

Soil moisture retrieval from multi-incidence angle observations at L-band

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Abstract: Soil moisture is an important environmental variable in regulating energy fluxes and water infiltration near the soil surface. This makes it a significant parameter in meteorological and climate modelling applications. While ground measurement of soil moisture at a large spatial scale is cumbersome and time-consuming, remote sensing offers the advantage of frequent observations in time and space. The most promising remote sensing technique for soil moisture observations is microwave radiometry at L-band, which is highly sensitive to moisture and less affected by roughness and canopy attenuation than compared to shorter wavelengths in the microwave range. Consequently, the first dedicated mission for global Soil Moisture and Ocean Salinity mapping (SMOS), launched in November 2009, has a passive microwave radiometer at L-band (1.4 GHz) that uses a two-dimensional interferometric Y-shaped antenna.

The novel design of this satellite, yielding multi-incidence angle observations, provides a unique opportunity to acquire accurate information on near surface soil moisture. However, the newly developed algorithms for this mission need to be thoroughly tested on a wide range of land surface conditions and spatial resolutions, since their parameterization has been mostly limited to small scale field studies that focused on data from tower radiometers and simulation experiments. The SMOS mission is based on the relationship between the measured brightness temperature and the dielectric constant of the soil, which is related to its moisture content. Since this relationship is affected by a range of factors, including surface roughness and vegetation cover, the SMOS mission is relying on the multi-incidence angle observations to estimate some of the ancillary parameters required by the retrieval algorithm.

In order to assess the performance of the core algorithm used by SMOS, multi-angle airborne data at L-band were studied from an Australian field campaign in 2005 (NAFE - National Airborne Field Experiment). The flights were conducted across three focus areas capturing a range of vegetation and soil moisture conditions on several observation days. The airborne instrument operated was the Polarimetric L-band Multi-beam Radiometer (PLMR) which provided dual-polarized brightness temperature measurements at six different incidence angles. The multi-angle observations were obtained by deploying a push-broom sensor rotated such that all beams were looking along the flight track, three forward and three backward, respectively. Corresponding ground sampling activities at specific focus farms included near surface-soil moisture, profile soil temperature, vegetation temperature, vegetation water content and biomass measurements. Additional rainfall, soil moisture profile and soil temperature data were collected at permanent monitoring sites nearby.

In this research the L-MEB model was used to investigate the soil moisture retrieval results obtained when only specific ranges of multi-angle brightness temperature observations over wheat canopy were used. Moreover, the impact of varying moisture conditions and multi-parameter retrievals were studied to further assess the model performance and soil moisture accuracy. The results demonstrated overall good soil moisture estimates in relation to the ground measurements ($\Delta SM = 0-0.03 \text{ m}^3/\text{m}^3$), if i) soil moisture was retrieved solely and ii) all available brightness temperature data collected across 0-50° incidence angles were used. However when attempting the simultaneous retrieval of soil moisture together with ancillary data and focusing on specific angular ranges of observations, large variations in soil moisture estimates were observed. In particular, L-band data collected at incidence angles of 10° or higher seemed to be more strongly affected by the canopy, since vegetation effects of the dominant vertical wheat structure increased with larger incidence angles. Hence, L-band data measured at near-nadir views (0-10°) produced the soil moisture results closest to those measured - independently of the observed moisture conditions - when the optical depth and/or the surface roughness parameter were retrieved simultaneously with soil moisture.

Keywords: L-MEB, microwave radiometry, multi-incidence angle, NAFE, remote sensing, SMOS

