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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, and 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 $\tau = b \times \text{VWC}$ [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 [11] 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

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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

Pixel label	Main land use	Main land cover	Variability (vol./vol.)	RMSE (vol./vol.)	Correlation coefficient	Regression slope	Bias (% vol.)	Number of days
Y2a	grazing	grass	0.026	0.035	0.87	0.87	0.007	10
Y2b	grazing	grass	0.031	0.026	0.94	1.0	0.014	10
Y2c	grazing	grass	0.030	0.034	0.91	0.83	0.017	10
Y2d	grazing	grass	0.035	0.042	0.83	1.1	0.005	10
Y2e	grazing	grass	0.036	0.043	0.79	0.78	-0.008	10
Y2f	grazing	grass	0.038	0.034	0.87	0.88	0.031	10
Y2g	grazing	grass	0.041	0.034	0.92	1.2	0.008	10
Y2h	grazing	grass	0.040	0.030	0.92	1.0	0.009	10
Y2i	grazing	grass	0.042	0.023	0.94	0.89	0.004	10
Y9a	fallow	grass	0.034	0.034	0.72	0.41	0.004	10
Y9b	fallow	grass	0.025	0.024	0.90	0.74	0.012	9
Y9c	grazing	grass	0.030	0.028	0.90	1.3	-0.012	8
Y9d	cropping/grazing	alfalfa	0.068	0.027	0.75	0.43	0.001	10
Y9e	cropping	oats/barley	0.032	0.032	0.89	0.48	0.003	10
Y9f	grazing	grass	0.044	0.026	0.84	0.75	0.003	10
Y9g	cropping*	alfalfa	0.098	0.10	0.92	0.50	-0.090	10
Y9h	cropping	grass	0.059	0.042	0.85	0.58	0.022	10
Y9i	cropping	grass	0.032	0.023	0.92	0.72	-0.006	10
Y12a	cropping*	wheat	0.033	0.056	0.85	0.52	-0.044	8
Y12b	grazing	grass	0.029	0.027	0.89	0.80	-0.007	8
Y12c	grazing	grass	0.027	0.037	0.81	0.95	0.007	8
Y12d	cropping*	wheat	0.13	0.14	0.68	0.47	-0.13	10
Y12e	cropping*	canola	0.11	0.12	0.75	0.80	-0.11	10
Y12f	grazing	grass	0.035	0.043	0.78	0.87	0.005	10
Y12g	cropping*	cut corn	0.090	0.089	0.86	0.93	-0.086	9
Y12h	grazing	grass	0.064	0.051	0.63	0.46	-0.017	10
Y12i	grazing	grass	0.083	0.033	0.87	0.82	-0.012	10

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

92 canopy were assumed to be minimal by assuming the vegetation
93 temperature throughout the canopy is equal to the near-surface
94 soil temperature. The soil roughness parameter H was set to
95 0.1 and the polarization-mixing parameter Q to 0 [2]. The b
96 parameter was set to a value 0.15, which is representative of
97 most agricultural crops [10], and the single scattering albedo ω
98 to 0.05 [2]. Water interception in vegetation was assumed to be
99 negligible. Note that one pixel included 20% of rice under flood
100 irrigation. The contribution of standing water was removed
101 from the total emission by simulating the L-band emission over
102 water as a function of surface water temperature and incidence
103 angle [12].

104

III. DATA

105 NAFE'06 was undertaken during three weeks in Novem-
106 ber 2006 over a 40 by 60 km area in southeastern Australia
107 (-34.9° N; 146.1° E). In this letter, the study area is composed
108 of 27 1-km resolution pixels included in three farms noted as
109 Y2, Y9, and Y12. Land use and land cover are listed in Table I.
110 Within each 1-km area, the 0–6-cm soil moisture was measured
111 on a 250-m resolution grid using a Hydraprobe. An average of
112 three successive measurements ~ 1 m apart was made at each
113 node of the sampling grid, resulting in about 50 measurements
114 within each 1-km pixel. Note that the calibration equation that
115 was applied to all measurements is site specific [13].

