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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 L-band 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 0.09 vol./vol., while for irrigated crops (5 pixels), the rmse was 0.03 vol./vol. for pixels dominated by irrigated crops (5 pixels), and the rmse was 0.04 vol./vol. for pixels not dominated by irrigated crops (12 pixels), and the bias was −0.004 vol./vol. For pixels dominated by irrigated crops (5 pixels), 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 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 SMOS (Soil Moisture and Ocean Salinity) forward model parameters [1] are retrieved from the soil microwave emissivity, which is calculated using the incidence angle, Fresnel equations, and the soil dielectric permittivity. The soil microwave emissivity is calculated using the incidence angle and the Fresnel equations, and the soil dielectric permittivity is computed using the Dobson model [8].

The approach used was to apply SMOS default parameters uniformly over 27 L-band validation pixels, retrieve 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 formula [7] to express the polarized 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. The soil microwave emissivity is computed using the Dobson model [8].

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 soil temperature in the 0–5-cm soil layer, deep soil temperature (50 cm), and the default parameter values were used in [2]. The effects of temperature gradients within the soil.
TABLE I
MEAN 1-km FIELD VARIABILITY OF GROUND MEASUREMENTS AND RMSE, CORRELATION COEFFICIENT, SLOPE OF THE LINEAR REGRESSION, AND MEAN DIFFERENCE (BIAS) BETWEEN 1-km RESOLUTION RETRIEVALS AND 1-km FIELD AVERAGES FOR EACH OF THE 27 VALIDATION PIXELS. THE NUMBER OF SAMPLING DAYS IS ALSO LISTED

