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Use of TerraSAR-X Data to Retrieve Soil Moisture Over Bare Soil Agricultural Fields

Nicolas Baghdadi, Maelle Aubert, and Mehrez Zribi

Abstract—The retrieval of the bare soil moisture content from TerraSAR-X data is discussed using empirical approaches. Two cases were evaluated: 1) one image at low or high incidence angle and 2) two images, one at low incidence and one at high incidence. This study shows by using three databases collected between 2008 and 2010 over two study sites in France (Orgeval and Villamblain) that TerraSAR-X is a good remote sensing tool for the retrieving of surface soil moisture with accuracy of about 3% (rmse). Moreover, the accuracy of the soil moisture estimate does not improve when two incidence angles (26° – 28° or 50° – 52°) are used instead of only one. When compared with the result obtained with a high incidence angle (50° – 52°), the use of low incidence angle (26° – 28°) does not enable a significant improvement in estimating soil moisture (about 1%).

Index Terms—Soil moisture, TerraSAR-X images.

I. INTRODUCTION

RADAR SIGNAL is a function of soil moisture and surface roughness in the case of bare soil. The possibility of retrieving these soil parameters was little investigated from X-band synthetic aperture radar (SAR). However, many studies were carried out by using C-band radar data (e.g., [1]–[4]). With the launch of satellites using the X-band (~ 9.6 GHz), such as TerraSAR-X and COSMO-SkyMed, the use of X-band data to derive soil parameters became possible. A radar configuration that minimizes the effects of surface roughness is recommended for a better estimate of soil moisture when using only one incidence angle. The optimal radar incidences in C-band for the retrieval of soil moisture are smaller than 35° [4].

Soil moisture estimation from SAR images is carried out by using physical or statistical models. Physical approach consists in using a physical model, such as the integral equation model [5], to predict the radar backscattering coefficient from SAR and soil parameters (wavelength, polarization, incidence angle, surface roughness, and soil dielectric constant). Statistical models based on experimental measurements are also often used in soil moisture estimation. For bare soils, the increase of radar signal (σ°) is supposed to be linear with the volumetric soil



Fig. 1. Location of study sites. (1) Orgeval. (2) Villamblain.

moisture for values between 5% and 35% [6]. Moreover, σ° increases with soil surface roughness and follows an exponential or logarithmic behavior (e.g., [4] and [7]).

Very few studies analyzed the sensitivity of TerraSAR-X data to bare soil surface parameters. Baghdadi *et al.* [8] have observed that the radar signal at X-band is slightly more sensitive to surface roughness at high incidence angle than at low incidence angle. The difference observed between radar signals reflected by the roughest and smoothest areas increases with the radar wavelength. Moreover, results showed that the sensitivity of radar signal to surface roughness is better with PALSAR in L-band than with TerraSAR-X in X-band and that the C- and X-bands are similar sensitivity results. In this letter, only *in situ* soil moisture measurements in very wet conditions between 25% and 40% are available. Results obtained showed that the backscattering coefficient at X-band is stable when the moisture content ranges between 25% and 35% and that it decreases beyond this threshold.

Aubert *et al.* [9] have showed that the sensitivity of the TerraSAR-X signal to soil moisture is very important at low and high incidence angles. In comparison to results published with C-band SAR data, this sensitivity of the radar signal to soil moisture is higher in X-band. The second important result concerns the potential of the fine spatial resolution of TerraSAR (1 m) in the detection of soil moisture variations at the within-plot scale. The spatial distribution of slaking crust could be detected when soil moisture variation is observed between soil crusted and soil without crust. Indeed, areas covered by slaking crust could have greater soil moisture and, consequently, a greater backscattering signal than soils without crust.

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TABLE I
 CHARACTERISTICS OF TERRASAR-X IMAGES AND SUMMARY OF GROUND-TRUTH MEASUREMENTS (*mv*, *rms*, AND *L*)

Date dd-mm-yy	Site	Pol.-Inc.	Fields number	<i>mv</i> (%) (min;max)	<i>rms</i> (cm) (min;max)	<i>L</i> (cm) (min;max)
06-02-08	Villamblain	HH-52°	8	(27 ; 34)	(1.3 ; 3.1)	(4.5 ; 9.1)
07-02-08	Villamblain	HH-28°	8	(27 ; 34)	(1.3 ; 3.1)	(4.5 ; 9.1)
12-02-08	Orgeval	HH-50°	6	(31 ; 36)	(1.8 ; 3.3)	(5.0 ; 9.3)
13-02-08	Orgeval	HH-26°	6	(31 ; 35)	(1.8 ; 3.3)	(5.0 ; 9.3)
17-03-09	Orgeval	HH-26°	7	(25 ; 32)	(1.7 ; 2.3)	(4.8 ; 6.9)
18-03-09	Orgeval	HH-50°	7	(24 ; 30)	(1.7 ; 2.3)	(4.8 ; 6.9)
25-03-09	Orgeval	HH-50°	3	(28 ; 29)	(2.0 ; 2.7)	(4.8 ; 5.7)
26-03-09	Orgeval	HH-26°	3	(24 ; 31)	(2.0 ; 2.7)	(4.8 ; 5.7)
08-04-09	Orgeval	HH-26°	6	(17 ; 26)	(1.1 ; 2.1)	(3.7 ; 6.0)
09-04-09	Orgeval	HH-50°	6	(15 ; 26)	(1.1 ; 2.1)	(3.7 ; 6.0)
01-03-10	Orgeval	HH-50°	6	(33 ; 40)	(1.9 ; 2.9)	(5.9 ; 7.5)
02-03-10	Orgeval	HH-26°	6	(33 ; 37)	(1.9 ; 2.9)	(5.9 ; 7.5)
12-03-10	Orgeval	HH-50°	7	(13 ; 25)	(1.1 ; 2.6)	(4.6 ; 7.0)
13-03-10	Orgeval	HH-26°	7	(15 ; 22)	(1.1 ; 2.6)	(4.6 ; 7.0)

