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To cite this version:

HAL Id: ird-00425320
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Submitted on 20 Oct 2009

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Assessing the SMOS Soil Moisture Retrieval Parameters With High-Resolution NAFE’06 Data

Olivier Merlin, Jeffrey Phillip Walker, Rocco Panciera, Maria José Escorihuela, and Thomas J. Jackson

Abstract—The spatial and temporal invariance of Soil Moisture and Ocean Salinity (SMOS) forward model parameters for soil moisture retrieval was assessed at 1-km resolution on a diurnal basis with data from the National Airborne Field Experiment 2006. The approach used was to apply the SMOS default parameters uniformly over 27 1-km validation pixels, retrieve soil moisture from the airborne observations, and then to interpret the differences between airborne and ground estimates in terms of land use, parameter variability, and sensing depth. For pastures (17 pixels) and nonirrigated crops (5 pixels), the root mean square error (rmse) was 0.03 volumetric (vol./vol.), soil moisture with a bias of 0.004 vol./vol. For pixels dominated by irrigated crops (5 pixels), the rmse was 0.10 vol./vol., and the bias was −0.09 vol./vol. The correlation coefficient between bias in irrigated areas and the 1-km field soil moisture variability was found to be 0.73, which suggests either 1) an increase of the soil dielectric roughness (up to about one) associated with small-scale heterogeneity of soil moisture or and 2) a difference in sensing depth between an L-band radiometer and the in situ measurements, combined with a strong vertical gradient of soil moisture in the top 6 cm of the soil.

Index Terms—Airborne experiment, calibration, L-band radiometry, National Airborne Field Experiment (NAFE), retrieval algorithm, soil moisture, Soil Moisture and Ocean Salinity (SMOS).

I. INTRODUCTION

THE SOIL Moisture and Ocean Salinity (SMOS, [1]) retrieval algorithm for soil moisture is based on an L-band emission (forward) model calibrated for different soil and vegetation classes [2], [3]. The main parameters involved in the model are the near-surface soil moisture, soil texture, soil surface roughness, soil effective temperature, and vegetation optical depth. In the SMOS level 2 processor [4], brightness temperature is simulated at a 1–4-km resolution by the forward model (land use and land cover are assumed to be uniform at 1–4-km resolution), aggregated to the SMOS observation scale (~40 km), and then compared with the SMOS observed brightness temperature. The angular and polarization capabilities of the SMOS antenna will allow retrieval of several additional parameters (e.g., vegetation optical depth and soil roughness). However, the performance of multiparameter retrieval approaches [5] depends on how well the parameters bounds are estimated, i.e., a priori knowledge of minimum and maximum values. Retrieval assumes that the parameters are rather stable at 1–4-km resolution. However, few experiments have provided multiple angle and polarization L-band data at the intermediate resolution of ~1 km to verify this assumption.

One objective of the National Airborne Field Experiment 2006 (NAFE’06) was to map L-band brightness temperature at 1-km resolution over a range of surface conditions including grassland (pasture and fallow), dry land cropping (wheat, barley, oats) and irrigated cropping (wheat, alfalfa, canola, rice, and corn) [6]. During NAFE’06, ground measurements of the 0–6-cm soil moisture were made coincident with 1-km resolution flights on ten days during the three-week campaign that included two rainfall events of about 7 and 13 mm. NAFE’06 provided a unique data set to test the spatial invariance of retrieval parameters over various land uses, vegetation covers, and surface conditions at 1-km resolution. The approach used was to apply SMOS default parameters uniformly over 27 1-km validation pixels, retrieve surface soil moisture from the airborne observations, and then to interpret differences between airborne and ground estimates in terms of land use, parameter variability, and sensing depth.

II. L-BAND EMISSION MODEL

The SMOS forward model is based on the L-band Microwave Emission of the Biosphere model described in [2]. It includes the tau-omega formulation [7] to express the polarized (H or V) brightness temperature as a function of incidence angle, soil effective temperature, soil emissivity, and nadir optical depth (τ) and single-scattering albedo (ω) of the canopy. The soil microwave emissivity is calculated using the incidence angle, the Fresnel equations, and the soil dielectric permittivity that is computed using the Dobson model [8] and ancillary soil texture. The soil roughness is accounted for using the approach described in [9], which is based on two best fit parameters H and Q. The nadir optical depth τ is related to vegetation water content (VWC) by τ = b × VWC [10] with b a coefficient that is generally obtained from field measurements. In this letter, only the H-polarization (and H-polarized parameters) will be considered.

