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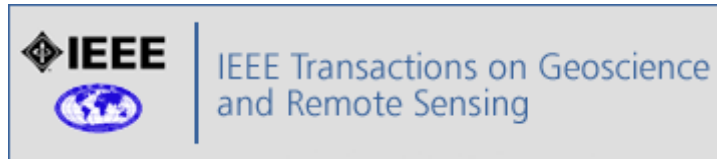
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**Wheat canopy structure and surface roughness effects on multi-angle observations at L-band**

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# Wheat canopy structure and surface roughness effects on multi-angle observations at L-band

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5 22 **Abstract**—The capability of multi-angle observations of the Soil moisture and Ocean Salinity  
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7 23 (SMOS) mission is expected to significantly improve the inversion of soil microwave emissions  
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9 24 for soil moisture by enabling the simultaneous retrieval of the vegetation optical depth and other  
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11 25 surface parameters. Consequently, this paper investigates the relationship between soil moisture  
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13 26 and brightness temperature at multiple incidence angles using airborne L-band data from the  
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15 27 National Airborne Field Experiment (NAFE) in Australia in 2005. A forward radio brightness  
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17 28 model was used to predict the passive microwave response at a range of incidence angles, given  
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19 29 inputs of i) ground measured soil and vegetation properties and ii) default model parameters for  
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21 30 vegetation and roughness characterization. Simulations were made across various dates and  
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23 31 locations with wheat cover and evaluated against the available airborne observations. The  
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25 32 comparison showed a significant underestimation of the measured brightness temperatures by the  
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27 33 model, when using the default parameterization. This discrepancy subsequently led to a soil  
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29 34 moisture retrieval error of up to  $0.3 \text{ m}^3 \text{ m}^{-3}$ . The analysis found that i) the roughness value  $H_r$  was  
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31 35 too low, which was then adjusted as a function of the soil moisture; while ii) the vegetation  
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33 36 structure parameters  $tt_h$  and  $tt_v$  were reduced by calibrating them from a single flight and testing  
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35 37 them for different moisture conditions and locations. The simulation error between the forward  
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37 38 model predictions and the airborne observations was improved from  $\text{rmse}=31.3 \text{ K}$  (26.5 K) to  
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39 39  $\text{rmse}=2.3 \text{ K}$  (5.3 K) for wet and (dry) soil moisture conditions, respectively.  
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50 41 **Index Terms**—L-band Microwave Emission of the Biosphere (L-MEB), National Airborne  
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52 42 Field Experiment (NAFE), Microwave radiometry, Multi-angle, Remote Sensing, Soil Moisture  
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54 43 and Ocean Salinity (SMOS)  
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## I. INTRODUCTION

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

The Soil Moisture and Ocean Salinity (SMOS) satellite was launched in November 2009 by the European Space Agency (ESA) and designed to provide global maps of the surface soil moisture fields with an accuracy better than  $0.04 \text{ m}^3 \text{ m}^{-3}$  for the nominal case of bare or low vegetated soils (non-nominal 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-dimensional interferometric L-band radiometer to overcome the constraints given by the proportional relation between the antenna diameter and the resulting spatial resolution and hence achieves the desired pixel size of less than 50 km. Moreover one of the innovative features of SMOS is its capability of multi-incidence angle observations, that are

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4 67 obtained by the along-track movement of the satellite and the corresponding quasi-simultaneous  
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6 68 acquisition of a series of brightness temperatures for a range of angles over the same location on  
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8 69 earth. Previous studies [11]-[13] have shown that there are significant angular signatures on the  
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10 70 measured radiometer signal associated with various land surface features and that in some cases  
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12 71 it is difficult to separate the contribution of the vegetation from the actual soil emission based on  
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14 72 single angle measurements. Thus, by understanding these angular dependencies, it has been  
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16 73 suggested that model parameters such as vegetation attenuation and surface roughness may be  
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18 74 simultaneously estimated, resulting in an enhanced and presumably more accurate soil moisture  
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20 75 retrieval [14]. Due to the absence of comparable spaceborne observations regarding the novel  
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22 76 SMOS configuration, retrieval algorithms such as L-MEB (L-band and Microwave Emission of  
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24 77 the Biosphere [15]) have been primarily tested and developed using synthetic simulations [16]  
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26 78 and small scale field experiments (SMOSREX [17], MELBEX [18] and EuroSTARRS [19]),  
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28 79 with the modeling of incidence angle relationships based on only a subset of the possible land  
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30 80 cover types. Consequently, the derived relationships and the model interactions between land  
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32 81 surface variables and observed brightness temperature response need to be verified at larger  
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34 82 spatial scales and extended for a wider range of land surface conditions.  
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41 83 The objective of this paper is to compare multi-angle L-band data from airborne observations  
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43 84 with simulated brightness temperatures using the L-MEB model and ground truth data as input.  
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45 85 Subsequently, the performance of the forward model parameterization is evaluated based on  
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47 86 different soil moisture conditions and locations and additional parameterizations are tested, that  
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49 87 included i) modifications of the modeled roughness and vegetation structure characterization.  
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## 89 II. EXPERIMENTAL DATA SET

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

### 95 A. Study Area

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

### 108 B. Airborne multi-angle Data

109 The primary airborne instrument used in the NAFE'05 campaign was the Polarimetric L-band  
110 Multi-beam Radiometer (PLMR), which operates at a frequency of 1.413 GHz with a bandwidth  
111 of 24 MHz. During the field experiment the L-band radiometer was typically used to measure