71 At least one research question remained open. It concerns
 72 the precision of the soil moisture estimates in bare agricultural
 73 soils. The objective of this study is to examine the potential of
 74 TerraSAR-X data for retrieving volumetric soil moisture over
 75 bare soils. This work evaluates if the use of two incidence
 76 angles at X-band [one low (26°–28°) and one high (50°–52°)]
 77 improves the accuracy of the estimate of surface soil moisture
 78 in comparison to only one incidence (low or high). TerraSAR-X
 79 sensor has the advantage to acquire on the same study site
 80 image pairs at low and high incidence angles within one day.
 81 The goal of this work is to compare the findings with C- and
 82 X-band data. At C-band, several studies have shown that the
 83 use of two incidence angles provides distinct improvement in
 84 the soil moisture estimate, in comparison with results obtained
 85 using a single incidence (e.g., [1], [2], and [4]). Moreover,
 86 low incidence angle is better than the high incidence angle
 87 for estimating soil moisture with C-band SAR data. This letter
 88 investigates this research question.

During the period of February–April (our SAR acquisitions), 99
 the main crops are wheat and colza. They cover approximately 100
 50% of the agricultural area. The remaining surface corre- 101
 sponds to plowed soils awaiting future cultivation (corn and 102
 potato). 103

B. TerraSAR-X Images 104

Fourteen TerraSAR-X images (X-band ~9.65 GHz) were 105
 acquired during the years of 2008, 2009, and 2010 (Table I). 106
 The radar data are available in HH polarization, with incidence 107
 angles (θ) of 26°, 28°, 50°, and 52°. The imaging mode 108
 used was spotlight with a pixel spacing of 1 m. Radiometric 109
 calibration using multilook ground range detected TerraSAR-X 110
 images was first carried out using the following equation [10]: 111

$$\sigma_i^\circ(\text{dB}) = \log_{10}(Ks \cdot DN_i^2 - NEBN) + 10 \log_{10}(\sin \theta_i). \quad (1)$$

This equation transforms the amplitude of backscattered sig- 112
 nal for each pixel (DN_i) into a backscattering coefficient (σ°) 113
 in decibels. Ks is the calibration coefficient, and $NEBN$ is 114
 the noise equivalent beta naught. All TerraSAR-X images were 115
 then georeferenced using GPS points with a root-mean-square 116
 error of the control points of approximately one pixel (i.e., 1 m). 117
 This coregistration error was overcome by removing two 118
 boundary pixels from each training plot relative to the limits 119
 defined by the GPS control points. The mean backscattering 120
 coefficients were calculated from calibrated SAR images by 121
 averaging the linear σ° values of all pixels within reference 122
 fields. 123

II. STUDY AREA AND DATA SET

89

A. Study Site

91 Data were acquired over two mainly agricultural sites
 92 (Fig. 1). The Villamblain site is located in the south of Paris,
 93 France (latitude 48°01' N and longitude 1°35' E) with soil
 94 composed of 30% clay, 60% silt, and 10% sand. The second
 95 site is situated in the Orgeval watershed, located in the east of
 96 Paris, France (latitude 48°51' N and longitude 3°07' E). The soil
 97 has a loamy texture, composed of 78% silt, 17% clay, and 5%
 98 sand. Both of these two sites are very flat.

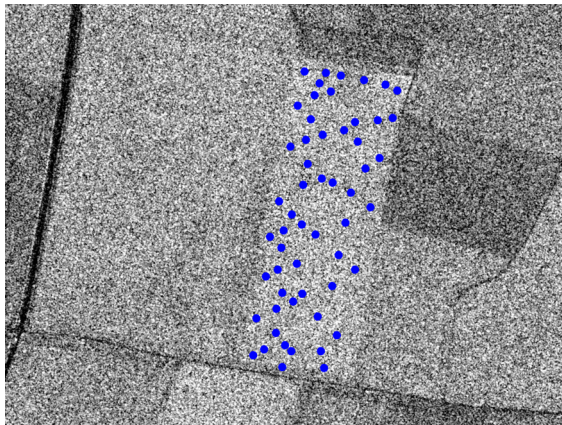


Fig. 2. Example of volumetric soil moisture measurements taken on a reference field.

124 C. Field Data

125 Simultaneously with TerraSAR-X acquisition, field mea-
 126 surements of soil moisture and surface roughness have been
 127 achieved on several bare soil reference fields of at least 2 ha.
 128 In the case of TerraSAR-X in spotlight mode (pixel spacing of
 129 1 m), this corresponds to a surface of 20 000 pixels or more.

130 The volumetric water content at field scale was assumed to be
 131 equal to the mean value estimated from several samples (20–40
 132 measurements per field; Fig. 2) collected from the top 5 cm
 133 of soil using the gravimetric method. The soil moistures range
 134 from 13% to 40%.