<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>
</tr>
</thead>
<tbody>
<tr>
<td>Y2a</td>
<td>grazing</td>
<td>grass</td>
<td>0.026</td>
<td>0.035</td>
<td>0.87</td>
<td>0.87</td>
<td>0.007</td>
<td>10</td>
</tr>
<tr>
<td>Y2b</td>
<td>grazing</td>
<td>grass</td>
<td>0.031</td>
<td>0.026</td>
<td>0.94</td>
<td>1.0</td>
<td>0.014</td>
<td>10</td>
</tr>
<tr>
<td>Y2c</td>
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<td>grass</td>
<td>0.030</td>
<td>0.034</td>
<td>0.91</td>
<td>0.83</td>
<td>0.017</td>
<td>10</td>
</tr>
<tr>
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<td>grazing</td>
<td>grass</td>
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<td>0.042</td>
<td>0.83</td>
<td>1.1</td>
<td>0.005</td>
<td>10</td>
</tr>
<tr>
<td>Y2e</td>
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<td>grass</td>
<td>0.036</td>
<td>0.043</td>
<td>0.79</td>
<td>0.78</td>
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<td>10</td>
</tr>
<tr>
<td>Y2f</td>
<td>grazing</td>
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<td>0.034</td>
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<td>0.88</td>
<td>0.031</td>
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</tr>
<tr>
<td>Y2g</td>
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<td>grass</td>
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<td>1.2</td>
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</tr>
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<td>grass</td>
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<td>0.030</td>
<td>0.92</td>
<td>1.0</td>
<td>0.009</td>
<td>10</td>
</tr>
<tr>
<td>Y2i</td>
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<td>grass</td>
<td>0.042</td>
<td>0.023</td>
<td>0.94</td>
<td>0.89</td>
<td>0.004</td>
<td>10</td>
</tr>
<tr>
<td>Y2a</td>
<td>fallow</td>
<td>grass</td>
<td>0.034</td>
<td>0.034</td>
<td>0.72</td>
<td>0.41</td>
<td>0.004</td>
<td>10</td>
</tr>
<tr>
<td>Y2b</td>
<td>fallow</td>
<td>grass</td>
<td>0.025</td>
<td>0.024</td>
<td>0.90</td>
<td>0.74</td>
<td>0.012</td>
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</tr>
<tr>
<td>Y2c</td>
<td>fallow</td>
<td>grass</td>
<td>0.030</td>
<td>0.028</td>
<td>0.90</td>
<td>1.3</td>
<td>-0.012</td>
<td>8</td>
</tr>
<tr>
<td>Y2d</td>
<td>cropping/grazing</td>
<td>alfalfa</td>
<td>0.068</td>
<td>0.027</td>
<td>0.75</td>
<td>0.43</td>
<td>0.001</td>
<td>10</td>
</tr>
<tr>
<td>Y2e</td>
<td>cropping</td>
<td>oats/barley</td>
<td>0.032</td>
<td>0.032</td>
<td>0.89</td>
<td>0.48</td>
<td>0.003</td>
<td>10</td>
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<tr>
<td>Y2f</td>
<td>grazing</td>
<td>grass</td>
<td>0.044</td>
<td>0.026</td>
<td>0.84</td>
<td>0.75</td>
<td>0.003</td>
<td>10</td>
</tr>
<tr>
<td>Y2g</td>
<td>cropping*</td>
<td>alfalfa</td>
<td>0.098</td>
<td>0.10</td>
<td>0.92</td>
<td>0.50</td>
<td>-0.090</td>
<td>10</td>
</tr>
<tr>
<td>Y2h</td>
<td>cropping</td>
<td>grass</td>
<td>0.059</td>
<td>0.042</td>
<td>0.85</td>
<td>0.58</td>
<td>0.022</td>
<td>10</td>
</tr>
<tr>
<td>Y2i</td>
<td>cropping</td>
<td>grass</td>
<td>0.032</td>
<td>0.023</td>
<td>0.92</td>
<td>0.72</td>
<td>-0.006</td>
<td>10</td>
</tr>
<tr>
<td>Y2a</td>
<td>cropping*</td>
<td>wheat</td>
<td>0.033</td>
<td>0.056</td>
<td>0.95</td>
<td>0.85</td>
<td>-0.044</td>
<td>8</td>
</tr>
<tr>
<td>Y2b</td>
<td>grazing</td>
<td>grass</td>
<td>0.029</td>
<td>0.027</td>
<td>0.89</td>
<td>0.80</td>
<td>-0.007</td>
<td>8</td>
</tr>
<tr>
<td>Y2c</td>
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<td>grass</td>
<td>0.027</td>
<td>0.037</td>
<td>0.81</td>
<td>0.95</td>
<td>0.007</td>
<td>8</td>
</tr>
<tr>
<td>Y2d</td>
<td>cropping*</td>
<td>wheat</td>
<td>0.13</td>
<td>0.14</td>
<td>0.68</td>
<td>0.47</td>
<td>-0.13</td>
<td>10</td>
</tr>
<tr>
<td>Y2e</td>
<td>cropping*</td>
<td>canola</td>
<td>0.11</td>
<td>0.12</td>
<td>0.75</td>
<td>0.80</td>
<td>-0.11</td>
<td>10</td>
</tr>
<tr>
<td>Y2f</td>
<td>grazing</td>
<td>grass</td>
<td>0.035</td>
<td>0.043</td>
<td>0.78</td>
<td>0.87</td>
<td>0.005</td>
<td>10</td>
</tr>
<tr>
<td>Y2g</td>
<td>cropping*</td>
<td>cut corn</td>
<td>0.090</td>
<td>0.089</td>
<td>0.86</td>
<td>0.93</td>
<td>-0.086</td>
<td>9</td>
</tr>
<tr>
<td>Y2h</td>
<td>grazing</td>
<td>grass</td>
<td>0.064</td>
<td>0.051</td>
<td>0.63</td>
<td>0.46</td>
<td>-0.017</td>
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</tr>
<tr>
<td>Y2i</td>
<td>grazing</td>
<td>grass</td>
<td>0.083</td>
<td>0.033</td>
<td>0.87</td>
<td>0.82</td>
<td>-0.012</td>
<td>10</td>
</tr>
</tbody>
</table>

* includes at least one crop that was irrigated during NAFE’06.

