so the following discussion concentrates only on the basic principles of L-MEB.

The presence of vegetation and the resulting interaction with the soil surface emission are described in terms of a simplified (zero-order) solution of the radiative transfer approach, also known as the tau–omega model. This algorithm assumes that the influence of the vegetation layer on the P-polarized soil reflectivity (r_{GP}) is accounted for by vegetation attenuation (γ_P) and scattering effects (ω_P), resulting in a composite brightness temperature (TB_P) as follows:

$$TB_P = (1-\omega_P)(1-\gamma_P)(1+\gamma_P r_{\mathrm{GP}})\cdot T_C + (1-r_{\mathrm{GP}})\gamma_P \cdot T_G \quad (1)$$

TABLE II
PARAMETERIZATION OF THE FORWARD MODELS STUDIED

MODEL ID	ROUGHNESS			VEGETATION				COMMENT
	H_R	N_{Rh}	N_{Rv}	tt_h	tt_v	ω_h	ω_v	
M1_def	0.1	0	0	1	8	0	0	Model with default parameterization proposed by [15]
M2_HR	1.5-1.6·SM[a] 1.6-1.0·SM[b]	0	0	1	8	0	0	Model with H_R=f(SM) parameterization as suggested by [26]
M3_opt	1.5-1.6·SM[a] 1.6-1.0·SM[b]	0	0	0.2	1.4	0	0	Model parameterization includes H_R=f(SM) [26] and optimized vegetation structure values calibrated from multi-angle data from Merriwa Park 09/11/2005

SM: Soil Moisture;
[a]linear roughness function for Merriwa Park; [b]linear roughness function for Cullingral

where T_G and T_C correspond to the effective soil and vegetation temperatures (in kelvins), respectively. The reflectivity of the underlying soil surface is a function of the wave polarization, the observation frequency, and the incidence angle and can be quantified for nonsmooth surfaces by calculating the smooth surface Fresnel reflectivity ($r^*_{\rm GP}$) and adjusting it through the use of a set of soil roughness parameters (i.e., H_R and $N_{\rm RP}$)

$$r_{\rm GP} = r^*_{\rm GP} \cdot \exp\left[-H_R \cos\theta^{(N_{\rm RP})}\right]. \tag{2}$$

Note that $N_{\rm RP}$ is introduced to parameterize the angular dependence of the surface roughness. The attenuation effect caused by the canopy, also referred to as transmissivity, is expressed as a function of the vegetation optical depth (τ_P) and the incidence angle (θ)

$$\gamma_P = \exp[-\tau_R/\cos\theta]. \tag{3}$$

The optical depth given in (3) describes a modified optical depth which considers the canopy contribution in terms of $\tau = \tau_{\rm NAD} \times f(\theta, P)$, with $\tau_{\rm NAD}$ being the nadir estimate of the overall optical depth ($\theta = 0^\circ$), which is independent of both the incidence angle and the polarization. The parameter $\tau_{\rm NAD}$ can be computed as a linear function of the VWC and the empirical parameter b_P, which is mainly dependent on the sensor frequency, polarization, canopy type, and plant structure [24]

$$\tau_{\rm NAD} = VWC \cdot b_P. \tag{4}$$

In order to correct for nonnadir views on the optical depth, particularly with regard to the vegetation structure, i.e., in our case, the dominantly vertical structure of the wheat canopy, two additional specific vegetation structure parameters tt_h and tt_v (h and v denoting horizontal and vertical polarizations, respectively) are introduced that account for the angular effect on the optical depth and, hence, on the vegetation transmissivity

$$\tau_P = \tau_{\rm NAD}(\sin^2\theta \cdot tt_P + \cos^2\theta). \tag{5}$$

Considering a value of $tt_P > 1$ or $tt_P < 1$ results in either an increasing or decreasing trend of the optical depth, respectively, as a function of the incidence angle. The particular case of $tt_v = tt_h = 1$ corresponds to the isotropic state, where the optical depth of the standing canopy is assumed to be independent of both polarization and incidence angle.