135 In most studies of microwave measurements carried out over
 136 bare soils, the experimental relationship between soil moisture
 137 and backscattering coefficient is provided by mean volumetric
 138 water contents measured to a soil depth, generally 0–5 cm
 139 or 0–10 cm. Indeed, only some studies using theory results
 140 are available at X-band. These studies suggest a penetration
 141 depth maybe lower than 5 cm. No experimental measurements
 142 are made in field condition, and the low penetration depth
 143 of X-band is only based on theoretical study. Therefore, the
 144 penetration depth of the X-band is not yet well known.

145 Roughness measurements were made using needle pro-
 146 filometers (1 m long and with 2-cm sampling intervals). Ten
 147 roughness profiles were sampled for each training field (parallel
 148 and perpendicular to the row direction). From these measure-
 149 ments, the two roughness parameters, i.e., root mean square
 150 (*rms*) surface height and correlation length (*L*), were calcu-
 151 lated using the mean of all correlation functions. The *rms*
 152 surface heights range from 1.1 to 3.3 cm, and the correlation
 153 length (*L*) varies from 2.3 cm in sown fields to 9.3 cm in plowed
 154 fields.

155 III. METHODOLOGY

156 The retrieval of soil moisture from TerraSAR-X images
 157 by means of empirical approaches requires the development
 158 of experimental relationships between $\sigma_{\text{TerraSAR-X}}^{\circ}$ and the
 159 measured soil moisture. TerraSAR data acquired in two config-
 160 urations of incidence angles ($\sim 26^{\circ}$ and $\sim 50^{\circ}$) were used with
 161 ground measurements conducted over bare soil. The sensitivity
 162 of TerraSAR signal to soil moisture is the greatest for low

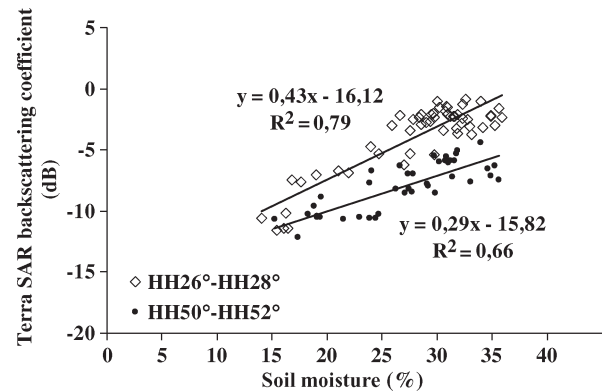


Fig. 3. TerraSAR-X signal versus volumetric soil moisture (measured at a depth of 5 cm). Each point corresponds to the average backscattering coefficient in decibels for one reference field. Thirty points are used for each of the two configurations HH26°–28° and HH50°–52° (data sets of 2008 and 2009).

incidence angle (0.43 dB/% for 26°–28° and 0.29 dB/% for 163
 50°–52°; Fig. 3). For a confidence level of 95%, there are sig- 164
 nificant relationships between the TerraSAR-X backscattering 165
 coefficient and the *in situ* soil moisture because the *p*-values are 166
 much less than 0.05 (*p*-value $< 2.2 \times 10^{-16}$ for HH26°–28° 167
 and *p*-value $= 1.52 \times 10^{-10}$ for HH50°–52°). 168

169 Studies using C-band (ERS, RADARSAT, ASAR, etc.) 169
 showed lower sensitivities between radar signal and soil mois- 170
 ture, between 0.2 and 0.3 dB/% for low incidence angles 171
 and about 0.1 dB/% for high incidence angles (e.g., [2] and 172
 [11]–[13]). 173

174 The objective of this study is to analyze the influence of 174
 incidence angle on the accuracy of the soil moisture estimate. 175
 Configurations in HH polarization with single incidence an- 176
 gle (26°–28° or 50°–52°) were studied. Next, multi-incidence 177
 TerraSAR-X images acquired at both low and high θ values 178
 with one-day-spaced dates and only minor variations in soil 179
 characteristics were used to analyze the possible improvement 180
 in the soil moisture estimates when two incidences are used. 181

182 The empirical relationship between the radar backscattering 182
 coefficient (σ°) and the volumetric soil moisture (*mv*) for bare 183
 soil surfaces without taking into account the *rms* surface height 184
 is given by (e.g., [14]; Fig. 3) 185

$$\sigma_{\text{dB}}^{\circ} = f(mv, \theta)_{\text{dB}} = \delta mv + \xi. \quad (2)$$

186 This simplified relationship is valid for *mv* values between 186
 5% and 35% [6]. The coefficient δ is dependent on SAR pa- 187
 rameters (radar wavelength, incidence angle, and polarization), 188
 while the coefficient ξ is controlled by SAR parameters and 189
 surface roughness. Experimental data of σ° and *mv* show slope 190
 δ values of about 0.43 dB/% for HH26°–28° and 0.29 dB/% for 191
 HH50°–52°. 192

193 The relationship obtained between σ° and the *rms height* 193
 independent of row direction, correlation length, and soil mois- 194
 ture could be written as an exponential relationship of the form 195
 $\sigma_{\text{dB}}^{\circ} = g(rms, \theta)_{\text{dB}} = \mu e^{-krms} + c$ [15], [16] or a logarithmic 196
 relationship of the form $\sigma_{\text{dB}}^{\circ} = g(rms, \theta)_{\text{dB}} = \mu \ln(rms) + 197$
 c [1]. 198