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3 112 dual-polarized brightness temperatures in pushbroom mode at six viewing angles ( $\pm 7^\circ$ ,  $\pm 21.5^\circ$ ,  
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5 113  $\pm 37.5^\circ$ ). However, regarding the multi-angle data collection, PLMR was mounted on the aircraft  
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8 114 in an along-track configuration, resulting in three PLMR beams pointing forward and three  
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10 115 backward with respect to the flight direction of the aircraft. Consequently, as the aircraft moved  
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12 116 along its flight path, this setup provided a minimum of six quasi-simultaneous multi-incidence  
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14 117 angle observations of the same location on earth with a  $17^\circ$  (3-dB) antenna beamwidth. The  
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16 118 nominal flight altitude was about 750 m which corresponds to a spatial resolution of  
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18 119 approximately 250 m. In general, an area of  $1.5 \text{ km} \times 6 \text{ km}$  was covered by four to five parallel  
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20 120 South-North oriented flight lines at each of the three farms. Dual-polarized multi-angle data were  
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22 121 acquired on four days (once a week) at Merriwa Park, and one day each for Midlothian and  
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24 122 Cullingral, respectively. Additionally, specific dive flights (i.e. successive steep  
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26 123 ascents/descents) were conducted immediately following the multi-angle flights over the focus  
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28 124 farms in order to provide observations with an even wider range of incidence angles ( $\sim 3\text{-}60^\circ$ ).

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34 125 Calibration of the PLMR instrument was carried out on a daily basis before and after the flight  
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36 126 using both the sky (cold calibration) and a blackbody box (warm calibration) as target.  
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38 127 Supplementary in-flight calibration checks were made through flights over a large water body  
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40 128 that was continuously monitored in terms of surface water temperature and salinity. A detailed  
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42 129 description of the complete calibration procedures can be found in [20]. Considering the range of  
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44 130 brightness temperature measurements over land during the campaign (150-300 K), the PLMR  
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46 131 accuracy was estimated by [20] to be higher than 0.7 K for H-polarization and 2 K for V-  
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48 132 polarization. The calibrated radiometer observations have further been processed to provide local  
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50 133 incidence angle and effective footprint size information taking into account ground topography,  
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52 134 aircraft position and attitude. Finally, the data were filtered to eliminate large aircraft yaw and  
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3 135 roll angles due to turbulences and wind forces. As a result, sun glint effects in the external beams  
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6 136 were also reduced.

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9 137 *C. Ground Data*

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11 138 Extensive ground sampling activities were conducted coincident with the airborne  
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13 139 observations, focusing on an area of approximately 1.5 km × 3.0 km at each farm (see Fig. 1).  
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15 140 The measurements of near-surface soil moisture (0-5 cm) were made using the Hydraprobe Data  
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17 141 Acquisition System (HDAS, [22]), which consists of a Hydraprobe soil moisture sensor, a Global  
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19 142 Positioning System (GPS) and a handheld pocket PC that has a Geographic Information System  
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21 143 (GIS) installed to provide a visual output of the sampling location and the corresponding soil  
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23 144 moisture observation. The HDAS measurements were made over a spatial sampling grid with  
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25 145 varying spacing from 6.25 m to 2 km. The high-resolution sampling (6.25 m - 12.5 m) was  
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27 146 mainly concentrated on an area of 150 m × 150 m within the cropping fields at Merriwa Park and  
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29 147 Cullingral and within a large patch of native grass at Midlothian. The surrounding areas were  
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31 148 sampled at coarser spatial scales. The Hydraprobe standard soil moisture product was calibrated  
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33 149 against gravimetric soil samples from the field and laboratory data and corrected for temperature  
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35 150 effects, resulting in an estimated accuracy of  $\pm 0.033 \text{ m}^3 \text{ m}^{-3}$  [22]. The gravimetric samples were  
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37 151 further analyzed in terms of soil texture and soil properties (Table I). Supplementary data  
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39 152 including land use, surface roughness, rock cover fraction, rock temperature, dew amount,  
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41 153 vegetation biomass and vegetation water content were also recorded at each farm site. Climate  
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43 154 data were available through an existing in-situ monitoring network  
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45 155 ([www.eng.newcastle.edu.au/sasmas/SASMAS/sasmas.htm](http://www.eng.newcastle.edu.au/sasmas/SASMAS/sasmas.htm)) collecting long-term soil moisture  
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47 156 (0-5 cm, 0-30 cm, 30-60 cm and 60-90 cm), soil temperature (0-5 cm and 0-30 cm) and rainfall  
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49 157 data. During the campaign a few stations were temporarily upgraded with additional  
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3 158 instrumentation including thermal infrared sensors (TIR), surface soil-temperature profiles (1  
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5 159 cm, 2.5 cm and 4 cm) and leaf wetness sensors to determine the presence of dew. Midlothian,  
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8 160 Merriwa Park and Cullingral were each equipped with one permanent and one temporary  
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10 161 monitoring station. The latter was always located within the high-resolution soil moisture  
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12 162 sampling area of the focus farm.

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15 163 This paper focuses on the use of multi-incidence angle airborne observations and ground data  
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17 164 collected across the cropping fields at Merriwa Park and Cullingral. Both sites were covered by  
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19 165 mature wheat, whereas Midlothian was predominantly characterized by native grass and lucerne.  
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21 166 Consequently, data collected across the Midlothian site was not considered in this study. Table I  
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23 167 summarizes the main features of the Merriwa Park and Cullingral study sites showing an overall  
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25 168 dynamic soil moisture range of about  $0.05\text{-}0.55\text{ m}^3\text{m}^{-3}$  for Merriwa Park over the entire period.  
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27 169 Moist soil conditions were generally observed at the start of the campaign in response to  
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29 170 significant rainfall in the area, while towards the end of the field experiment the topsoil showed  
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31 171 substantial drying effects. Cullingral was only covered once with multi-angle flights and  
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33 172 corresponding in-situ soil moisture measurements during the campaign. The spatial soil moisture  
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35 173 distribution across Cullingral ranged from  $0.05\text{-}0.25\text{ m}^3\text{m}^{-3}$  on the observation day.  
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### 42 174 III. RADIATIVE TRANSFER MODEL