1 INTRODUCTION

The retrieval of soil moisture from L-band microwave observations over vegetated areas is relatively complex compared to bare soil conditions, since the additional vegetation contribution on the emission signal needs to be accounted for within the model. Thus, with the increasing number of input parameters, even more ground information is needed to ensure accurate soil moisture estimates from remote sensing instruments, such as the recently launched Soil Moisture and Ocean Salinity (SMOS) satellite (Kerr *et al.*, 2010a). The ancillary data might be obtained from different ground and space borne instruments. However, issues due to spatial or temporal discrepancies between the different data sources arise. Consequently, previous work has studied the use of dual-polarized multi-incidence angle L-band data to retrieve soil moisture simultaneously with some of the ancillary data needed as model input (Wigneron *et al.*, 2000). It was shown that these so-called multi-parameter retrievals using the multi-angle capability of sensors such as that deployed by SMOS may enhance the overall retrieval process, depending on the field of view, the moisture conditions, the vegetation type and growth state. However, if a radiometer instrument is only capable of brightness temperature acquisition at a very narrow range of incidence angles compared to SMOS ($\sim 0\text{--}60^\circ$), the accuracy of soil moisture estimated from multi-parameter retrieval might change depending on the angular range chosen for multi-angle observations; e.g. the near nadir measurements of SMOS are strongly affected by the low antenna gain in that particular area of the field of view. Hence, this paper analyses the multi-angular soil moisture retrieval quality over a wheat canopy site using airborne brightness temperature data collected at different ranges of incidence angles. The effect of i) changing moisture conditions and ii) the type and number of simultaneously retrieved parameters on the model performance are also investigated.

2 EXPERIMENTAL DATA

The data used in this paper was sourced from the National Airborne Field Experiment (NAFE'05), conducted during October–November 2005 in South-East Australia (Panciera *et al.*, 2008). The campaign focused on the northern part of the Goulburn River catchment (32° S, 150° E) located in New South Wales (Figure 1). Within the main study region of 40×40 km, several smaller focus areas were selected for intensive airborne and ground operations at farm scale. The experimental data set comprised among others, airborne multi-incidence angle L-band measurements together with ground information from extensive in-situ sampling and monitoring stations. The Merriwa Park farm (Figure 1), which was the focus of this paper, had a gently sloping topography and was characterized by a mixture of wheat and grass land use on a silty clay loam soil.

2.1. Airborne Data

The airborne microwave radiometer used in the NAFE'05 campaign was the Polarimetric L-band Multi-beam Radiometer (PLMR), which is capable of dual-polarized brightness temperature measurements (TB) at a frequency of 1.413 GHz and bandwidth of 24 MHz. The instrument is equipped with six receiving beams, with fixed look angles of $\pm 7^\circ$, $\pm 21.5^\circ$ and $\pm 38.5^\circ$. For the multi-angle flights, PLMR was mounted in along-track configuration on the aircraft. This provided three beams pointing forward and three beams backward with respect to the flight direction of the aircraft. Considering an aircraft pitch of approximately 4° , the resulting look angles of the six PLMR beams were typically 3° , 11° , 17° , 26° , 34° and 43° in along-track mode. Consequently, as the aircraft moved along its flight path at a nominal altitude of 750 m, quasi-simultaneous multi-angle measurements at approximately 250 m spatial resolution were made for the same location on earth. The multi-angle data were acquired in the early afternoon between 12:00 pm and 3:00 pm on a total of four observation days (2–Nov, 9–Nov, 16–Nov and 23–Nov). The PLMR instrument was calibrated before and after each flight using cold (sky) and warm (blackbody box) calibration targets. Additional in-flight calibration checks were conducted through low-altitude flights across a large water body, which was monitored for surface water temperature and salinity. The instrument accuracy is given as 0.7 K for H- and 2 K for V-polarization (Panciera *et al.*, 2008). Further processing of the multi-angle data included

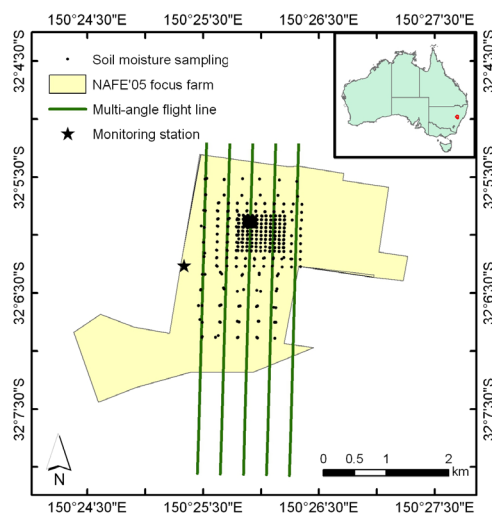


Figure 1. Outline of the Merriwa Park focus farm with the aircraft flight lines, the ground soil moisture sampling grid (6.25 m – 2 km) and the location of monitoring stations overlain. Inset: Location of the NAFE'05 test site in Australia.

calculation of the effective footprint size and the local incidence angle, taking into account the surface topography, aircraft position and attitude. Moreover, some of the PLMR data with large yaw and/or roll angles caused by strong cross-wind and turbulence were filtered.