199 With taking into account of both soil roughness and soil 199
 moisture, the radar signal in decibel scale may be written as 200

AQ8

AQ9

AQ10

TABLE II
 INVERSION MODELS FOR ESTIMATING SOIL MOISTURE AND STATISTICS ON THE VALIDATION OF THESE MODELS

TerraSAR-X data - HH	Calibration phase Model	R ²	Validation phase		
			Bias	std	RMSE
26°-28°	$mv(\%) = 2.31 \sigma_{dB} + 37.19$	0.79	0.52	2.76	2.81
50°-52°	$mv(\%) = 3.43 \sigma_{dB} + 54.30$	0.66	2.95	2.83	4.09
26°-28° and 50°-52°	$mv(\%) = 1.67 \sigma_{dB}(\theta_{low}) + 0.55 \sigma_{dB}(\theta_{high}) + 38.22$	0.69	1.65	2.46	2.91

201 the sum of two functions that describe the dependence of the
 202 radar signal on soil moisture (f : linear) and surface roughness
 203 (g : exponential) (e.g., [1] and [4])

$$\sigma_{dB}^{\circ} = f(mv, \theta)_{dB} + g(rms, \theta)_{dB} = \delta, mv + \mu, e^{-krms} + \tau \quad (3)$$

204 where k is the radar wavenumber ($\sim 2 \text{ cm}^{-1}$ for TerraSAR-X).
 205 This equation neglects the effect of the correlation length
 206 L on the backscattering coefficient. To take account of the
 207 correlation length, Zribi and Deschambre [1] proposed a new
 208 roughness parameter Z_s , defined by rms^2/L , which is the
 209 product of the rms surface height and the slope of the soil
 210 surface (rms/L). Thus, the empirical model linking σ° and Z_s
 211 could be written as $\sigma_{dB}^{\circ} = \delta mv + \eta e^{-kZ_s} + \psi$.

212 In the case of one SAR image characterized by one inci-
 213 dence ($\theta = 26^{\circ}-28^{\circ}$ or $50^{\circ}-52^{\circ}$), inversion model is written as
 214 follows:

$$mv = \alpha \sigma^{\circ}(\theta) + \beta. \quad (4)$$

215 The use of two incidence angles eliminates the effects of
 216 roughness and thus allows linking the backscattering coefficient
 217 to the soil moisture only. For two images acquired with low
 218 and high incidence angles, the estimate of soil moisture can
 219 be obtained by solving (3) for two incidences (substituting the
 220 e^{-krms} of $\sigma^{\circ}(\theta_{low})$ into $\sigma^{\circ}(\theta_{high})$)

$$mv = \alpha \sigma^{\circ}(\theta_{low}) + \beta \sigma^{\circ}(\theta_{high}) + \gamma. \quad (5)$$

221 α and β depend on δ and μ , whereas γ is a function of δ , μ ,
 222 and τ (in both incidence angles).

223 The form of (5) should be the same if the Z_s parameter was
 224 used.

225 The empirical models given in (4) and (5) were then fitted to
 226 experimental data acquired in 2008 and 2009 by using the least
 227 squares method (cf. Table II). The validation of these models
 228 was tested in using the data set of 2010 (13 points for each of
 229 the two configurations HH26° and HH50°). The inputs are the
 230 mean backscattering coefficients in decibels calculated for each
 231 reference field.

232 IV. RESULTS AND DISCUSSION

233 The inversion procedures were applied in order to retrieve
 234 soil moisture. The results obtained in the validation phase
 235 with one low incidence show inversion errors in the estimation

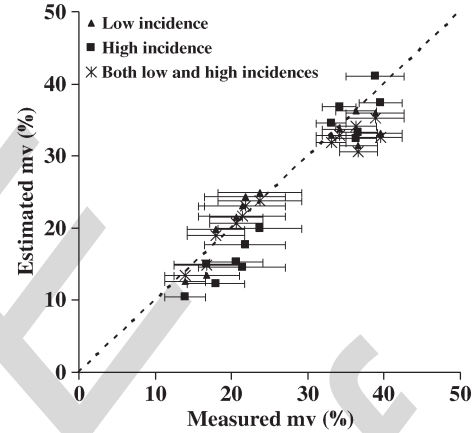


Fig. 4. Comparison between the estimated mv values and those measured. The error bars on the measured soil moisture values correspond to one standard deviation.

of mv of about 3% for incidence angles. The use of high
 236 incidences ($50^{\circ}-52^{\circ}$) gives slightly poorer results with an rmse
 237 of about 4%. The accuracy of the soil moisture estimate remains
 238 unchanged by using TerraSAR-X multi-incidence data (both
 239 low and high incidence angles) with an rmse of about 3%
 240 (Table II). Fig. 4 shows the good agreement between estimated
 241 and measured mv values.

242 In contrast, large errors in the retrieved soil moisture were
 243 observed at C-band for a single incidence angle (rmse of about
 244 6% for 20° and 9% for 40°) [4]. This is due to the fact that the
 245 radar signal is much more sensitive to surface roughness at high
 246 radar wavelength. The accuracy is strongly improved with the
 247 use of both low and high incidences (rmse of about 3.5%) (e.g.,
 248 [1], [2], and [4]).