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

JD	Mean (standard deviation)		
	soil moisture (vol./vol.)	brightness temperature (K)	soil temperature ($^\circ$ C)
304	0.051 (0.053)	266 (7.7)	41 (7.0)
306	0.057 (0.058)	269 (7.7)	36 (2.4)
308	0.11 (0.075)	246 (7.8)	39 (1.2)
309	0.085 (0.063)	259 (8.8)	39 (1.3)
311	0.078 (0.067)	266 (8.0)	38 (6.0)
313	0.059 (0.056)	267 (8.1)	39 (1.4)
317	0.22 (0.055)	216 (13)	29 (5.7)
318	0.18 (0.047)	240 (9.5)	31 (4.8)
320	0.16 (0.055)	243 (11)	22 (6.0)
322	0.098 (0.040)	263 (9.9)	44 (1.1)

Concurrently with ground observations, the H- and 116
V-polarized brightness temperature was measured at 1-km res- 117
olution by the airborne Polarimetric L-band Multibeam Ra- 118
diometer (PLMR). Flights were undertaken in the window 119
8:00 A.M.–10:30 A.M. on Julian day (JD) 304, 306, 308, 120

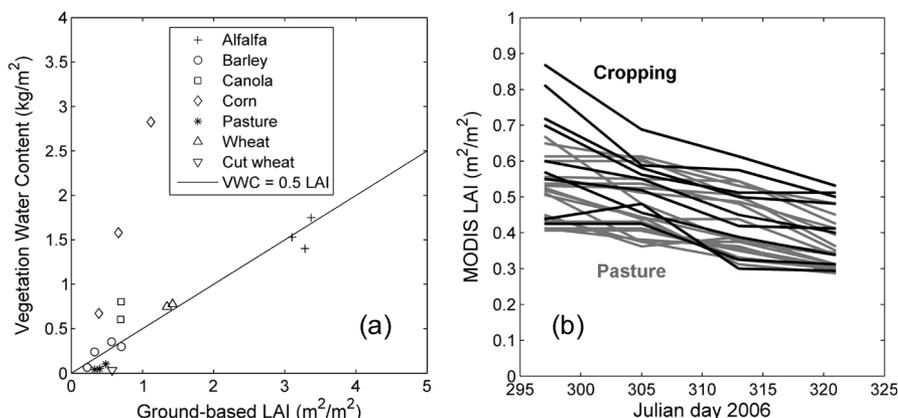


Fig. 1. (Left) Ground-based measurement of VWC versus LAI for each vegetation type in the study area, and (right) time series of MODIS eight-day LAI product extracted for each 1-km pixel.

121 309, 311, 313, 320, and 322 and in the window 11:00 A.M.–
 122 1:30 P.M. on JD 317 and 318. The same flight lines were
 123 kept across the campaign to obtain approximately the same
 124 incidence angle over each pixel. Note that changes in aircraft
 125 attitude were accounted for during processing by correcting the
 126 zero tilt and roll incidence angle of the six beams (which are
 127 $\pm 7^\circ$, $\pm 21.5^\circ$, $\pm 38.5^\circ$) with respect to the topography. Details
 128 about PLMR and its calibration can be found in [14]. Some
 129 minor occurrences of sunglint were detected in the NAFE'06
 130 area, but not over the sampling areas [15].

131 To compare ground and airborne observations, the point-
 132 scale soil moisture measurements were averaged at 1-km res-
 133 olution within each of the 27 validation pixels. The along
 134 track 1-km resolution radiometric measurements (together with
 135 incidence angle) were also averaged within each 1-km pixel.
 136 Note that the mean number of PLMR acquisitions along a
 137 1-km run was about 30 (with a time step of about 1.5 s and an
 138 aircraft speed of 200 km/h). During the three-week experiment,
 139 the mean soil moisture ranged from about 0.05 to 0.20 vol./vol.
 140 corresponding to a mean brightness temperature of 270 K and
 141 220 K, respectively (see Table II).