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45 175 The radiative transfer model used in this study is the L-band Microwave Emission of the  
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47 176 Biosphere (L-MEB) model [15], which is the core element of the operational soil moisture  
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49 177 retrieval algorithm developed for SMOS [23]. A detailed description of the model structure and  
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51 178 parameterization is presented in [15], so the following discussion concentrates only on the basic  
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53 179 principles of L-MEB.  
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57 180 The presence of vegetation and the resulting interaction with the soil surface emission are  
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3 181 described in terms of a simplified (zero-order) solution of the radiative transfer approach, also  
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5 182 known as the tau-omega model. This algorithm assumes that the influence of the vegetation layer  
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8 183 on the  $p$ -polarized soil reflectivity ( $r_{GP}$ ) is accounted for by vegetation attenuation ( $Y_p$ ) and  
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10 184 scattering effects ( $\omega$ ) and results in a composite brightness temperature ( $TB_p$ ) as follows:  
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$$13 \quad 185$$

$$14 \quad 186 \quad TB_p = (1 - \omega_p)(1 - Y_p)(1 + Y_p r_{GP})T_C + (1 - r_{GP})Y_p T_G, \quad (1)$$

$$15$$

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20 188 where  $T_G$  and  $T_C$  correspond to the effective soil and vegetation temperature [K], respectively.  
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22 189 The reflectivity of the underlying soil surface ( $r_{GP}$ ) is a function of the wave polarization, the  
23  
24 190 observation frequency and the incidence angle, and can be quantified for non-smooth surfaces by  
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26 191 calculating the smooth surface Fresnel reflectivity ( $r_{GP}^*$ ) and adjusting it through the use of a set  
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28 192 of soil roughness parameters (i.e.  $H_r$  and  $N_{rp}$ ):  
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$$32 \quad 193$$

$$33 \quad 194 \quad r_{GP} = r_{GP}^* \cdot \exp[-H_r \cos(\theta)^{N_{rp}}]. \quad (2)$$

$$34$$

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39 196 Note, that  $N_{rp}$  is introduced to parameterize the angular dependence of the surface roughness.  
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41 197 The attenuation effect caused by the canopy, also referred to as transmissivity, is expressed as a  
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43 198 function of the vegetation optical depth ( $\tau_p$ ) and the incidence angle ( $\theta$ ):  
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$$47 \quad 199$$

$$48 \quad 200 \quad Y_p = \exp(-\tau_p / \cos(\theta)). \quad (3)$$

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54 202 The optical depth in turn can be computed as a linear function of the vegetation water content  
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56 203 (VWC) and the empirical parameter  $b_p$ , which is mainly dependent on the sensor frequency,  
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3 204 polarization, canopy type and plant structure [24]:  
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$$\tau_{nad} = VWC \cdot b_p . \quad (4)$$
  
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13 208 Since (4) is strictly valid for nadir observations ( $\theta=0^\circ$ ), two additional specific vegetation  
14 209 structure parameters  $tt_h$ ,  $tt_v$  ( $h$  and  $v$  denoting horizontal and vertical polarization) are introduced  
15 210 that account for the angular effect on the optical depth and hence on the vegetation  
16 211 transmissivity:  
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$$\tau_p = \tau_{nad} (\sin^2(\theta) \cdot tt_p + \cos^2(\theta)) . \quad (5)$$
  
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30 215 Considering a value of  $tt_p > 1$  or  $tt_p < 1$  results either in an increasing or decreasing trend of the  
31 216 optical depth, respectively, as a function of the incidence angle. The particular case of  $tt_v = tt_h = 1$   
32 217 corresponds to the isotropic state, where the optical depth of the standing canopy is assumed to  
33 218 be independent of both polarization and incidence angle.  
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#### 40 219 IV. MODELING APPROACH AND PARAMETERIZATION