249 The dependence of the radar signal at X-band on surface
 250 roughness in agricultural areas was described as weak by
 251 several works ([8], [14], and [17]). Results of these studies
 252 show that the influence of surface roughness on the radar signal
 253 increases with increasing radar wavelength. Moreover, this
 254 dependence is mainly significant for low levels of roughness.
 255 At X-band, Baghdadi *et al.* [4], [8] showed that the sensitivity
 256 of σ° to surface roughness becomes weak for $rms > 1 \text{ cm}$.
 257 Thus, the effect of surface roughness on radar signal becomes
 258 weak in X-band, which improves the estimates of soil moisture,
 259 particularly for $rms > 1 \text{ cm}$. Moreover, the multi-incidence
 260 approaches become less effective because the effect of surface
 261 roughness that we try to eliminate is relatively weak at X-band
 262 compared to C-band.

TABLE III
 TERRASAR-X COVERAGE SIMULATION FOR ORGEVAL SITE BETWEEN
 SEPTEMBER 2 AND 12, 2010 (ORBIT CYCLE)

Time	02 sep.	03 sep.	04 sep.	05 sep.	06 sep.	07 sep.	08 sep.	09 sep.	10 sep.	11 sep.	12 sep.
θ (°)	-	39	58	50	26	-	26	50	58	39	-

264

V. CONCLUSION

265 This study examined the potential of TerraSAR-X data for
 266 estimating soil moisture (mv) over bare soils. TerraSAR-X
 267 images collected between 2008 and 2010 over two study sites in
 268 France were used. SAR images were acquired at HH polariza-
 269 tion and for incidence angles of 26° , 28° , 50° , and 52° . The goal
 270 of this work was to compare estimates of mv obtained from
 271 various incidence configurations and to find the best sensor
 272 configuration in incidence angle for measuring the bare soil
 273 moisture.

274 This study tested empirical models for soil moisture inver-
 275 sion from one incidence (low or high) and multi-incidence
 276 TerraSAR-X data (both low and high incidences). The results
 277 of this study may be summarized as follows.

278 1) For a single incidence, the retrieval algorithm performed
 279 very well for low and high incidence angles. The rmses
 280 for the soil moisture estimate are about 3% for 26° – 28°
 281 and 4% for 50° – 52° .

282 2) The accuracy of the soil moisture estimate does not
 283 improve when two incidence angles (rmse is about 3%)
 284 are used.

285 These results appear promising for the development of sim-
 286 plified algorithms for retrieving soil moisture from TerraSAR-
 287 X data and for monitoring temporal moisture changes. Table III
 288 lists the different observation possibilities for the Orgeval study
 289 site within one orbit cycle (11 days). This site could be imaged 8
 290 times within 11 days (two images for each following incidence:
 291 $\sim 26^\circ$, 39° , 50° , and 58°) and 24 times within one month.
 292 The soil moisture mapping frequency with low incidence angle
 293 (26°) or with both low and high incidence angles (26° and 50°)
 294 is possible six times within one month. The incidence of 39° can
 295 also be used, which would increase to 12 the TerraSAR-X scene
 296 number within one month. This very short revisit time makes
 297 TerraSAR-X a very useful source for the soil moisture mapping.
 298 Moreover, the increase in the acquisition frequency is much
 299 awaited for the soil moisture data assimilation in hydrological
 300 modeling.

301 In addition, the very high spatial resolution (metric) of the
 302 TerraSAR-X sensor is also very promising for local estimation
 303 of soil moisture at the within agricultural field scale. It offers a
 304 great potential in terms of improving the quality of soil moisture
 305 mapping for catchment areas where the parcels are of small
 306 size.

307

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AQ11

AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1 = “In” was changed to “by.” Please check if the original thought was retained.

AQ2 = Please provide the expanded form of the acronym “COSMO-SkyMed.”

AQ3 = Please provide the expanded form of the acronym “ORFEO.”

AQ4 = “French Space Study Center” was changed to “National Space Study Center.” Please check if appropriate.

AQ5 = Please provide the expanded form of the acronym “UMR TETIS.”

AQ6 = The acronyms “CESBIO” and “IRD” were defined as “Centre d’Etudes Spatiales de la BIOSphère” and “Institut de Recherche pour le Développement,” respectively. Please check if appropriate.

AQ7 = Please provide the expanded form of the acronym “PALSAR.”

AQ8 = All occurrences of “ $2.2e^{-16}$ ” were changed to “ $< 2.2 \times 10^{-16}$.” Please check if appropriate.

AQ9 = Please provide the expanded forms of the acronyms “ERS,” “RADARSAT,” and “ASAR.”

AQ10 = This sentence was reworded for clarity. Please check if the original thought was retained.

AQ11 = Please check the URL provided in Ref. [10]. Page was not found.

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Proof

Use of TerraSAR-X Data to Retrieve Soil Moisture Over Bare Soil Agricultural Fields

Nicolas Baghdadi, Maelle Aubert, and Mehrez Zribi

Abstract—The retrieval of the bare soil moisture content from TerraSAR-X data is discussed using empirical approaches. Two cases were evaluated: 1) one image at low or high incidence angle and 2) two images, one at low incidence and one at high incidence. This study shows by using three databases collected between 2008 and 2010 over two study sites in France (Orgeval and Villamblain) that TerraSAR-X is a good remote sensing tool for the retrieving of surface soil moisture with accuracy of about 3% (rmse). Moreover, the accuracy of the soil moisture estimate does not improve when two incidence angles (26° – 28° or 50° – 52°) are used instead of only one. When compared with the result obtained with a high incidence angle (50° – 52°), the use of low incidence angle (26° – 28°) does not enable a significant improvement in estimating soil moisture (about 1%).