TABLE II
MEAN AND STANDARD DEVIATION OF 0–6-cm SOIL MOISTURE, H-POLARIZED BRIGHTNESS TEMPERATURE, AND NEAR-SURFACE SOIL TEMPERATURE FOR EACH OF THE TEN SAMPLING DAYS AT TIME OF AIRCRAFT OVERPASS. TWO RAINFALL EVENTS OCCURRED DURING THE THREE-WEEK CAMPAIGN WITH ~7 mm ON JD 306-307 AND ~13 mm ON JD 316-317

<table>
<thead>
<tr>
<th>JD (day)</th>
<th>Mean soil moisture (vol./vol.)</th>
<th>Mean brightness temperature (K)</th>
<th>Mean soil temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>0.051 (0.053)</td>
<td>266 (7.7)</td>
<td>41 (7.0)</td>
</tr>
<tr>
<td>306</td>
<td>0.057 (0.058)</td>
<td>269 (7.7)</td>
<td>36 (2.4)</td>
</tr>
<tr>
<td>308</td>
<td>0.11 (0.075)</td>
<td>246 (7.8)</td>
<td>39 (1.2)</td>
</tr>
<tr>
<td>309</td>
<td>0.085 (0.063)</td>
<td>259 (8.8)</td>
<td>39 (1.3)</td>
</tr>
<tr>
<td>311</td>
<td>0.078 (0.067)</td>
<td>266 (8.0)</td>
<td>38 (6.0)</td>
</tr>
<tr>
<td>313</td>
<td>0.098 (0.056)</td>
<td>267 (8.1)</td>
<td>39 (1.4)</td>
</tr>
<tr>
<td>317</td>
<td>0.22 (0.055)</td>
<td>216 (13)</td>
<td>29 (5.7)</td>
</tr>
<tr>
<td>318</td>
<td>0.18 (0.047)</td>
<td>240 (9.5)</td>
<td>31 (4.8)</td>
</tr>
<tr>
<td>320</td>
<td>0.16 (0.055)</td>
<td>243 (11)</td>
<td>22 (6.0)</td>
</tr>
<tr>
<td>322</td>
<td>0.098 (0.040)</td>
<td>263 (9.9)</td>
<td>44 (1.1)</td>
</tr>
</tbody>
</table>

III. DATA

NAFE’06 was undertaken during three weeks in November 2006 over a 40 by 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, 120...
The mean number of PLMR acquisitions along a track 1-km resolution radiometric measurements (together with incidence angle) were also averaged within each 1-km pixel. Note that the mean number of PLMR acquisitions along a 1-km run 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. corresponding to a mean brightness temperature of 270 K and 220 K, respectively (see Table II).

VWC was estimated from MODIS/Terra 1-km resolution eight-day LAI products on JD 297, 305, 313, and 312 using the relationship $VWC = 0.5 \text{ LAI}$ [16]. VWC maps were then linearly interpolated between dates and regrided on the same 1-km grid as processed PLMR brightness temperature. The relationship between VWC and LAI during NAFe’06 is shown in Fig. 1(a) using ground observations obtained during the campaign. The slope 0.5 appears to hold for all vegetation types encountered except for corn, which has a slope of about three. However, there was very little corn in the study area. The mean and standard deviation of soil moisture was computed as the standard deviation of the ground measurements within the 1-km PLMR pixel. In most cases, the difference between ground measurements and airborne estimates was smaller than the 1-km field variability (see Table I). However, a significant bias was apparent for the five farms Y2, Y9, and Y12. The 1-km field variability of soil moisture was the only free parameter 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 each 1-km pixel (Y9g) contained a measurable fraction (20%) of standing water. Table I lists for each of the 27 validation pixels the root-mean-square error (RMSE) and variability (whisker) with the soil moisture retrieval for each 1-km pixel.
mean square error (rmse), the correlation coefficient, and the bias between airborne retrievals and ground measurements. For the 22 nonirrigated pixels, the rmse is 0.033 (±0.009) vol./vol. with a correlation coefficient of 0.85 (±0.07) and a bias of 0.004 (±0.010) vol./vol. when using the SMOS default parameters. For the five irrigated pixels, the rmse is 0.10 (±0.032) vol./vol. with a correlation coefficient of 0.81 (±0.10) and a bias of −0.093 (±0.034) vol./vol.