41 220 The L-MEB forward model was used to generate dual-polarized brightness temperatures at a  
42 221 range of incidence angles and moisture conditions by implementing the NAFE'05 data described  
43 222 in Section II. The model set up was based on two types of input parameters: i) default model  
44 223 parameters as a function of the land cover class and ii) ground truth information collected at the  
45 224 focus farms. The available ground data for the two focus farms Merriwa Park and Cullingral  
46 225 included soil moisture, soil texture, bulk density, soil profile temperature, vegetation water  
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3 226 content and vegetation temperature data. The input soil moisture was calculated by averaging all  
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5 227 high-resolution, near-surface ground measurements falling within the same PLMR footprint for  
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8 228 each observation day. The total number of HDAS measurements was generally between ~250-  
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10 229 300 points per observation day and radiometer footprint. Further model input included a special  
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12 230 set of parameters for surface roughness and vegetation characterization, i.e. variables  $H_R$  and  $N_{RP}$   
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14 231 for the soil layer and  $tt_P$ ,  $\omega_p$  and  $b_P$  for the wheat canopy. These values were sourced from the  
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16 232 study by [15], in which the parameters had been calibrated from the PORTOS-93 experiment  
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18 233 over wheat at the Avignon test site in France [25]. This parameterization proposed by [15] is  
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20 234 hereafter referred to as the ‘default’ parameter set. Using the ground data and the default  
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22 235 parameterization, brightness temperature estimates were calculated for both H- and V-  
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24 236 polarization and incidence angles ranging from 0-50°. The forward simulations were done for all  
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26 237 available dates at Merriwa Park and Cullingral with the L-MEB results compared against the  
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28 238 actual airborne multi-incidence angle observations of the corresponding day and test site. Further  
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30 239 to the default model simulations described above, two additional parameter sets were tested  
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32 240 based on modifications of the initial model parameterization (Table II). In the second forward  
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34 241 model approach the default parameterization was changed in terms of a single model parameter;  
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36 242 the soil roughness value  $H_R$  given in [15] was replaced by a soil moisture dependent roughness  
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38 243 value proposed by [26] for the same study site. The basis for using a soil roughness value as a  
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40 244 function of soil moisture is due to a phenomenon known as “dielectric roughness”, which  
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42 245 contributes to volume scattering of the signal coming from deeper soil layers, and is assumed to  
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44 246 be caused by a variation of dielectric properties within the soil column due to a non-uniform  
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46 247 distribution of the water particles at micro-scale [27],[28]. Thus, in addition to the spatial  
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48 248 variations in the surface height (“geometric roughness”), it has been postulated that the  
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3 249 “dielectric roughness” should also be accounted for in terms of an effective  $H_R$  parameter. The  
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6 250 study by [26] was based on high-resolution (62.5 m), single-angle PLMR data from the  
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8 251 NAFE’05 experiment and suggested that the default  $H_R$  value in L-MEB was too low for  
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10 252 vegetation with dominant vertical structure such as wheat and barley. Note that [29] also had to  
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12 253 increase the  $H_R$  parameter for their studies when they used airborne L-band data over the same  
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14 254 test site but acquired by the EMIRAD radiometer, suggesting that the higher roughness values  
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16 255 were not related to an instrument-specific bias of the PLMR instrument itself. Moreover, [26]  
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18 256 found that the on-site calibrated  $H_R$  value demonstrated a notable temporal variation which  
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20 257 correlated with the observed moisture conditions during the field experiment. These results were  
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22 258 consistent with those published by [30] over bare soil at the SMOSREX test site. Hence [26]  
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24 259 developed a simple linear relationship between  $H_R$  and the soil moisture content for the  
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26 260 NAFE’05 test sites, which estimated lower  $H_R$  values with increasing moisture content.  
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28 261 Considering these results, the second parameterization had been set to include a roughness value  
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30 262 specifically calculated for each observation date depending on the corresponding soil moisture  
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32 263 information of that day. Note that since this linear function is soil type-specific, the defined  
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34 264 relationship between roughness effects and soil moisture is different for Merriwa Park and  
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36 265 Cullingral, where the soil texture changes from silty clay loam to silty loam, respectively (see  
37  
38 266 Table I).  
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46 267 The third parameter set included two modifications compared to the default L-MEB  
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48 268 parameterization: i)  $H_R$  calculated as a function of the actual soil moisture content (as in the  
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50 269 second model approach) and ii) calibrated vegetation structure variables  $tt_h$  and  $tt_v$  using the  
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52 270 available multi-incidence data for one of the four observation days. These vegetation parameters  
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54 271 were estimated through an optimization routine which had been applied to a single flight day  
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3 272 over Merriwa Park (9 November 2005). The calibrated values for  $tt_h$  and  $tt_v$  corresponded,  
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5 273 respectively, to a decrease ( $tt_h < 1$ ) and increase ( $tt_v > 1$ ) of the optical depth with the incidence  
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8 274 angle at each polarization, which was expected due to the dominantly vertical structure of the  
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10 275 wheat canopy. This parameterization was then applied to all remaining observation days at  
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12 276 Merriwa Park to assess its performance. Subsequently, the calibrated model variables were  
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15 277 further tested on airborne data from Cullingral in order to study their robustness and to verify the  
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17 278 parameterization derived from the Merriwa Park study site. The assumption that the remaining  
18  
19 279 vegetation values as proposed by [15] for i) the vegetation parameter  $b$  and ii) the single  
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21 280 scattering albedo  $\omega$  were representative was justified based on: i) a site-specific calibration  
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23 281 across the available observation dates that showed no significant variations from  $b=0.08$  and  $\omega$   
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25 282  $=0$  and ii) the fact that the parameterization resulted from an extensive literature review by [15].  
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27 283 Further analysis of the three parameterizations included the inversion of the L-MEB model to  
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29 284 solve an optimization problem for the retrieval of soil moisture given *a priori* ground truth  
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31 285 information. The algorithm was based on a minimized cost function that calculated the quadratic  
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33 286 difference between the measured and simulated brightness temperatures.  
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## 40 287 V. RESULTS AND DISCUSSION

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42 288 The comparison of the L-MEB predicted brightness temperature response with the airborne  
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44 289 multi-angle observations from Merriwa Park and Cullingral for incidence angles ranging from 0-  
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46 290  $50^\circ$  showed significant discrepancies depending on the model parameterization chosen (Fig. 2).  
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48 291 Using the default L-MEB parameterization, the forward model consistently underestimated the  
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50 292 multi-angle observations at H-polarization, whereas at V-polarization (especially for large  
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52 293 incidence angles and wet soil conditions) the simulated brightness temperatures were much  
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56 294 higher than those observed. Furthermore, the exhibited angular trends of the dual-polarized  
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3 295 observations were only partially captured by the simulation results. Hence, differences of up to  
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6 296 ~40 K in brightness temperatures were observed, particularly within the range of low angles.  
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8 297 While this difference decreased for the vertical polarized curve with larger incidence angles, the  
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10 298 simulated horizontal brightness temperatures were always lower than the measured data. Note,  
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12 299 that for wet conditions at Merriwa Park during the first two observation days, the simulated  
13  
14 300 horizontally polarized curve is relatively flat due to the high vegetation water content and the  
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16 301 corresponding large value for the optical depth. The explanation behind this trend is that both the  
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18 302 attenuation of the soil emission and the emission by the wheat canopy itself increased, causing  
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20 303 the effective composite brightness temperature of both media to be closer to the effective  
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22 304 temperature of the vegetation. So with larger incidence angles, the attenuation of the vegetation  
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24 305 increased with respect to the  $1/\cos(\theta)$  relationship as shown in equation (3). Setting a default  
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26 306 value of 1 for  $tt_h$  further assumes that there are no significant angular dependencies across the  
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28 307 observed wheat canopy at H-polarization. The comparison of the predicted and observed  
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30 308 brightness temperatures across the four observation days at Merriwa Park produced a root mean  
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32 309 square error (rmse) ranging from 38 K to 26 K for wet and dry conditions, respectively (Fig. 3),  
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34 310 when using the default parameters.