2.2. Ground Data

Extensive ground sampling was conducted at the focus farm within an area of $1.5 \times 3.0 \text{ km}^2$, concurrent to the airborne observations. The near-surface (0-5 cm) soil moisture measurements (SM) were made with the Hydraprobe Data Acquisition System (HDAS), which includes a Hydraprobe soil moisture sensor, a Global Positioning System (GPS) and a handheld pocket PC (Merlin *et al.*, 2007). The calibration of the Hydraprobe standard soil moisture product was based on gravimetric soil samples and laboratory data. Considering the correction of temperature effects, the estimated accuracy of the HDAS system is $\pm 0.033 \text{ m}^3/\text{m}^3$ (Merlin *et al.*, 2007). During the campaign, surface moisture contents were measured between 9:00 am to 1:30 pm on a regular grid with varying resolution. The spacing between the individual sampling points ranged from 6.25 m to 2 km and was designed in such a way that the high-resolution sampling zone was located within the cropping area of the Merriwa Park focus farm (Figure 1). Supplementary data including surface roughness, vegetation type, dew amount, vegetation water content and biomass were also collected by the ground teams. Long-term profile soil moisture (0-5 cm, 0-30 cm, 30-60 cm and 60-90 cm), soil temperature (0-5 cm and 0-30 cm) and rainfall records were available from an existing in-situ monitoring network (Rüdiger *et al.*, 2007). Moreover, temporary monitoring stations were set up during the period of the campaign and equipped with thermal infrared sensors (TIR), surface soil temperature instrumentation (1 cm, 2.5 cm and 4 cm) and leaf wetness sensors. The overall dynamic range of surface soil moisture measured was between $0.14\text{-}0.46 \text{ m}^3/\text{m}^3$ at Merriwa Park. In response to a significant rainfall event before the start of the campaign, substantial drying effects of the topsoil were observed throughout the field experiment.

3 RADIOMETRIC MODEL

The core component of the operational soil moisture retrieval algorithm for SMOS is the L-band Microwave Emission of the Biosphere model (L-MEB), explained in detail in Wigneron *et al.* (2007) and implemented into the Community Microwave Emission Modelling Platform (CMEM) (Drusch *et al.*, 2009). This radiative transfer model is a simplified (zero-order) solution to describe the p -polarized ground emission (e_{GP}) taking into account the presence of an overlying vegetation layer (with $p=H$ for horizontal and $p=V$ for vertical polarization). The contribution of the canopy to the soil reflectivity ($r_{GP} = 1 - e_{GP}$) is modelled in terms of the vegetation attenuation (γ_P) and scattering effects (ω_P), which together result in a composite brightness temperature (T_{B_P}) [K]. Considering the soil and vegetation components and the effective temperature [K] of both media, i.e. soil T_G and vegetation T_C , the so-called tau-omega model is given as (Mo *et al.*, 1982)

$$T_{B_P} = (1 - \omega_P)(1 - \gamma_P)(1 + \gamma_P r_{GP}) \cdot T_C + (1 - r_{GP})\gamma_P \cdot T_G. \quad (1)$$

The reflectivity of the soil surface can be estimated by the Fresnel reflectivity (r_{GP}^*) and adjusted for non-smooth surfaces through the use of additional parameters, such as H_R and N_{RP} (Wang and Choudhury, 1981):

$$r_{GP} = r_{GP}^* \cdot \exp[-H_R \cos \theta^{N_{RP}}]. \quad (2)$$

The H_R parameter is included as a semi-empirical effective surface roughness parameter and N_{RP} for the dependency of the surface roughness on the incidence angle (θ). When modelling of the canopy attenuation, further referred to as transmissivity, the angular effect on the signal needs also to be taken into account through the optical depth (τ_P) by