IV. MODELING APPROACH AND PARAMETERIZATION

The L-MEB forward model was used to generate dual-polarized brightness temperatures at a range of incidence angles and moisture conditions using the NAFE'05 data described in Section II. The model setup was based on a combination of two types of input fields: 1) ground truth information collected at the focus farms and 2) default model parameters as a function of the land cover class. The available ground data included surface soil moisture, soil texture, bulk density, soil profile temperature, VWC, and vegetation temperature data. The input surface soil moisture was calculated by averaging all high-resolution near-surface ground measurements falling within the same PLMR footprint for each observation day. The total number of HDAS measurements was generally between ~250 and 300 points per observation day and radiometer footprint. Further model input included a special set of parameters for surface roughness and vegetation characterization, i.e., variables H_R and $N_{\rm RP}$ for the soil layer and tt_P, ω_P, and b_P for the wheat canopy (see Table II). These values were sourced from the study in [15], in which the parameters had been calibrated from the PORTOS-93 experiment over wheat at the Avignon test site in France [25]. The parameterization proposed in [15] is hereafter referred to as the "default" parameter set (M1_def). Using the ground data and the default parameterization, brightness temperature estimates were calculated for both H- and V-polarizations and incidence angles ranging from 0° to 50°. The forward simulations were undertaken for all available dates at Merriwa Park and Cullingral with the L-MEB results compared against the actual airborne multi-incidence-angle observations of the corresponding day and test site.

Further to the default model simulations described previously (M1_def), two additional parameter sets were tested based on modifications of the initial model parameterization (Table II). In the second forward model approach (M2_HR), the default parameterization was changed in terms of a single model parameter; the soil roughness value H_R given in [15] was replaced by the surface soil moisture-dependent roughness value proposed in [26] for the same study site. The basis for using a soil roughness value as a function of surface soil moisture is due to a phenomenon known as "dielectric roughness," which contributes to volume scattering of the signal coming from deeper soil layers and is assumed to be caused by a variation of dielectric properties within the soil column due to a nonuniform distribution of the water particles at microscale [27], [28]. Thus, in addition to the spatial variations in the surface height ("geometric roughness"), it has been postulated that the "dielectric roughness" should also be accounted for in terms of an effective H_R parameter. The study in [26] was based on high-resolution (62.5 m) single-angle PLMR data from the NAFE'05 experiment and suggested that the default H_R value in L-MEB was too low for vegetation with dominantly vertical structure such as wheat and barley. Note that Saleh et al. [29] also had to increase the H_R parameter for their studies when using airborne L-band data acquired by the EMIRAD radiometer over