Index Terms—Soil moisture, TerraSAR-X images.

I. INTRODUCTION

RADAR SIGNAL is a function of soil moisture and surface roughness in the case of bare soil. The possibility of retrieving these soil parameters was little investigated from X-band synthetic aperture radar (SAR). However, many studies were carried out by using C-band radar data (e.g., [1]–[4]). With the launch of satellites using the X-band (~ 9.6 GHz), such as TerraSAR-X and COSMO-SkyMed, the use of X-band data to derive soil parameters became possible. A radar configuration that minimizes the effects of surface roughness is recommended for a better estimate of soil moisture when using only one incidence angle. The optimal radar incidences in C-band for the retrieval of soil moisture are smaller than 35° [4].

Soil moisture estimation from SAR images is carried out by using physical or statistical models. Physical approach consists in using a physical model, such as the integral equation model [5], to predict the radar backscattering coefficient from SAR and soil parameters (wavelength, polarization, incidence angle, surface roughness, and soil dielectric constant). Statistical models based on experimental measurements are also often used in soil moisture estimation. For bare soils, the increase of radar signal (σ°) is supposed to be linear with the volumetric soil



Fig. 1. Location of study sites. (1) Orgeval. (2) Villamblain.

moisture for values between 5% and 35% [6]. Moreover, σ° increases with soil surface roughness and follows an exponential or logarithmic behavior (e.g., [4] and [7]).

Very few studies analyzed the sensitivity of TerraSAR-X data to bare soil surface parameters. Baghdadi *et al.* [8] have observed that the radar signal at X-band is slightly more sensitive to surface roughness at high incidence angle than at low incidence angle. The difference observed between radar signals reflected by the roughest and smoothest areas increases with the radar wavelength. Moreover, results showed that the sensitivity of radar signal to surface roughness is better with PALSAR in L-band than with TerraSAR-X in X-band and that the C- and X-bands are similar sensitivity results. In this letter, only *in situ* soil moisture measurements in very wet conditions between 25% and 40% are available. Results obtained showed that the backscattering coefficient at X-band is stable when the moisture content ranges between 25% and 35% and that it decreases beyond this threshold.

Aubert *et al.* [9] have showed that the sensitivity of the TerraSAR-X signal to soil moisture is very important at low and high incidence angles. In comparison to results published with C-band SAR data, this sensitivity of the radar signal to soil moisture is higher in X-band. The second important result concerns the potential of the fine spatial resolution of TerraSAR (1 m) in the detection of soil moisture variations at the within-plot scale. The spatial distribution of slaking crust could be detected when soil moisture variation is observed between soil crusted and soil without crust. Indeed, areas covered by slaking crust could have greater soil moisture and, consequently, a greater backscattering signal than soils without crust.

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TABLE I
 CHARACTERISTICS OF TERRASAR-X IMAGES AND SUMMARY OF GROUND-TRUTH MEASUREMENTS (*mv*, *rms*, AND *L*)

Date dd-mm-yy	Site	Pol.-Inc.	Fields number	<i>mv</i> (%) (min;max)	<i>rms</i> (cm) (min;max)	<i>L</i> (cm) (min;max)
06-02-08	Villamblain	HH-52°	8	(27 ; 34)	(1.3 ; 3.1)	(4.5 ; 9.1)
07-02-08	Villamblain	HH-28°	8	(27 ; 34)	(1.3 ; 3.1)	(4.5 ; 9.1)
12-02-08	Orgeval	HH-50°	6	(31 ; 36)	(1.8 ; 3.3)	(5.0 ; 9.3)
13-02-08	Orgeval	HH-26°	6	(31 ; 35)	(1.8 ; 3.3)	(5.0 ; 9.3)
17-03-09	Orgeval	HH-26°	7	(25 ; 32)	(1.7 ; 2.3)	(4.8 ; 6.9)
18-03-09	Orgeval	HH-50°	7	(24 ; 30)	(1.7 ; 2.3)	(4.8 ; 6.9)
25-03-09	Orgeval	HH-50°	3	(28 ; 29)	(2.0 ; 2.7)	(4.8 ; 5.7)
26-03-09	Orgeval	HH-26°	3	(24 ; 31)	(2.0 ; 2.7)	(4.8 ; 5.7)
08-04-09	Orgeval	HH-26°	6	(17 ; 26)	(1.1 ; 2.1)	(3.7 ; 6.0)
09-04-09	Orgeval	HH-50°	6	(15 ; 26)	(1.1 ; 2.1)	(3.7 ; 6.0)
01-03-10	Orgeval	HH-50°	6	(33 ; 40)	(1.9 ; 2.9)	(5.9 ; 7.5)
02-03-10	Orgeval	HH-26°	6	(33 ; 37)	(1.9 ; 2.9)	(5.9 ; 7.5)
12-03-10	Orgeval	HH-50°	7	(13 ; 25)	(1.1 ; 2.6)	(4.6 ; 7.0)
13-03-10	Orgeval	HH-26°	7	(15 ; 22)	(1.1 ; 2.6)	(4.6 ; 7.0)