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41 311 The overall model performance was improved by introducing the soil moisture dependent  
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43 312 roughness value  $H_r$  (second model parameterization) from the site-specific calibration presented  
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45 313 by [26]. Consequently, an upward translation of the modelled brightness temperature curves was  
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47 314 achieved resulting in a closer agreement with the actual observations. The corresponding root  
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49 315 mean square errors ranged between 9.6 K (wet) to 2.9 K (dry), and were thus significantly  
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51 316 reduced compared to the default model parameterization output. However, the simulated angular  
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53 317 behaviour was still unable to capture the observed brightness temperature trend exhibited at large  
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3 318 angles ( $> 25^\circ$ ), which was especially dominant for moist conditions at Merriwa Park at the start  
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5 319 of the campaign. Moreover, for relatively low moisture contents ( $< 0.1 \text{ m}^3\text{m}^{-3}$ ) the curve shift  
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8 320 forced by the moisture adjusted roughness value towards higher brightness temperatures was too  
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11 321 strong. Hence, the predicted emissions tended to overestimate the brightness temperature  
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13 322 measurements especially for dry conditions. A site-specific calibration of  $H_r$  based on the multi-  
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15 323 angle observations available for Merriwa Park (not shown in this paper) confirmed a non-linear  
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17 324 relationship between soil moisture and surface roughness. Specifically, the calibration showed i)  
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20 325 a positive correlation between surface roughness and soil moisture for dry conditions resulting in  
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22 326 small  $H_r$  values for dry soil, and ii) a negative trend for soil moisture values of  $\sim 0.20 \text{ m}^3\text{m}^{-3}$  or  
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24 327 higher by decreasing the roughness effect with increasing moisture content. These findings also  
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27 328 agreed with the results published by [31] who investigated the impact of soil moisture on surface  
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29 329 roughness using single-angle NAFE'05 data. In that study the decrease of the roughness effect  
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32 330 for low soil moisture was associated with a reduced dielectric heterogeneity at micro-scale  
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34 331 during the drying process of the clay loam soils that dominate the study area. That is, the micro-  
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36 332 scale variability and thus the dielectric roughness would peak at intermediate soil moisture  
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39 333 content and decrease in very wet or very dry conditions. Hence, applying a reduced roughness  
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41 334 parameter from a non-linear function for dry conditions would ultimately produce better results  
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44 335 when comparing the forward simulations and the airborne measurements. The current SMOS  
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46 336 Level 2 soil moisture retrieval algorithms [23] include the sensitivity of surface roughness on soil  
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48 337 moisture in terms of a simple linear function such as that applied in this study. The roughness  
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50 338 estimation, however, is confined by the field capacity as an upper limit and a transition moisture  
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53 339 point as the lower limit, with both parameters being a function of the soil texture (sand/clay  
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55 340 content). Above and below these two points the roughness value is a constant, and the minimum  
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3 341  $H_r$  value is expressed by  $H_rMIN=(2k\sigma)^2$  [32], with  $k$  being the wave number and  $\sigma$  defined as the  
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6 342 surface root mean square height. Note, that i) the corresponding minimum and maximum  $H_r$   
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8 343 values are dependent on the actual land cover type observed and ii) the maximum  $H_rMAX$   
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10 344 parameter is retrieved from the individual SMOS scene.

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13 345 The L-MEB parameterization of the third model included i) the moisture dependent roughness  
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15 346 factor  $H_r$  tested in the second model approach and ii) specifically calibrated vegetation structure  
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17 347 parameters  $tt_h$  and  $tt_v$ , that account for the angular dependency of the vegetation attenuation. The  
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19 348 corresponding forward model results showed the overall best agreement with the airborne data  
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21 349 (rmse=2.5-5.3 K) and the trend of the predicted dual-polarization curves captured that of the  
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23 350 measured data for both moist and dry soil moisture conditions. Compared to the default  
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25 351 parameterization and the high  $tt_v$  value of 8 obtained for the vertically dominated wheat canopy  
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27 352 [15], the vegetation structure parameters calibrated and tested in this study were significantly  
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29 353 lower and closer to unity ( $\sim 1$ ). Though it should be noted, that an individual calibration of the  $tt_p$   
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31 354 parameters for each single day suggested a value of  $tt_v = 3$  in one case, but overall only minor  
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33 355 variations across the different dates were observed. Consequently, the calibrated vegetation  
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35 356 structure parameters from the 9<sup>th</sup> of November 2005 were validated on different moisture  
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37 357 conditions and locations (Cullingral), confirming the good results obtained using this particular  
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39 358 parameterization. Further analysis showed that using the individually estimated  $tt_p$  values for  
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41 359 each observation day, instead of the values calibrated from the 9 November 2005, improved the  
42  
43 360 model rmse performance by 0.1 K at most. Moreover, the results demonstrated that the  
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45 361 adjustment of both angular correction parameters had a more significant impact on the predicted  
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47 362 brightness temperatures, when the ground measured vegetation water content was high ( $>1.9$   
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49 363  $\text{kg/m}^2$ ) and thus, the attenuation effects of the canopy and its own contribution to the composite  
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3 364 brightness temperature increased as well. Consequently, both structure parameters play a major  
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6 365 role especially for large incidence angles ( $> 30^\circ$ ) where the path length of the emitted energy  
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8 366 through the vegetation layer is longer.  
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10 367 The soil moisture retrieval based on an iterative least-squared algorithm resulted in a range of  
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12 368 soil moisture values depending on the model parameterizations chosen (Fig. 4). The default  
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15 369 parameterization generally produced too low soil moisture values with a maximum difference of  
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17 370  $\sim 0.3 \text{ m}^3\text{m}^{-3}$ , if compared against the measured soil moisture. The overall best result with the  
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19 371 retrieved soil moisture being close ( $\leq 0.04 \text{ m}^3\text{m}^{-3}$ ) to the observed moisture conditions was  
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22 372 achieved using the optimized set of parameters, which included the soil moisture dependent  
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24 373 roughness value  $H_r$  and the calibrated vegetation structure values  $tt_p$  (third model approach).  
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## 28 374 VI. CONCLUSION