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

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

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

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

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

Having considered the uncertainty in retrieval model inputs and ground measurement data, it was concluded that the poor retrieval results in irrigated areas was due to either a difference in sensing depth between ground and airborne measurements and/or an error in the modeling of soil roughness. The first hypothesis to consider was the different depths of soil involved in the direct and remote measurements. During or immediately after irrigation, the soil moisture of the first layer sensed by the L-band radiometer (0–3 cm according to [17]) could be different to the soil moisture of the lower layer (3–6 cm) that was measured using 0–6-cm Hydraprobes. This hypothesis is supported by the relatively high correlation (estimated to 0.73) between the 275 bias on retrievals and the 1-km field soil moisture variability [231] and/or an error in the modeling of soil roughness. The first hypothesis was to consider the different depths of soil involved in the direct and remote measurements. During or immediately after irrigation, the soil moisture of the first layer sensed by the L-band radiometer (0–3 cm according to [17]) could be different to the soil moisture of the lower layer (3–6 cm) that was measured using 0–6-cm Hydraprobes. This hypothesis is supported by the relatively high correlation (estimated to 0.73) between the 275 bias on retrievals and the 1-km field soil moisture variability [231]. However, no information on the soil moisture profile in the top 6 cm was available to confirm the link between vertical and horizontal variability. The second hypothesis was to consider an increase of the “dielectric roughness” with the variability of moisture within the soil. To illustrate the possible impact of the soil moisture variability on soil dielectric roughness, parameter H was retrieved in the four irrigated pixels of Y12 by setting soil moisture to ground measurements. Fig. 3(b) shows that the retrieved effective roughness does increase (up to about one) as a function of the 1-km field soil moisture variability with a correlation coefficient estimated to 0.67.
The temporal and spatial invariance of the SMOS forward model parameters was assessed at a 1-km resolution on a 299 diurnal basis using the NAFE'06 data. The approach used 299 was to apply the SMOS default parameters uniformly over 27 1-km pixels, retrieve soil moisture from the airborne observa- 299 tions, and then to interpret differences between airborne and 299 ground estimates in terms of land use, parameter variability, and 299 sensing depth. For nonirrigated (grazing and cropping) areas, 299 the rmse on retrievals was 0.03 vol./vol., and the correlation 299 coefficient with ground measurements was 0.85. The impact 299 of soil geometric roughness was noted by correlating the slope 300 of the linear regression between airborne and ground estimates 301 with agricultural practices. A roughness parameter 302 \( H = 0.1 \) was found to be appropriate for grazing areas (slope 303 was about one), while a slightly higher roughness was identified 304 for cropping areas (slope was about 0.7). A significant mean 3055 difference of \(-0.09\) vol./vol. between airborne and ground 306 estimates was observed in the five irrigated pixels. As no 307 parameter (soil texture, soil geometric roughness, vegetation) 308 could explain this bias, it is suggested that either a strong 309 vertical gradient of near-surface soil moisture in irrigated areas 310 made the 0–6-cm ground measurements generally wetter than 311 the 0–3-cm retrievals and/or the small-scale variability of soil 312 moisture made the effective soil roughness increase up to 313 about one.

**Acknowledgment**

The authors would like to thank the NAFE’06 participants. 315 The NAFEs have been made possible through recent infrastruc- 317 ture (LE0453434 and LE0560930) and research (DP0557543) 318 funding from the Australian Research Council, and the col- 319 laboration of a large number of scientists from throughout 319 Australia, U.S., and Europe. Initial setup and maintenance of 320 the study catchments was funded by a research Grant 321 (DP0343778) from the Australian Research Council and by the 322 Cooperative Research Centre for Catchment Hydrology.

**References**


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