$$\gamma_P = \exp[-\tau_P / \cos \theta]. \quad (3)$$

The optical depth as shown in (3) is strictly valid for nadir-views only and can be approximated using a linear function of the vegetation water content (VWC) [kg/m^2] and the empirical parameter b_P . The latter is mainly dependent on sensor frequency, polarization, canopy type and plant structure (Jackson and Schmugge, 1991):

$$\tau_{NAD} = VWC \cdot b_P. \quad (4)$$

Consequently, to correct for non-nadir observations two additional vegetation structure parameters tt_P are introduced, that account for an increasing ($tt_P > 1$) or decreasing ($tt_P < 1$) trend in the optical depth and hence in the vegetation transmissivity as a function of the incidence angle. For the particular case of $tt_P = 1$, the τ_P of the standing canopy is independent of polarization and incidence angle, which is defined as isotropic state.

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

For the purpose of this study, the L-MEB model was used to solve an optimization problem between the airborne dual-polarized brightness temperatures and the forward simulated brightness temperatures by iteratively minimizing a cost-function through least-square to retrieve soil moisture and ancillary data. Consequently, the number of parameters that were retrieved simultaneously depended on the number of available brightness temperature measurements for the same location on earth.

4 MULTI-INCIDENCE ANGLE SOIL MOISTURE RETRIEVAL

In order to investigate how a specific angular range of brightness temperature measurements performs for soil moisture retrieval, all available L-band data within a designated PLMR pixel over the Merriwa Park wheat area were categorized according to their incidence angle information (Table 1). Note that due to the configuration of the PLMR instrument, there were a few cases where groups classified at a finer angular scale did not contain any data, but have been included for the sake of completeness. The total number of TB_p studied (collected across incidence angles of 0-50°) depended on the individual observation day, but ranged from 15 observations on the 16th November 2005 to 27-32 observations for the three remaining days. The corresponding HDAS measurements for the particular day/pixel comprised about ~250-300 points, which were averaged and the spatial variability estimated from the standard deviation.

The soil moisture retrieval was classified into single-parameter retrieval (soil moisture) and multi-parameter retrieval, considering - apart from soil moisture (SM) - additional model parameters as unknown. These ancillary parameters included the surface roughness H_R and the vegetation water content VWC . The vegetation water content was calculated from the retrieved optical depth information using Equation 4. The semi-empirical roughness parameter H_R was set as either dependent on the retrieved soil moisture $H_R=f(SM)$ or independent within the retrieval process. The concept of a soil moisture dependent H_R parameter is also applied in the processing of SMOS data (Kerr *et al.*, 2010b), since work by Escorihuela *et al.* (2007) indicated better retrieval results when taking into account the topsoil moisture content for determining H_R . With regard to the NAFE'05 data set, similar results were found for the study site and the different moisture conditions observed (Peischl *et al.*, 2011; Panciera *et al.*, 2009a; 2009b). Recent findings suggest that the soil water contribution in H_R might alternatively result from a difference in sampling depth between the L-band radiometer observations and the ground measurements (Escorihuela *et al.*, 2010). The remaining L-MEB model parameters including soil texture, soil temperature, vegetation temperature, vegetation scattering albedo and further surface roughness characterization were taken mostly from literature (Wigneron *et al.*, 2007) or available in-situ measurements. The parameterization used in this study had been previously confirmed and tested for the same test site (Peischl *et al.*, 2011), demonstrating maximum root mean square errors of 2-5 K. The soil moisture retrievals were performed i) on all four multi-angle flight days over the Merriwa Park cropping area and ii) for each individual group of angular brightness temperature measurements across the different scenarios (Table 1).