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31 375 This paper has presented simulations of brightness temperatures at a range of incidence angles  
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33 376 and the subsequent comparison with multi-incidence angle airborne observations over two wheat  
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35 377 canopy test sites in eastern Australia. The forward model used in this research was the L-band  
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37 378 Microwave Emission of the Biosphere (L-MEB) model which is one of the core elements of the  
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39 379 SMOS soil moisture retrieval algorithm. Apart from the default model parameterization proposed  
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42 380 by [15], two additional parameterizations were studied, including modifications of the surface  
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44 381 roughness and vegetation structure characterization. The performance of the individual model  
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46 382 approach was not only assessed based on changing moisture conditions, but also for different  
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48 383 locations in order to test its robustness. The agreement of the predicted and the measured  
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50 384 brightness temperature data from different the forward model parameterizations varied  
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52 385 significantly; with the observed discrepancy being much larger for wet conditions than for dry  
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55 386 soil moisture values. However, compared to the results using the default model parameterization,  
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3 387 a stepwise improvement was achieved by firstly introducing a soil moisture dependent roughness  
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5 388 factor and secondly by optimizing the vegetation structure parameters. Consequently, the dual-  
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7 389 polarized brightness temperature predictions were improved by minimizing the rmse from 38.1  
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9 390 K to 2.3 K for wet soil conditions ( $\sim 0.45 \text{ m}^3 \text{ m}^{-3}$ ) and from 26.5 K to 5.3 K for dry soils ( $\sim 0.13$   
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11 391  $\text{m}^3 \text{ m}^{-3}$ ).

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15 392 This study proves that neglecting the sensitivity of the surface roughness parameter  $H_r$  on soil  
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17 393 moisture leads to a significant underestimation of the soil emission at L-band, which would  
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19 394 consequently affect the overall soil moisture retrieval accuracy. Furthermore, it was shown that  
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21 395 the transmissivity of a dominantly vertical canopy structure and the angular dependency of the  
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23 396 optical depth should not be neglected for vegetation water contents of  $> 1.9 \text{ kg/m}^2$  and wet soil  
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25 397 conditions ( $> 0.4 \text{ m}^3 \text{ m}^{-3}$ ), otherwise the error introduced into the retrieved soil moisture product  
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27 398 for the given data set could be up to  $0.3 \text{ m}^3 \text{ m}^{-3}$ . Though it should be noted that considering the  
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29 399 spatial resolution of SMOS observations and a footprint size of approximately  $\sim 42 \text{ km}$ , which  
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31 400 captures a mixture of land cover types, the angular effect is likely to be minor for SMOS  
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33 401 products. However, this issue needs to be investigated in future research to understand the impact  
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35 402 of the angular vegetation structure effects on the soil moisture retrieval at satellite scale. Based  
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37 403 on the demonstrated results, the effect of dominantly vertically structured canopies should be  
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39 404 assessed by comparing the single-angle and multi-angle soil moisture retrieval performance  
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41 405 using both passive microwave data from airborne observations and SMOS.  
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56 409 within the framework of the Moisture Map project.  
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**TABLES**

TABLE I: Characteristics of selected NAFE'05 focus farms with multi-incidence angle observations

TABLE II: Parameterization of the three forward models studied

**FIGURES**

Fig. 1. Locations of NAFE'05 Focus farms, multi-angle flight lines, soil moisture measurements and monitoring stations in the Goulburn River catchment, New South Wales, Australia.

Fig. 2. Dual-polarized brightness temperature estimates plotted against incidence angle and compared to multi-angle PLMR observations over wheat canopy available for Merriwa Park and Cullingral. The forward simulations were based on three different model parameterization (default, Hr-cal, optimized) as given in Table II. Note, that only the data from 9 Nov 2005 at Merriwa Park were used for model calibration (optimized model), whereas the remaining datasets were used for validation purpose.

Fig. 3. Scatterplot of the L-MEB model simulations in comparison with independent ground data from Merriwa Park at different observation dates using the default model parameterization (dots) [15], the site-specific roughness parameterization (crosses) [26] and the optimized model parameterization (circles). The root mean square errors [K] are given for all model approaches.

Fig. 4. Scatterplot showing the retrieved against the measured 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 three model parameterizations discussed in Section IV.

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

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

<sup>a</sup>across area with wheat cover

TABLE II  
PARAMETERIZATION OF THE THREE FORWARD MODELS STUDIED

| MODEL     | ROUGHNESS   |          |          |        | VEGETATION |            |            |  | COMMENT |
|-----------|---|----------|----------|--------|------------|------------|------------|--|---------|
|           | $H_r$   | $N_{rh}$ | $N_{rv}$ | $tt_h$ | $tt_v$     | $\omega_h$ | $\omega_v$ |  |         |
| Default   | 0.1   | 0        | 0        | 1      | 8          | 0          | 0          | Parameterization proposed by [15]  |         |
| Hr-cal    | 1.5-1.6-SM <sup>a</sup> **<br>1.6-1.0-SM <sup>a</sup> *** | 0        | 0        | 1      | 8          | 0          | 0          | Soil moisture dependent $H_r$ component [26]   |         |
| Optimized | 1.5-1.6-SM <sup>a</sup> **<br>1.6-1.0-SM <sup>a</sup> *** | 0        | 0        | 0.2    | 1.4        | 0          | 0          | Soil moisture dependent $H_r$ [26] and optimized vegetation structure values calibrated from multi-incidence angle data from Merriwa Park 09/11/2005 |         |

<sup>a</sup>SM: Soil Moisture; \*Roughness function for Merriwa Park; \*\*Roughness function for Cullingral