71 At least one research question remained open. It concerns
 72 the precision of the soil moisture estimates in bare agricultural
 73 soils. The objective of this study is to examine the potential of
 74 TerraSAR-X data for retrieving volumetric soil moisture over
 75 bare soils. This work evaluates if the use of two incidence
 76 angles at X-band [one low (26°–28°) and one high (50°–52°)]
 77 improves the accuracy of the estimate of surface soil moisture
 78 in comparison to only one incidence (low or high). TerraSAR-X
 79 sensor has the advantage to acquire on the same study site
 80 image pairs at low and high incidence angles within one day.
 81 The goal of this work is to compare the findings with C- and
 82 X-band data. At C-band, several studies have shown that the
 83 use of two incidence angles provides distinct improvement in
 84 the soil moisture estimate, in comparison with results obtained
 85 using a single incidence (e.g., [1], [2], and [4]). Moreover,
 86 low incidence angle is better than the high incidence angle
 87 for estimating soil moisture with C-band SAR data. This letter
 88 investigates this research question.

During the period of February–April (our SAR acquisitions), 99
 the main crops are wheat and colza. They cover approximately 100
 50% of the agricultural area. The remaining surface corre- 101
 sponds to plowed soils awaiting future cultivation (corn and 102
 potato). 103

B. TerraSAR-X Images

Fourteen TerraSAR-X images (X-band ~9.65 GHz) were 105
 acquired during the years of 2008, 2009, and 2010 (Table I). 106
 The radar data are available in HH polarization, with incidence 107
 angles (θ) of 26°, 28°, 50°, and 52°. The imaging mode 108
 used was spotlight with a pixel spacing of 1 m. Radiometric 109
 calibration using multilook ground range detected TerraSAR-X 110
 images was first carried out using the following equation [10]: 111

$$\sigma_i^\circ(\text{dB}) = \log_{10}(Ks \cdot DN_i^2 - NEBN) + 10 \log_{10}(\sin \theta_i). \quad (1)$$

This equation transforms the amplitude of backscattered sig- 112
 nal for each pixel (DN_i) into a backscattering coefficient (σ°) 113
 in decibels. Ks is the calibration coefficient, and $NEBN$ is 114
 the noise equivalent beta naught. All TerraSAR-X images were 115
 then georeferenced using GPS points with a root-mean-square 116
 error of the control points of approximately one pixel (i.e., 1 m). 117
 This coregistration error was overcome by removing two 118
 boundary pixels from each training plot relative to the limits 119
 defined by the GPS control points. The mean backscattering 120
 coefficients were calculated from calibrated SAR images by 121
 averaging the linear σ° values of all pixels within reference 122
 fields. 123

II. STUDY AREA AND DATA SET

90 A. Study Site

91 Data were acquired over two mainly agricultural sites
 92 (Fig. 1). The Villamblain site is located in the south of Paris,
 93 France (latitude 48°01' N and longitude 1°35' E) with soil
 94 composed of 30% clay, 60% silt, and 10% sand. The second
 95 site is situated in the Orgeval watershed, located in the east of
 96 Paris, France (latitude 48°51' N and longitude 3°07' E). The soil
 97 has a loamy texture, composed of 78% silt, 17% clay, and 5%
 98 sand. Both of these two sites are very flat.

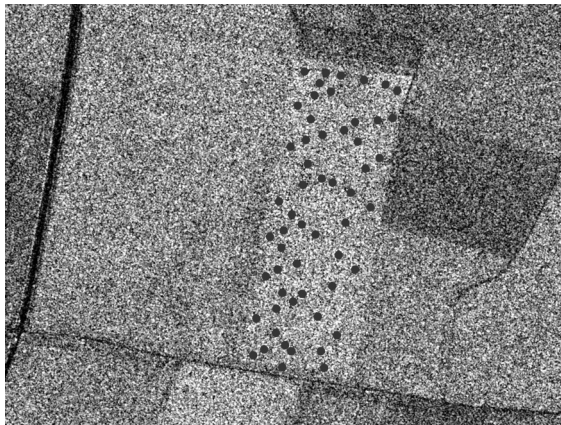


Fig. 2. Example of volumetric soil moisture measurements taken on a reference field.

124 C. Field Data

125 Simultaneously with TerraSAR-X acquisition, field mea-
 126 surements of soil moisture and surface roughness have been
 127 achieved on several bare soil reference fields of at least 2 ha.
 128 In the case of TerraSAR-X in spotlight mode (pixel spacing of
 129 1 m), this corresponds to a surface of 20 000 pixels or more.

130 The volumetric water content at field scale was assumed to be
 131 equal to the mean value estimated from several samples (20–40
 132 measurements per field; Fig. 2) collected from the top 5 cm
 133 of soil using the gravimetric method. The soil moistures range
 134 from 13% to 40%.

135 In most studies of microwave measurements carried out over
 136 bare soils, the experimental relationship between soil moisture
 137 and backscattering coefficient is provided by mean volumetric
 138 water contents measured to a soil depth, generally 0–5 cm
 139 or 0–10 cm. Indeed, only some studies using theory results
 140 are available at X-band. These studies suggest a penetration
 141 depth maybe lower than 5 cm. No experimental measurements
 142 are made in field condition, and the low penetration depth
 143 of X-band is only based on theoretical study. Therefore, the
 144 penetration depth of the X-band is not yet well known.