4.1. Single-parameter Retrieval

The single-parameter retrieval (1-P) focused solely on retrieving soil moisture and assumed all remaining L-MEB model input data as known. The resulting soil moisture estimates for each group of brightness temperatures (Table 1) are displayed in Figure 2. Generally, using all available angular brightness temperature observations for the 1-P soil moisture retrieval produced values close to the ground measurements for all observation days ($\Delta SM=0-0.03 \text{ m}^3/\text{m}^3$). However by focusing on brightness temperatures collected at specific incidence angle ranges, the simulation accuracy varied. In particular, TB_p associated with very large incidence angles ($>40^\circ$) tended to slightly overestimate soil moisture for very wet and very dry conditions. In addition, for soil moisture conditions less than $0.22 \text{ m}^3/\text{m}^3$, consistently lower values compared to the ground information were retrieved when only TB_p data at small incidence angles were used ($<15^\circ$). Overall, all grouped soil moisture retrievals were still within the range of the standard deviation of the ground measurements independent of the varying moisture conditions observed.

Table 1. Overview of grouping criteria for PLMR brightness temperature measurements according to their corresponding incidence angle information.

Scenario	Group Identifier for Incidence Angle Ranges [°]								
	1	2	3	4	5	6	7	8	9
A	0-50								
B	0-25	25-50							
C	0-15	15-30	30-50						
D	0-14	14-22	22-35	35-50					
E	0-10	10-20	20-30	30-40	40-50				
F	0-8	8-16	16-24	24-32	32-40	40-50			
G	0-7	7-14	14-21	21-28	28-35	35-42	42-50		
H	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-50

4.2. Multi-parameter Retrieval

The multi-parameter retrieval included three different combinations: i) simultaneous retrieval of soil moisture and vegetation water content; ii) simultaneous retrieval of soil moisture and the surface roughness parameter, and iii) simultaneous retrieval of soil moisture, vegetation water content and surface roughness. All model results are displayed in Figure 2 with the individual retrieval methods differentiated by symbol types. The 2-Parameter (2-P) retrieval of soil moisture and VWC showed for most observation days a reasonable agreement between measured and simulated soil moisture, when all available TB_p data were used ($\Delta SM=0.02-0.08 \text{ m}^3/\text{m}^3$). However, focusing on data collected at mid-range and in particular at high incidence angles decreased the soil moisture accuracy significantly ($\Delta SM=0.06-0.38 \text{ m}^3/\text{m}^3$). In contrast, very good retrieval results were obtained from TB_p observations at very small angles close to nadir-view ($0-5^\circ$), implicating less impact by the vegetation due to i) shorter path lengths through the canopy and ii) the effective composite temperature being closer to that of the soil. Further, for very dry soils and a canopy with low vegetation water content ($<1 \text{ kg}/\text{m}^2$) the vegetation contribution seemed to be less pronounced, enabling soil moisture estimates close to the ground measurements even for brightness temperature observations at angles of $\leq 25^\circ$.

The 2-P retrieval of soil moisture and H_R independently demonstrated a consistent improvement compared to the 1-P approach across all angular ranges, except for the case of low moisture content. The retrieved values followed exactly the angular behaviour of 1-P, which exhibited minor variations and corresponded well to the measurements in wet conditions. The soil moisture estimates for the last observation day, where the measured moisture was approximately $0.14 \text{ m}^3/\text{m}^3$, demonstrated a notable angular trend with increasing discrepancies between model and ground data, the larger the incidence angles of the brightness temperature