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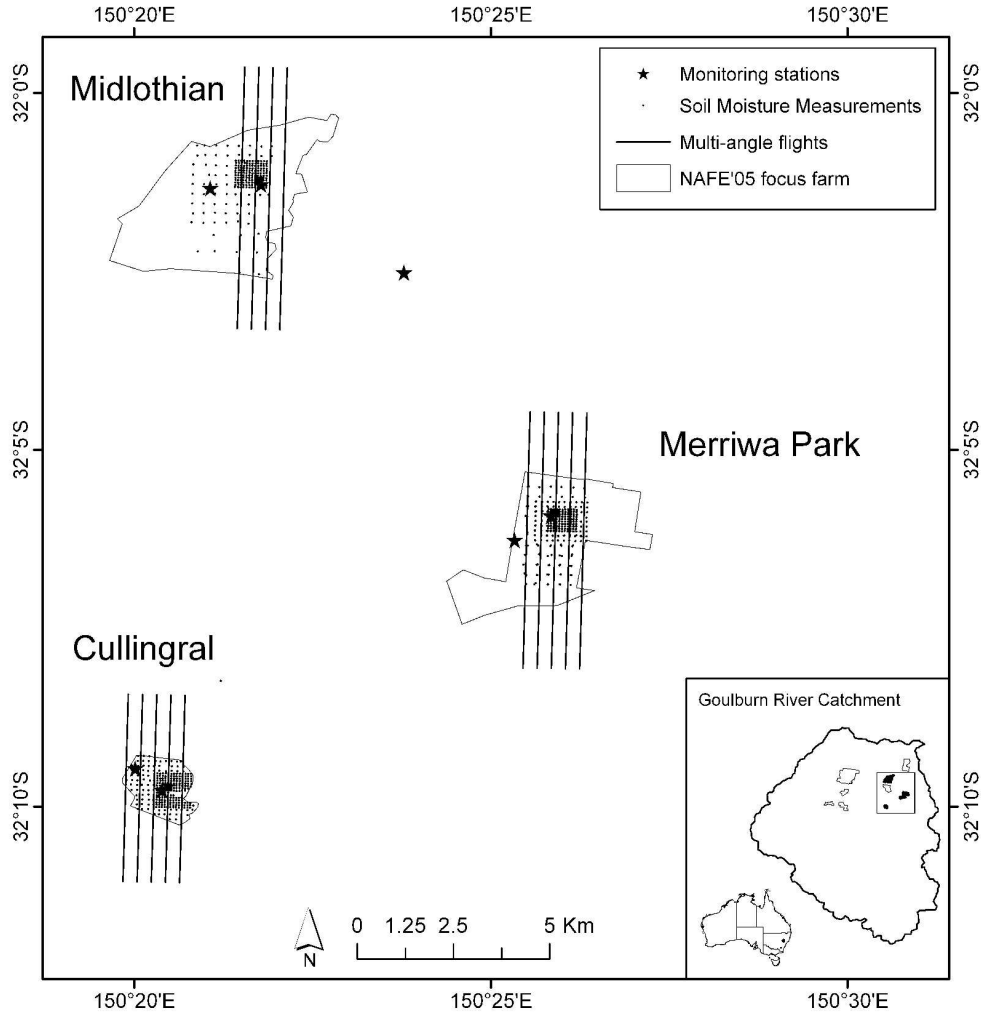


Fig. 1. Locations of NAFE'05 Focus farms, multi-angle flight lines, soil moisture measurements and monitoring stations in the Goulburn River catchment, New South Wales, Australia. 206x212mm (600 x 600 DPI)

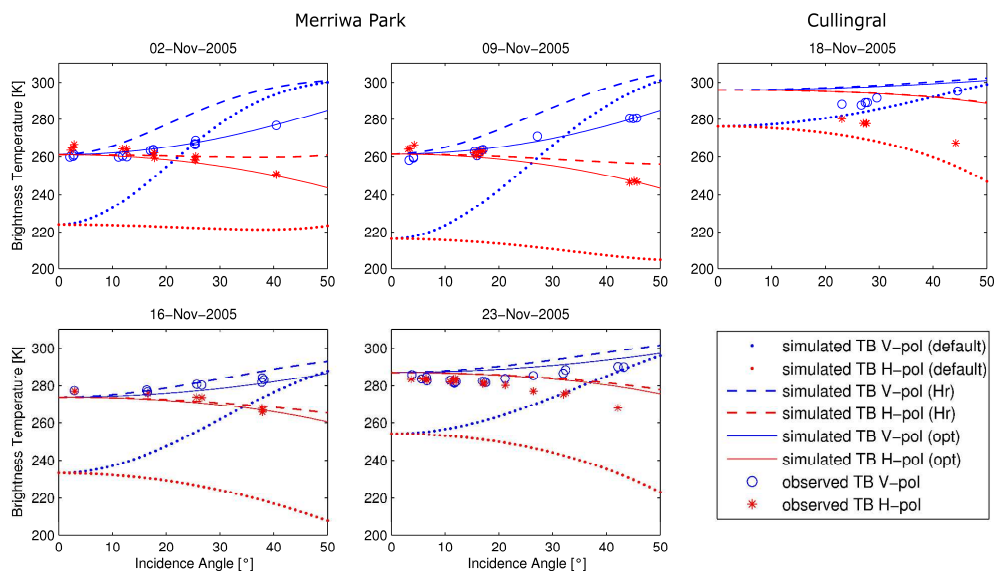


Fig. 2. Dual-polarized brightness temperature estimates plotted against incidence angle and compared to multi-angle PLMR observations over wheat canopy available for Merriwa Park and Cullingral. The forward simulations were based on three different model parameterization (default, Hr-cal, optimized) as given in Table II. Note, that only the data from 9 Nov 2005 at Merriwa Park were used for model calibration (optimized model), whereas the remaining datasets were used for validation purpose.