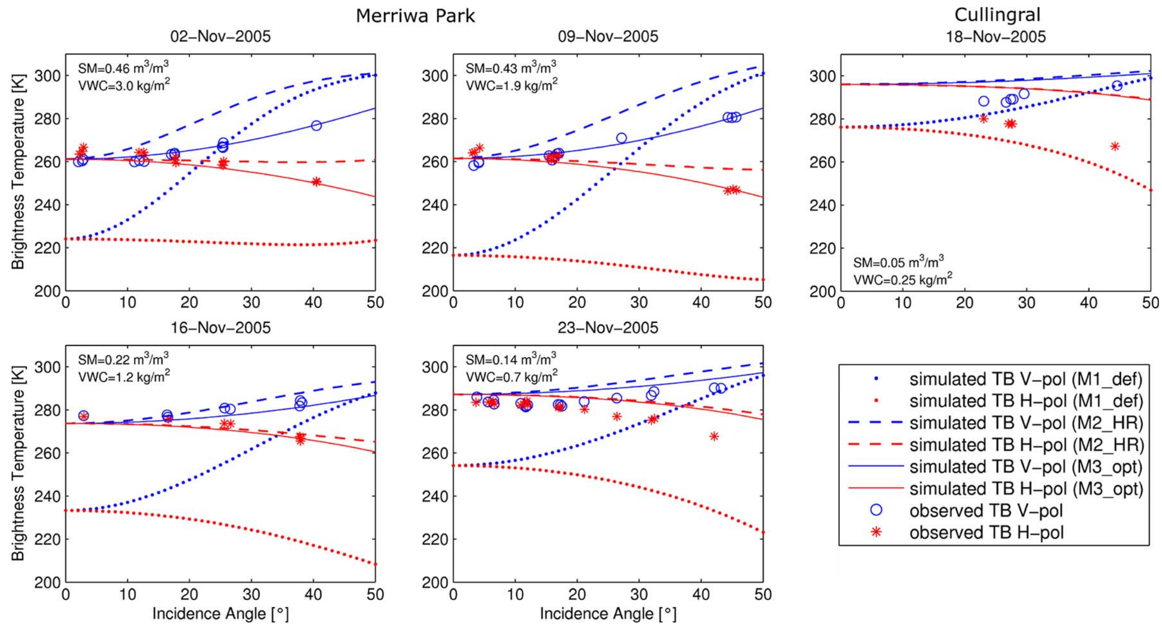

Fig. 2. Dual-polarized brightness temperature estimates plotted against incidence angle and compared to multiangle PLMR observations over wheat canopy for the Merriwa Park and Cullingral study sites. The measured soil moisture (SM) and the VWC are individually displayed for each observation day.

the same test site, suggesting that the higher roughness values were not related to an instrument-specific bias of the PLMR sensor itself. Moreover, Panciera *et al.* [26] found that the calibrated H_R value demonstrated a notable temporal variation which correlated with the observed moisture conditions during the field experiment. These results were consistent with those published in [30] over bare soil at the SMOSREX test site. Hence, Panciera *et al.* [26] developed a simple linear relationship between H_R and the surface soil moisture content for the NAFE'05 test sites, which estimated lower H_R values with increasing moisture content. Considering these results, the second parameterization had been set to include a roughness value specifically calculated for each observation date depending on the corresponding surface soil moisture information of that day. Note that, since this linear function is soil type specific, the defined relationship between roughness effects and surface soil moisture, based on earlier studies [26], is different for Merriwa Park and Cullingral, where the soil texture changes from silty clay loam to silty loam, respectively (see Table I). However, it should be pointed out that recent results in [31] revealed that the approach of an surface soil moisture-dependent roughness function $H_R = f(SM)$ might simply be compensating for a difference in sampling depths of the L-band observations and the ground measurements. Using data from the SMOSREX experimental site in France in 2004 [17], they found that the radiometer response was generally related to a sampling depth of 0–2 cm, with a shallower sampling depth (0–1 cm) for moist conditions.

The current SMOS Level 2 surface soil moisture retrieval algorithms [23] include the sensitivity of surface roughness on surface soil moisture in terms of a simple function, such as that applied in this study. However, the roughness estimation is confined by the field capacity as an upper limit and a transition moisture point as the lower limit, with both parameters being a function of the soil texture (sand/clay content). Above and below these two points, the roughness value is a constant, and the minimum H_R value is expressed by $H_{R\_\mathrm{MIN}} = (2k\sigma)^2$ [32], with k being the wavenumber and σ defined as the surface root-mean-square height. Note the following: 1) the corresponding minimum and maximum H_R values are dependent on the actual land cover type observed, and 2) the maximum H_{R_MAX} parameter is retrieved from the individual SMOS scene.