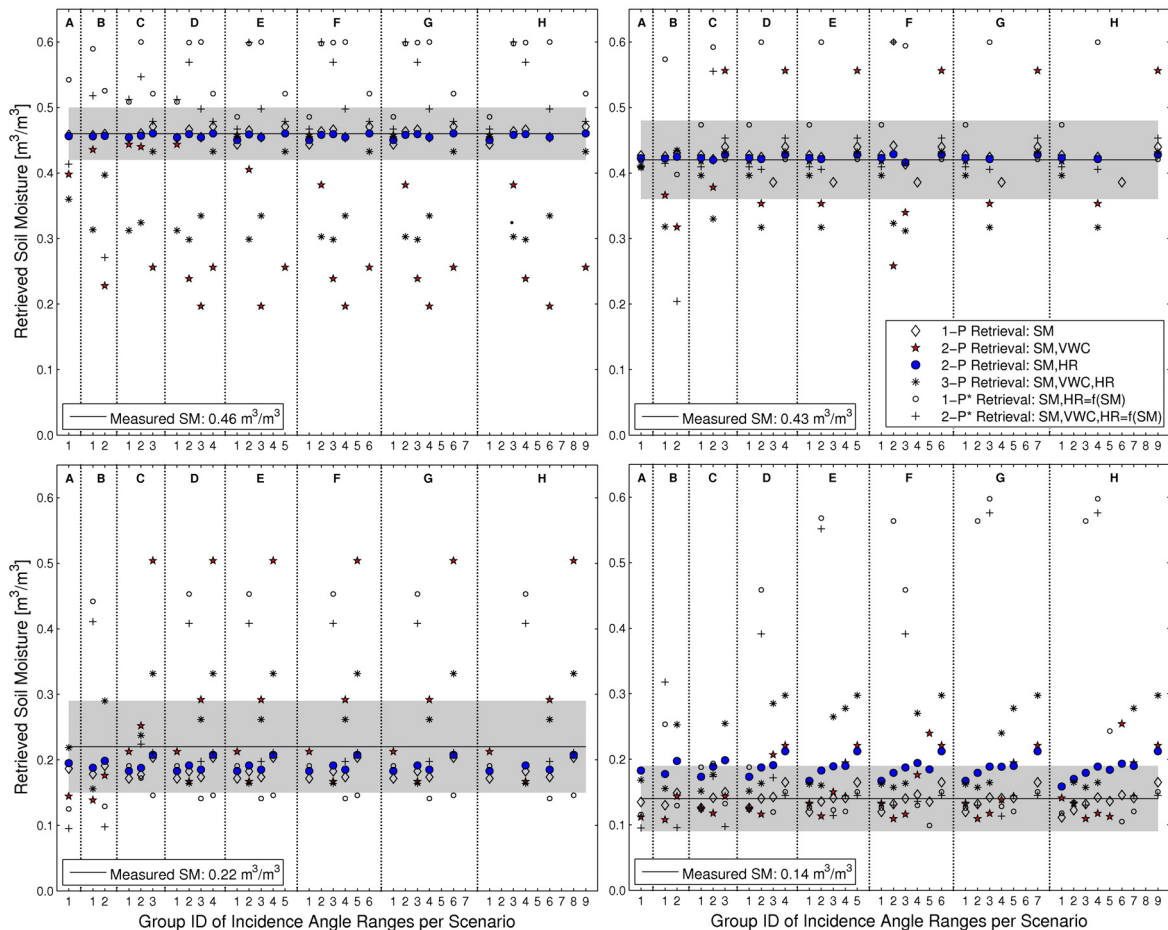


Figure 2. Comparison of modelled moisture values retrieved from airborne brightness temperature data at different incidence angles with measured ground soil moisture given as black line and its standard deviation indicated in grey. Refer to Table 1 for the angular information corresponding to each group and scenario displayed (scenarios are separated by vertical lines). The classification into n-parameter retrievals was based on both the number and type of parameters that were simultaneously derived with soil moisture (* in the legend indicates H_R retrieved as a function of SM).

observations were. This phenomenon might be induced by the increased angular dependency of the optical depth with larger angles causing the model to overcompensate for soil moisture by $\sim 0.05 \text{ m}^3/\text{m}^3$. With respect to the soil moisture retrieval together with H_R , but constraining the surface roughness value as dependent on the retrieved soil moisture value, a linear relationship proposed by Panciera *et al.* (2009a) was implemented into the L-MEB model. Hence, the retrieval was not regarded as an independent 2-P retrieval and instead rather considered as a 1-parameter retrieval (1-P*). The modelled soil moisture data were quite different to that estimated by the independent SM- H_R approach, and did not follow the angular variations of the 1-P retrieval at all. One feature was particularly evident: that soil moisture values retrieved for the incidence angle range of 15-20° were far higher than observed ($\Delta\text{SM}=0.14\text{-}0.46 \text{ m}^3/\text{m}^3$) across all observations days.