142 VWC was estimated from MODIS/Terra 1-km resolution
 143 eight-day LAI products on JD 297, 305, 313, and 312 using
 144 the relationship $VWC = 0.5 LAI$ [16]. VWC maps were then
 145 linearly interpolated between dates and regridded on the same
 146 1-km grid as processed PLMR brightness temperature. The
 147 relationship between VWC and LAI during NAFE'06 is shown
 148 in Fig. 1(a) using ground observations obtained during the
 149 campaign. The slope 0.5 appears to hold for all vegetation types
 150 encountered except for corn, which has a slope of about three.
 151 However, there was very little corn in the study area. The time
 152 series of MODIS LAI for grazing and cropping pixels is shown
 153 in Fig. 1(b). At 1-km resolution, LAI ranged from 0.4 to 0.8
 154 and generally decreased by about 0.1 during the three-week
 155 experiment.

156 To compute effective soil temperature, near-surface soil tem-
 157 perature was estimated by the MODIS/Terra 1-km resolution
 158 daily temperature on clear sky days (JD 304, 309, 311, 313,
 159 318, 320, and 322) and by the average of the 12 (six stations
 160 distributed in the study area with two replicates per station)
 161 simultaneous –1-cm soil temperature measurements on cloudy
 162 days (JD 306, 308, and 317). Note that the mean ground soil
 163 temperature was extracted for each pixel at the time of aircraft

overflight (ranging from 8:30 A.M. to 12:30 A.M.). Table II
 164 presents the time series of the mean and standard deviation of 165
 166 near-surface soil temperature. Soil temperature at 50-cm depth
 167 was also estimated from permanent monitoring stations in the
 168 study region.

169 Soil texture was analyzed for 12 0–5-cm soil samples col-
 170 lected in the study area. The mean and standard deviation of 170
 171 sand and clay fractions were estimated as 0.26 ± 0.10 and
 172 0.27 ± 0.11 , respectively. The highest measured sand fraction
 173 was 0.59 (with a clay fraction of 0.11) and the highest clay
 174 fraction was 0.49 (with a sand fraction of 0.11). In this letter,
 175 the sand and clay fractions are assumed to be uniform and
 176 set to 0.3.

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

IV. RETRIEVAL RESULTS

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

194 Fig. 2 compares the 1-km field soil moisture average (cross)
 195 and variability (whisker) with the soil moisture retrieval for
 196 farms Y2, Y9, and Y12. The 1-km field variability of soil
 197 moisture was computed as the standard deviation of the ground
 198 measurements within the 1-km PLMR pixel. In most cases,
 199 the difference between ground measurements and airborne
 200 estimates was smaller than the 1-km field variability (see
 201 Table I). However, a significant bias was apparent for the five
 202 irrigated pixels (labeled Y9g, Y12a,d,e,g), although only one
 203 pixel (Y9g) contained a measurable fraction (20%) of standing
 204 water. Table I lists for each of the 27 validation pixels the root
 205