The third parameter set (M3_opt) included two modifications compared to the default L-MEB parameterization: 1) H_R calculated as a function of the actual surface soil moisture content (as in M2_HR) and 2) calibrated vegetation structure variables $tt_h = 0.2$ and $tt_v = 1.4$ using the available multi-incidence-angle data for one of the four observation days. These new values for the vegetation parameters were estimated through an optimization routine which had been applied to a single flight day over Merriwa Park (November 9, 2005). The calibrated values for tt_h and tt_v corresponded to a decrease $(tt_h < 1)$ and an increase $(tt_v > 1)$, respectively, of the optical depth with the incidence angle at each polarization, which was expected due to the dominantly vertical structure of the wheat canopy. This parameterization was then applied to all remaining observation days at Merriwa Park to assess its performance. Subsequently, the calibrated model variables were further tested on airborne data from Cullingral in order to study their robustness and to verify the parameterization derived from the Merriwa Park study site. The assumption that the remaining vegetation values as proposed in [15] for 1) the vegetation parameter b and 2) the single scattering albedo ω were representative was justified based on the following: 1) a site-specific calibration across the available observation dates that showed no significant variations from $b = 0.08$ and $\omega = 0$ and 2) the fact that the parameterization resulted from an extensive literature review in [15]. Further analysis of the three parameterizations (M1_def, M2_HR, and M3_opt) included iterative inversion of the L-MEB model to solve an optimization problem for the retrieval of surface soil moisture given *a priori* ground truth information. The algorithm was based on a minimized cost function that calculated the quadratic difference between the measured and simulated brightness temperatures.

V. Results and Discussion

The comparison of the L-MEB predicted brightness temperature response with the airborne multiangle observations from Merriwa Park and Cullingral for incidence angles ranging from 0° to 50° showed significant discrepancies depending on the model parameterization chosen (Fig. 2). Using the default L-MEB parameterization (M1_def), the forward model consistently underestimated the multiangle observations at H-polarization, whereas at V-polarization (particularly for large incidence angles and wet soil conditions), the simulated brightness temperatures were much higher than those observed. Furthermore, the incidence-angle-related trends of the dual-polarized observations were only partially captured by the simulation results. Hence, differences of up to ∼40 K in brightness temperatures were observed, particularly within the range of low incidence angles. While this difference decreased for the vertically polarized curve with larger incidence angles, the simulated horizontal brightness temperatures were always lower than the measured data. Note that, for wet conditions at Merriwa Park during the first two observation days, the simulated horizontally polarized curve is relatively flat due to the high VWC and the corresponding large value for the optical depth. The explanation behind this trend is that both the attenuation of the soil emission and the emission by the wheat canopy itself increased, causing the effective composite brightness temperature of both media to be closer to the effective temperature of the vegetation. Therefore, with larger incidence angles, the attenuation of the vegetation increased with respect to the $1/\cos(\theta)$ relationship, as shown in (3). Setting a default value of one for tt_h further assumes that there are no significant angular dependencies across the observed wheat canopy at H-polarization. The comparison of the predicted and observed brightness temperatures across the four observation days at Merriwa Park produced a root-mean-square error (rmse) ranging from $rmse_{\mathrm{def}} = 38$ K to $rmse_{\mathrm{def}} = 26$ K for wet and dry conditions, respectively (Fig. 3), when using the default parameters.

The overall model performance was improved by introducing the surface soil moisture-dependent roughness value H_R (M2_HR) from the site-specific calibration presented in [26]. Consequently, an upward translation of the modeled brightness temperature curves was achieved, resulting in a closer agreement with the observations. The corresponding rmses for the Merriwa Park site ranged from $rmse_{\mathrm{HR}} = 9.6$ K (wet) to $rmse_{\mathrm{HR}} = 2.9$ K (dry) and were thus significantly reduced compared to the default model parameterization output. However, the simulated angular behavior was still unable to capture the observed brightness temperature trend exhibited at large incidence angles ($> 25°$), which was particularly dominant for moist conditions at Merriwa Park at the start of the campaign. Moreover, for relatively low moisture contents ($< 0.1\ \mathrm{m}^3/\mathrm{m}^3$), the curve shift forced by the moisture-dependent adjusted roughness value toward higher brightness temperatures was too strong. Hence, the predicted emissions tended to overestimate the brightness temperature measurements, particularly for dry conditions.