Since the main objective of this letter is to assess the stability of SMOS forward model parameters at a 1-km resolution, the SMOS default parameters were used. The soil effective temperature was computed based on the parameterization of using soil temperature in the 0–5-cm soil layer, deep soil temperature (50 cm), and the default parameter values presented in [2]. The effects of temperature gradients within the 91

Manuscript received June 10, 2008; revised October 21, 2008 and December 4, 2008.
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Digital Object Identifier 10.1109/LGRS.2008.2012727
canopy were assumed to be minimal by assuming the vegetation temperature throughout the canopy is equal to the near-surface soil temperature. The soil roughness parameter $H$ was set to 0.1 and the polarization-mixing parameter $Q$ to 0.2. The $b$ parameter was set to a value 0.15, which is representative of most agricultural crops [10], and the single scattering albedo $\omega$ to 0.05 [2]. Water interception in vegetation was assumed to be negligible. Note that one pixel included 20% of rice under flood irrigation. The contribution of standing water was removed from the total emission by simulating the L-band emission over water as a function of surface water temperature and incidence angle [12].

### III. Data

NAFE’06 was undertaken during three weeks in November 2006 over a 60 km area in southeastern Australia (−34.9°N; 146.1°E). In this letter, the study area is composed of 27 1-km resolution pixels included in three farms noted as Y2, Y9, and Y12. Land use and land cover are listed in Table I. Within each 1-km area, the 0–6-cm soil moisture was measured on a 250-m resolution grid using a Hydraprobe. An average of three successive measurements ~1 m apart was made at each node of the sampling grid, resulting in about 50 measurements within each 1-km pixel. Note that the calibration equation that was applied to all measurements is site specific [13].

Concurrently with ground observations, the H- and V-polarized brightness temperature was measured at 1-km resolution by the airborne Polarimetric L-band Multibeam Radiometer (PLMR). Flights were undertaken in the window 8:00 A.M.–10:30 A.M. on Julian day (JD) 304, 306, 308, 313, 315, 317, 318, 320, and 322.

### TABLE I

<table>
<thead>
<tr>
<th>Pixel label</th>
<th>Main land use</th>
<th>Main land cover</th>
<th>Variability (vol./vol.)</th>
<th>RMSE (vol./vol.)</th>
<th>Correlation coefficient</th>
<th>Regression slope</th>
<th>Bias (% vol.)</th>
<th>Number of days</th>
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<tr>
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<td>0.82</td>
<td>−0.012</td>
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</tbody>
</table>

* includes at least one crop that was irrigated during NAFE’06.
the mean number of PLMR acquisitions along a 1-km track was about 30 (with a time step of about 1.5 s and an aircraft speed of 200 km/h). During the three-week experiment, the mean soil moisture ranged from about 0.05 to 0.20 vol./vol. (see Table II). However, there was very little corn in the study area. The time of aircraft overflight (ranging from 8:30 A.M. to 12:30 A.M.). Table II presents the time series of the mean and standard deviation of near-surface soil temperature. Soil temperature at 50-cm depth was also estimated from permanent monitoring stations in the study region.

Soil surface roughness was measured with a pin profiler at five locations within each farm. As the link between the measured geometrical roughness and $H$ parameter is not well known [2], those measurements were not used in this letter.

IV. RETRIEVAL RESULTS

Airborne soil moisture was retrieved by minimizing a cost function. This cost function is defined as the root mean square difference between the H-polarized brightness temperature modeled by the radiative transfer model and that observed by the aircraft. All parameters were uniformly set to the values presented above, i.e., soil moisture was the only free parameter in the minimization. The V-polarized brightness temperature was not included in the cost function to simplify the interpretation of retrieval results due to the uncertainty of polarization dependence on the parameters (e.g., roughness). Note that the retrieval was done at the 1-km resolution and the effects of mixed surface in the 1-km resolution footprint were not accounted for except in the presence of standing water.

Fig. 2 compares the 1-km field soil moisture average (cross) and variability (whisker) with the soil moisture retrieval for 12 0–5-cm soil samples collected in the study area. The mean and standard deviation of sand and clay fractions were estimated as 0.26 ± 0.10 and 0.27 ± 0.11, respectively. The highest measured sand fraction was 0.59 (with a clay fraction of 0.11) and the highest clay fraction was 0.49 (with a sand fraction of 0.11). In this letter, the sand and clay fractions are assumed to be uniform and set to 0.3.

Soil surface roughness was estimated from permanent monitoring stations in the study area. However, there was very little corn in the study area. The time series of MODIS LAI for grazing and cropping pixels is shown in Fig. 1(b). At 1-km resolution, LAI ranged from 0.4 to 0.8 and generally decreased by about 0.1 during the three-week experiment.

To compute effective soil temperature, near-surface soil temperature was estimated by the MODIS/Terra 1-km resolution daily temperature on clear sky days (JD 304, 309, 311, 313, 318, 320, and 322) and by the average of the 12 (six stations distributed in the study area with two replicates per station) simultaneous −1-cm soil temperature measurements on cloudy days (JD 306, 308, and 317). Note that the mean ground soil temperature was extracted for each pixel at the time of aircraft
mean square error (rmse), the correlation coefficient, and the 207 bias between airborne retrievals and ground measurements. For 208 the 22 nonirrigated pixels, the rmse is 0.033 (±0.009) vol./vol. 209 with a correlation coefficient of 0.85 (±0.07) and a bias of 0.004 210 (±0.010) vol./vol. when using the SMOS default parameters. 211 For the five irrigated pixels, the rmse is 0.10 (±0.032) vol./vol. 212 with a correlation coefficient of 0.81 (±0.10) and a bias of 213 −0.093 (±0.034) vol./vol.