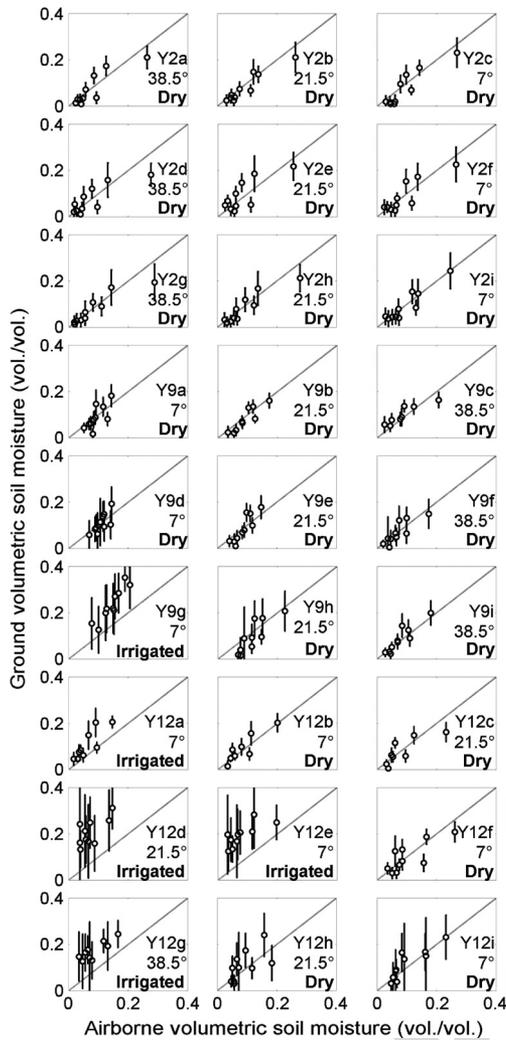


Fig. 2. One-kilometer (cross) field average and (whisker) variability of *in situ* measurements versus retrievals at the 27 1-km resolution validation pixels. Pixel label and mean incidence angle are also indicated.

206 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 $0.033 (\pm 0.009)$ vol./vol.
 209 with a correlation coefficient of $0.85 (\pm 0.07)$ 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 $0.10 (\pm 0.032)$ vol./vol.
 212 with a correlation coefficient of $0.81 (\pm 0.10)$ and a bias of
 213 $-0.093 (\pm 0.034)$ vol./vol.

214 The bias observed for the airborne soil moisture estimates in
 215 the five irrigated pixels could be explained by several factors:
 216 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

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

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

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 instead 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 .
 287

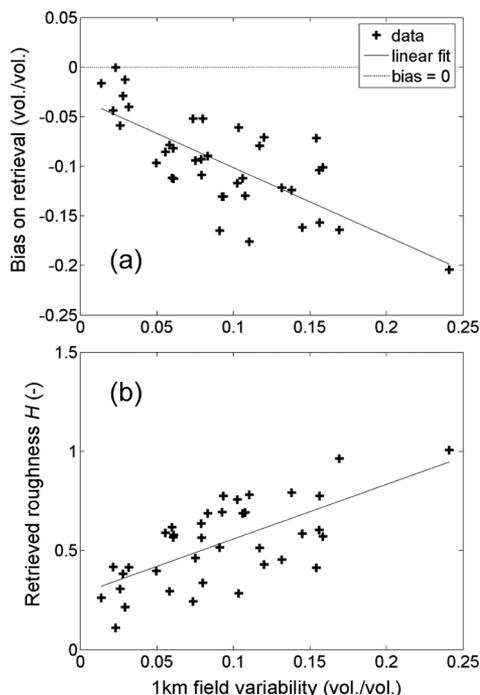


Fig. 3. Difference between (a) airborne and ground estimates and (b) retrieved soil roughness parameter H versus 1-km field soil moisture variability including data from the four irrigated pixels in Y12.

288

V. CONCLUSION

289 The temporal and spatial invariance of the SMOS forward
 290 model parameters was assessed at a 1-km resolution on a
 291 diurnal basis using the NAFE'06 data. The approach used
 292 was to apply the SMOS default parameters uniformly over 27
 293 1-km pixels, retrieve soil moisture from the airborne observa-
 294 tions, and then to interpret differences between airborne and
 295 ground estimates in terms of land use, parameter variability, and
 296 sensing depth. For nonirrigated (grazing and cropping) areas,
 297 the rmse on retrievals was 0.03 vol./vol. and the correlation
 298 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 $H = 0.1$
 302 was found to be appropriate for grazing areas (slope was
 303 about one), while a slightly higher roughness was identified
 304 for cropping areas (slope was about 0.7). A significant mean
 305 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.

314

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