A site-specific calibration of H_R based on the multiangle observations available for Merriwa Park (results not shown) demonstrated a nonlinear relationship between surface soil moisture and surface roughness. Specifically, the calibration

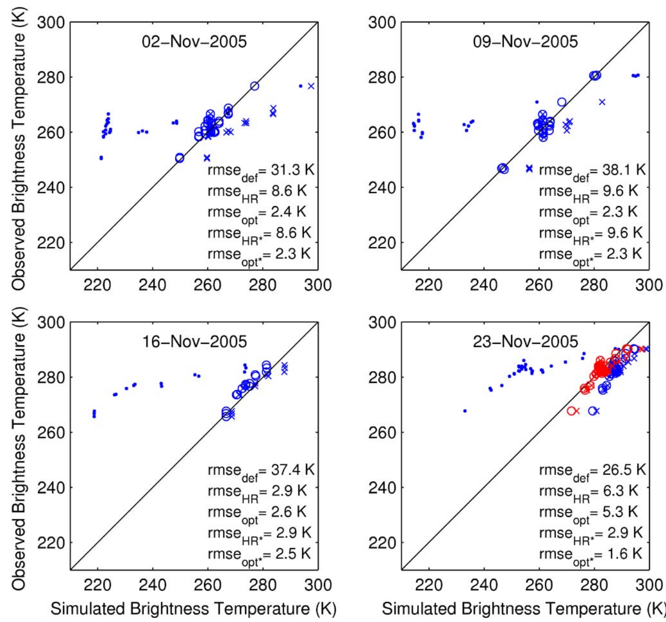

Fig. 3. Scatterplot of the L-MEB model simulations in comparison with independent ground data from Merriwa Park on different observation dates using (dots) the default model parameterization "M1_def" [15], (crosses) the site-specific roughness parameterization "M2_HR" [26], and (circles) the optimized model parameterization "M3_opt." Additionally, results based on a nonlinear daily-optimized $H_R^* = f(SM)$ approach are shown in red for days where model predictions were improved by more than 0.1 K compared to "M2_HR" and "M3_opt" results. The rmse calculated between the observed and simulated brightness temperatures is given for all model approaches on all days.

showed the following: 1) a positive correlation between the surface roughness parameter H_R and surface soil moisture for dry conditions, resulting in small H_R values for dry soil, and 2) a negative trend for surface soil moisture values of $\sim 0.20\ \mathrm{m}^3/\mathrm{m}^3$ or higher by decreasing the roughness effect with increasing moisture content. These findings also agreed with the results published in [33] which investigated the impact of surface soil moisture on surface roughness using single-angle NAFE'05 data. In that study, the decrease of the roughness effect for low surface soil moisture was associated with a reduced dielectric heterogeneity at microscale during the drying process of the clay loam soils that dominate the study area. That is, the microscale variability and, thus, the dielectric roughness peaked at intermediate surface soil moisture content and decreased toward very wet or very dry conditions. Applying a reduced roughness parameter optimized for dry conditions produced better results, as shown in red in Fig. 3 for November 23, 2005.

The L-MEB parameterization of the third model (M3_opt) with optimized H_R and tt_P parameters showed the overall best agreement with the airborne data considering the following: 1) the linear $H_R = f(SM)$ approach, i.e., $rmse_{\mathrm{opt}} = 2.3$–$5.3$ K, and 2) the nonlinear $H_R = f(SM)$ approach, i.e., $rmse^*_{\mathrm{opt}} = 1.6$–$2.6$ K. Moreover, the angular trend of the predicted dual-polarization curves captured that of the measured data for both moist and dry surface soil moisture conditions. Compared to the default parameterization and the high tt_v value of eight obtained for the vertically dominated wheat canopy [15], the vegetation structure parameters calibrated and tested in this study were significantly lower and closer to unity (∼1) (see Table II). However, it should be noted that an individual calibration of the tt_P parameters for each single day suggested