For the simultaneous 3-P retrieval of soil moisture, VWC and H_R was characterized by a strong variability of soil moisture estimates across the angles and observation days (Figure 2). In general, best soil moisture retrieval results were obtained from brightness temperature data measured at very small incidence angles (0-5°). This supports the earlier hypothesis of reduced signal interference by the canopy layer for near-nadir views. Besides, according to the observed ground conditions, the retrieved soil moisture values tended to underestimate the wet conditions and overestimate the dry conditions, with most of the results being outside the range of the standard deviation given per day. In contrast, the simultaneous 2-P* retrieval of soil moisture, VWC and the soil moisture dependent H_R , mainly yielded soil moisture values within the range of the standard deviation, which varied slightly across the angular ranges. In comparison with all other retrieval approaches, the minor angular variations were similar to that of the 1-P retrieval of soil moisture with no significant changes for varying moisture conditions.

In order to further assess the performance of the different retrieval approaches across the various incidence angles, the root mean square error (RMSE) between the observed and simulated brightness temperatures were compared for scenario H (Figure 3). Generally, the RMSE tended to decrease with increasing incidence angles for wet conditions, whereas for dry conditions there was little variation across the angles. Moreover, the RMSE calculated for the different n-parameter retrievals applied per observation day were very similar and did not demonstrate any of the discrepancies observed when the actual soil moisture estimates were compared (as shown in Figure 2). This aspect emphasises that the RMSE should not be used as a single criterion for the evaluation of the soil moisture retrieval approach.

5 CONCLUSION

This study investigated the impact of using airborne L-band brightness temperature measurements collected at specific ranges of incidence angles on the accuracy of predicted soil moisture estimates at farm scale. Moreover, multi-parameter retrievals and varying moisture conditions were assessed to find the most suitable angular range of observations for soil moisture retrieval over wheat canopy. In general, the best soil moisture estimates in comparison to ground data were modelled from brightness temperature data collected at incidence-angles between 0-5° among the overall multi-incidence angle range tested (0-50°). This might be related to the dominant vertical structure of the wheat canopy, which affected the soil emission and brightness temperature measurements at near-nadir view to a lesser extent than at large incidence angles, where longer path lengths of the emission through the vegetation layer are more likely to lead to stronger attenuation effects. Additionally, in the case of multi-parameter retrievals model predictions degraded where ancillary data about the vegetation (VWC) was unknown. In contrast, good results with only minor angular variations were observed when soil moisture and surface roughness were retrieved simultaneously. The changing moisture conditions did not show significant impact on the retrieval, except for very dry conditions where the contribution of the vegetation was reduced and instead the surface roughness component (and possibly an increased sampling depth) gained more weight

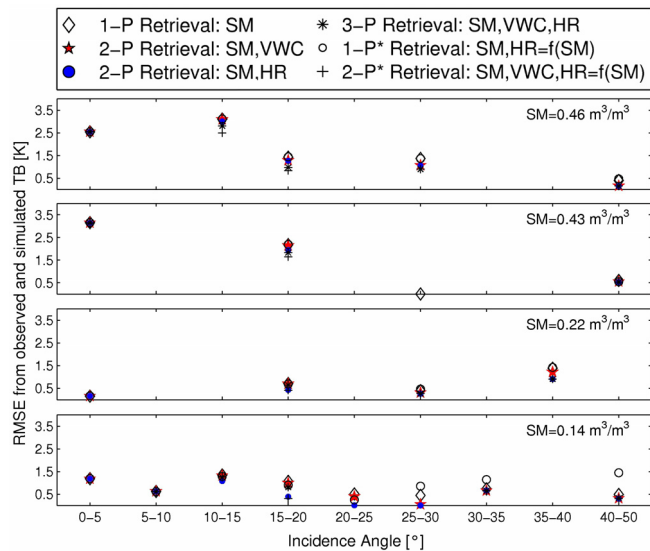


Figure 3. Calculated root mean square error (RMSE) between measured and simulated brightness temperatures (TB) derived for scenario H (Table 1) and n-parameter retrievals considering varying soil moisture conditions.

in the retrieval algorithm. Since the angular retrieval seemed to be closely linked to the vegetation structure, future work should extend the analysis to a wider range of land use types at varying spatial scales and consider combinations of different angular ranges. Moreover, the retrieval of further ancillary L-MEB parameters, such as the soil or vegetation temperature, should be investigated in particular with regard to SMOS data and the usage of descending orbits, where the vegetation temperature is most likely different to the effective temperature of the soil media.

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