253x145mm (600 x 600 DPI)

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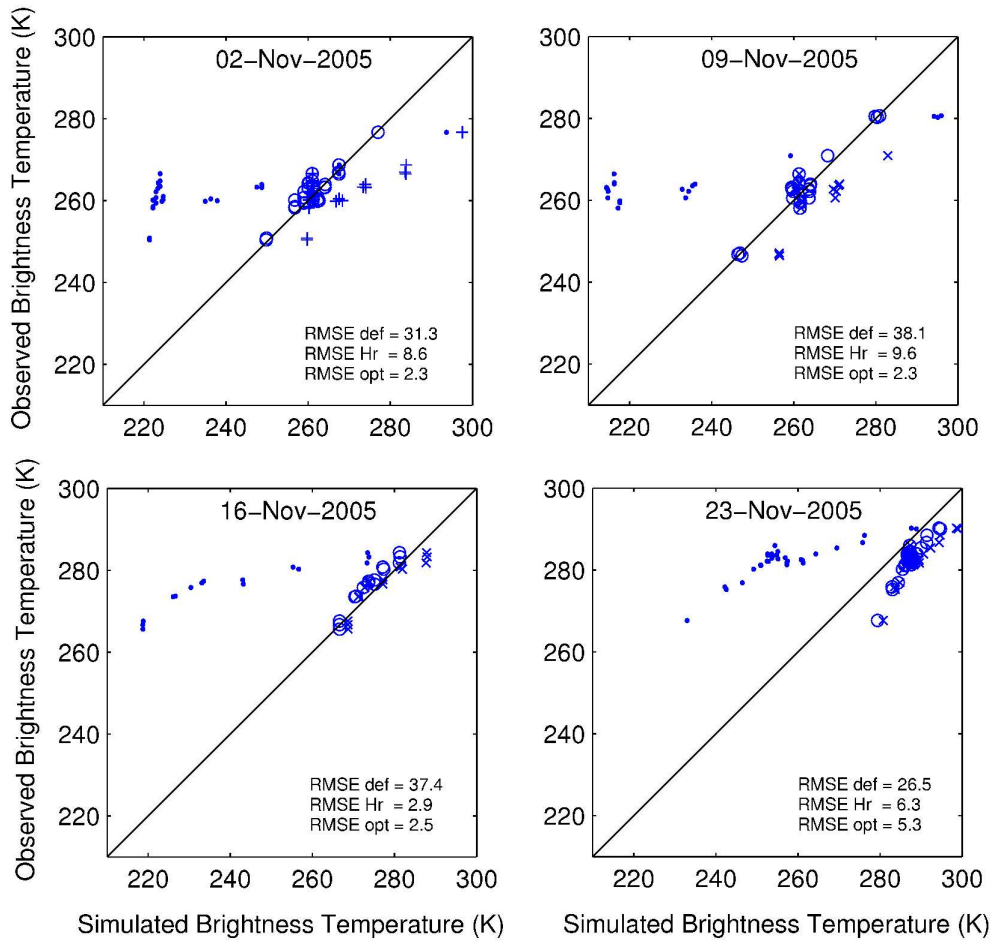


Fig. 3. Scatterplot of the L-MEB model simulations in comparison with independent ground data from Merriwa Park at different observation dates using the default model parameterization (dots) [15], the site-specific roughness parameterization (crosses) [26] and the optimized model parameterization (circles). The root mean square errors [K] are given for all model approaches.  
141x134mm (600 x 600 DPI)

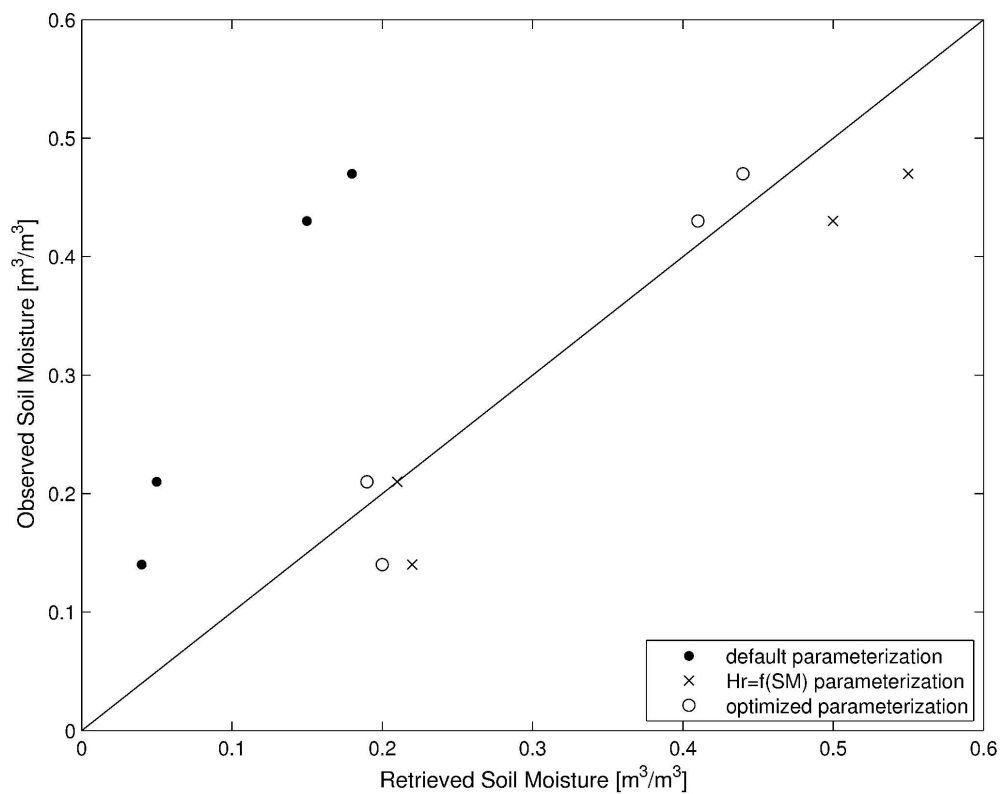


Fig. 4. Scatterplot showing the retrieved against the measured soil moisture values at the Merriwa Park focus farm for the four available observation days. The inverse application of the L-MEB model was made for all three model parameterizations discussed in Section IV.  
174x140mm (600 x 600 DPI)