TABLE III
COMPARISON OF GROUND-MEASURED SURFACE SOIL MOISTURE (STANDARD DEVIATION IN BRACKETS) WITH SURFACE SOIL MOISTURE VALUES RETRIEVED USING DIFFERENT SURFACE ROUGHNESSES AND VEGETATION STRUCTURE PARAMETERIZATIONS

Location	Date	HDAS SM (std) [m^3/m^3]	Model M1_def SM retrieved [m^3/m^3]	Model M2_HR SM retrieved [m^3/m^3]	Model M3_opt SM retrieved [m^3/m^3]
Merriwa Park	02-Nov-2005	0.46 (0.04)	0.18	0.55	0.44
Merriwa Park	09-Nov-2005	0.43 (0.06)	0.15	0.50	0.42
Merriwa Park	16-Nov-2005	0.22 (0.07)	0.05	0.21	0.19
Merriwa Park	23-Nov-2005	0.14 (0.05)	0.04	0.22 / 0.14*	0.20 / 0.14*
Cullingral	18-Nov-2005	0.05 (0.02)	0.03	0.30 / 0.05*	0.27 / 0.05*

SM: Soil Moisture
*Soil moisture retrieved using a non-linear, daily-optimized H_R=*f*(SM) approach

a value of $tt_v = 3$ in one case, but overall, only minor variations across the different dates were observed. Consequently, the calibrated vegetation structure parameters from November 9, 2005, were validated on different moisture conditions and locations (Cullingral), confirming the good results obtained using this particular parameterization. Note that further analysis (not shown) using the estimated tt_P values individually calibrated for each observation day, instead of the values retrieved from November 9, demonstrated only a minor improvement of the model rmse performance (0.3 K at most).

Overall, the results presented in this paper revealed that the adjustment of both angular correction parameters, based on the Merriwa Park November 9 data, had a more significant impact on the predicted brightness temperatures, when the ground-measured VWC was high (> 1.9 kg/m^2), and thus, the attenuation effects of the canopy and its own contribution to the composite brightness temperature were increased as well. Consequently, both structure parameters play a major role, particularly for large incidence angles ($> 30^\circ$) where the path length of the emitted energy through the vegetation layer is longer.

Using the available ground information (soil texture, soil temperature, VWC, etc.), together with the individual model parameterization (M1–M3; see Table II), the inverse problem was solved for surface soil moisture and compared to the HDAS measurements (Table III). The surface soil moisture retrieval based on an iterative least squared algorithm resulted in a range of surface soil moisture values per observation day depending on the model parameterizations chosen (Fig. 4). The default parameterization (M1_def) generally produced too low surface soil moisture values with a maximum difference of $\sim$0.3 $\mathrm{m}^3/\mathrm{m}^3$, when compared against the measured surface soil moisture at Merriwa Park. The overall best results for this site ($\leq 0.06\mathrm{m}^3/\mathrm{m}^3$ difference from observations) to the observed moisture conditions were achieved using the optimized set of parameters, which included the surface soil moisture-dependent roughness value H_R and the calibrated vegetation structure values tt_P (M3_opt). The results for Cullingral, where it was dry (0.05 $\mathrm{m}^3/\mathrm{m}^3$) on the day of observation, demonstrated that the default parameterization (M1_def) works well for this condition. However, the surface soil moisture retrieval was further improved by optimizing the surface roughness parameter H_R. Due to the relatively low VWC $\sim$0.25 kg/m^2 measured at the Cullingral site, the effect of the vegetation structure parameters was minor considering these extremely dry soil conditions.