The bias observed for the airborne soil moisture estimates in 215 the five irrigated pixels could be explained by several factors:

1. The spatial variability of soil texture, soil roughness and/or 217 vegetation. First, soil texture (i.e., sand and clay fractions) 218 impacts the modeled soil emissivity, which in turn impacts the 219 retrieved soil moisture. However, when using the parameters 220 of the soil with the highest measured sand fraction and then 221 those with the highest measured clay fraction in the retrieval 222 algorithm (results not shown), the root mean square difference 223 between the two output data sets was only 0.027 vol./vol., 224 which is much smaller than the observed bias (0.09 vol./vol.). 225

Soil geometric roughness impacts the slope of the relation- 226 ship between soil moisture retrievals and ground measurements. 227 In order to assess the variability of soil geometric roughness at 228 1-km resolution, we examined the slope of the linear regression 229 between airborne and ground estimates (Table I). The slope 230 is 0.87 ± 0.21 for grazing pixels, 0.56 ± 0.13 for dry land 231 cropping pixels, and 0.65 ± 0.20 for irrigated cropping pixels. 232 The difference in the slopes between the grazing and cropping 233 classes was associated with an increase in roughness with 234 agricultural practices in cropped fields (e.g., plowing, irrigation 235 rows, etc.). However, no significant difference in the slopes 236 was observed between the irrigated and nonirrigated areas. 237 Consequently, soil geometric roughness is not considered to be 238 the main cause of the bias observed in the irrigated pixels. 239

The last factor considered was vegetation. The different 240 effects (attenuation, scattering and emission) of vegetation at L- 241 band generally result in an increase of the surface emission. An 242 increase of vegetation optical depth would thus make the soil 243 moisture retrieval lower. However, vegetation cannot explain a 244 0.09 vol./vol. decrease in retrieved soil moisture because vege- 245 tation cover was relatively low at 1-km resolution (LAI ranged 246 from 0.4 to 0.8). Moreover, the b parameter was fixed in the 247 higher range for crops (0.05–0.20), which already maximizes 248 the vegetation impact on the modeled brightness temperature. 249 As an illustration, the irrigated canola in Y12e was harvested 250 during the middle of the campaign, but harvesting did not 251 remove the bias on retrievals (see Fig. 2).

If none of the parameters of the L-band emission model 252 can provide an obvious explanation of the bias found for the 253 airborne estimates, then one may argue that perhaps the ground 254 sensor calibration is not valid in irrigated areas. Four out of the 255 five irrigated pixels are located in the most clayey farm Y12, 256 and it is known that clay fraction can potentially increase the 257 ground sensor response [13]. However, soil type was similar 258 at the farm scale, and no significant bias was observed for the 259 five nonirrigated pixels of Y12 (see Fig. 2). Consequently, the 260 calibration of the ground sensor, which mainly depends on soil 261 type, is considered to be reliable for irrigated areas as well. 262

Having considered the uncertainty in retrieval model inputs 263 and ground measurement data, it was concluded that the poor 264 retrieval results in irrigated areas was due to either a difference 265 in sensing depth between ground and airborne measurements 266 and/or an error in the modeling of soil roughness. The first 267 hypothesis was to consider the different depths of soil involved 268 in the direct and remote measurements. During or immediately 269 after irrigation, the soil moisture of the first layer sensed by 270 the L-band radiometer (0–3 cm according to [17]) could be 271 different to the soil moisture of the lower layer (3–6 cm) that 272 affects the soil moisture measurements carried out by 273 using 0–6-cm Hydraprobes. This hypothesis is supported by 274 the relatively high correlation (estimated to 0.73) between the 275 bias on retrievals and the 1-km field soil moisture variability 276 [see Fig. 3(a)]. However, no information on the soil moisture 277 profile in the top 6 cm was available to confirm the link between 278 vertical and horizontal variability. The second hypothesis was 279 to consider an increase of the “dielectric roughness” with the 280 variability of moisture within the soil. To illustrate the possible 281 impact of the soil moisture variability on soil dielectric rough- 282 ness, parameter H was retrieved in the four irrigated pixels of 283 Y12 by setting soil moisture to ground measurements. Fig. 3(b) 284 shows that the retrieved effective roughness does increase (up 285 to about one) as a function of the 1-km field soil moisture 286 variability with a correlation coefficient estimated to 0.67.
E. Acknowledgment

The authors would like to thank the NAFE’06 participants. The NAFEs have been made possible through recent infrastructures (LE0453434 and LE0560930) and research (DP0557543) funding from the Australian Research Council, and the collaboration of a large number of scientists from throughout Australia, U.S., and Europe. Initial setup and maintenance of the study catchments was funded by a research Grant (DP0343778) from the Australian Research Council and by the Cooperative Research Centre for Catchment Hydrology.

REFERENCES


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