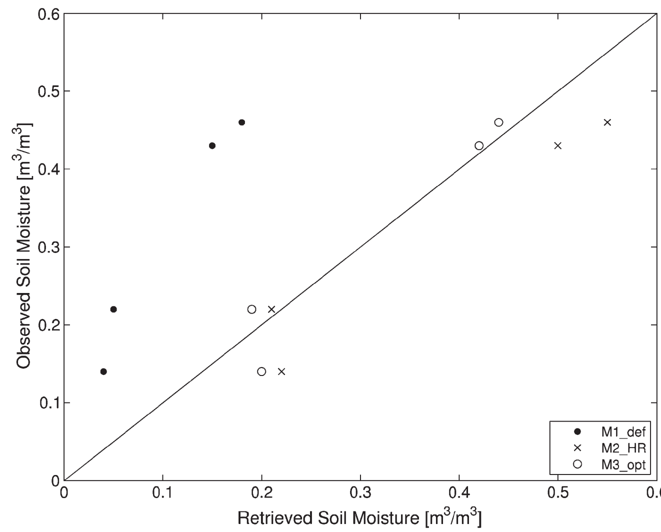

Fig. 4. Scatterplot showing the retrieved against measured surface soil moisture values at the Merriwa Park focus farm for the four available observation days. The inverse application of the L-MEB model was made for all model parameterizations discussed in Section IV.

VI. CONCLUSION

This paper has presented simulations of brightness temperatures at a range of incidence angles and the subsequent comparison with multi-incidence-angle airborne observations over two wheat canopy test sites in eastern Australia. The forward model used in this research was the L-MEB model which is one of the core elements of the SMOS surface soil moisture retrieval algorithm. Apart from the default model parameterization proposed in [15], two additional parameterizations were studied, including modifications of the surface roughness and vegetation structure characterization. The performance of the individual model approach was assessed based not only on changing moisture conditions but also on different locations in order to test its robustness. The agreement of the predicted and measured brightness temperature data from different forward model parameterizations varied significantly, with the observed discrepancy being much larger for wet conditions than for dry surface soil moisture values. However, compared to results using the default model parameterization, a stepwise improvement was achieved, first, by introducing a surface soil moisture-dependent roughness factor and, second, by retrieving new values for the vegetation structure parameters of wheat canopy ($tt_h = 0.2$ and $tt_v = 1.4$). Consequently, the dual-polarized brightness temperature predictions were improved by minimizing the rmse on November 2 from $rmse_{\mathrm{def}} = 38.1$ K to $rmse_{\mathrm{opt}} = 2.3$ K for wet soil conditions ($\sim$0.46 $\mathrm{m}^3/\mathrm{m}^3$) and from $rmse_{\mathrm{def}} = 26.5$ K to $rmse_{\mathrm{opt}} = 5.3$ K for dry soils ($\sim$0.14 $\mathrm{m}^3/\mathrm{m}^3$) on November 23.

This study confirms that neglecting the sensitivity of the surface roughness parameter H_R on surface soil moisture leads to a significant underestimation of the soil emission at L-band, which would consequently affect the overall surface soil moisture retrieval accuracy. However, it should be noted that the use of an surface soil moisture-dependent roughness value might mask the issue of incorrect sampling depths for comparison with the L-band radiometer [31]. Furthermore, it was shown that the transmissivity of a dominantly vertical canopy structure and the angular dependence of the optical depth should not be neglected for VWCs of > 1.9 kg/m^2 and wet soil conditions (> 0.4 m^3/m^3); otherwise, the error introduced into the retrieved surface soil moisture product for the given data set could be up to 0.3 m^3/m^3. Considering the spatial resolution of SMOS observations and a footprint size of approximately 42 km, which captures a mixture of land cover types, the angular effect of the various vegetation types and structures might be intensified, particularly for conditions of high VWC, causing additional errors in the SMOS surface soil moisture retrieval if not accurately accounted for. However, this issue needs to be investigated in future research to understand the impact of the angular vegetation structure effects on the surface soil moisture retrieval at satellite scale. Based on the demonstrated results, the effect of dominantly vertically structured canopies should be assessed by comparing the single-angle and multiangle surface soil moisture retrieval performances using both passive microwave data from airborne observations and SMOS.

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