145 Roughness measurements were made using needle pro-
 146 filometers (1 m long and with 2-cm sampling intervals). Ten
 147 roughness profiles were sampled for each training field (parallel
 148 and perpendicular to the row direction). From these measure-
 149 ments, the two roughness parameters, i.e., root mean square
 150 (*rms*) surface height and correlation length (*L*), were calcu-
 151 lated using the mean of all correlation functions. The *rms*
 152 surface heights range from 1.1 to 3.3 cm, and the correlation
 153 length (*L*) varies from 2.3 cm in sown fields to 9.3 cm in plowed
 154 fields.

155 III. METHODOLOGY

156 The retrieval of soil moisture from TerraSAR-X images
 157 by means of empirical approaches requires the development
 158 of experimental relationships between $\sigma_{\text{TerraSAR-X}}^{\circ}$ and the
 159 measured soil moisture. TerraSAR data acquired in two config-
 160 urations of incidence angles ($\sim 26^{\circ}$ and $\sim 50^{\circ}$) were used with
 161 ground measurements conducted over bare soil. The sensitivity
 162 of TerraSAR signal to soil moisture is the greatest for low

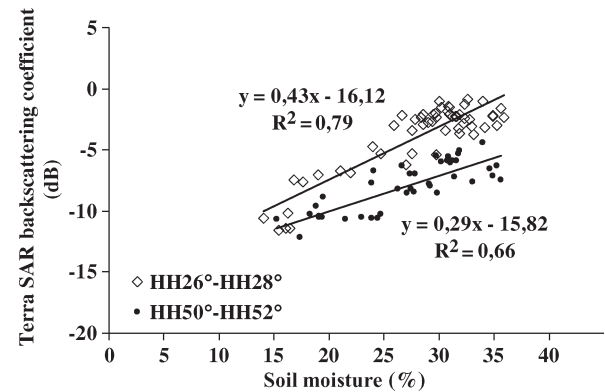


Fig. 3. TerraSAR-X signal versus volumetric soil moisture (measured at a depth of 5 cm). Each point corresponds to the average backscattering coefficient in decibels for one reference field. Thirty points are used for each of the two configurations HH26°–28° and HH50°–52° (data sets of 2008 and 2009).

incidence angle (0.43 dB/% for 26°–28° and 0.29 dB/% for 163
 50°–52°; Fig. 3). For a confidence level of 95%, there are sig- 164
 nificant relationships between the TerraSAR-X backscattering 165
 coefficient and the *in situ* soil moisture because the *p*-values are 166
 much less than 0.05 (*p*-value $< 2.2 \times 10^{-16}$ for HH26°–28° 167
 and *p*-value $= 1.52 \times 10^{-10}$ for HH50°–52°). 168

169 Studies using C-band (ERS, RADARSAT, ASAR, etc.) 169
 showed lower sensitivities between radar signal and soil mois- 170
 ture, between 0.2 and 0.3 dB/% for low incidence angles 171
 and about 0.1 dB/% for high incidence angles (e.g., [2] and 172
 [11]–[13]). 173

174 The objective of this study is to analyze the influence of 174
 incidence angle on the accuracy of the soil moisture estimate. 175
 Configurations in HH polarization with single incidence an- 176
 gle (26°–28° or 50°–52°) were studied. Next, multi-incidence 177
 TerraSAR-X images acquired at both low and high θ values 178
 with one-day-spaced dates and only minor variations in soil 179
 characteristics were used to analyze the possible improvement 180
 in the soil moisture estimates when two incidences are used. 181

182 The empirical relationship between the radar backscattering 182
 coefficient (σ°) and the volumetric soil moisture (*mv*) for bare 183
 soil surfaces without taking into account the *rms* surface height 184
 is given by (e.g., [14]; Fig. 3) 185

$$\sigma_{\text{dB}}^{\circ} = f(mv, \theta)_{\text{dB}} = \delta mv + \xi. \quad (2)$$

186 This simplified relationship is valid for *mv* values between 186
 5% and 35% [6]. The coefficient δ is dependent on SAR pa- 187
 rameters (radar wavelength, incidence angle, and polarization), 188
 while the coefficient ξ is controlled by SAR parameters and 189
 surface roughness. Experimental data of σ° and *mv* show slope 190
 δ values of about 0.43 dB/% for HH26°–28° and 0.29 dB/% for 191
 HH50°–52°. 192

193 The relationship obtained between σ° and the *rms height* 193
 independent of row direction, correlation length, and soil mois- 194
 ture could be written as an exponential relationship of the form 195
 $\sigma_{\text{dB}}^{\circ} = g(rms, \theta)_{\text{dB}} = \mu e^{-krms} + c$ [15], [16] or a logarithmic 196
 relationship of the form $\sigma_{\text{dB}}^{\circ} = g(rms, \theta)_{\text{dB}} = \mu \ln(rms) + 197$
 c [1]. 198

199 With taking into account of both soil roughness and soil 199
 moisture, the radar signal in decibel scale may be written as 200

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TABLE II
 INVERSION MODELS FOR ESTIMATING SOIL MOISTURE AND STATISTICS ON THE VALIDATION OF THESE MODELS

TerraSAR-X data - HH	Calibration phase Model	R ²	Validation phase		
			Bias	std	RMSE
26°-28°	$mv(\%) = 2.31 \sigma_{dB} + 37.19$	0.79	0.52	2.76	2.81
50°-52°	$mv(\%) = 3.43 \sigma_{dB} + 54.30$	0.66	2.95	2.83	4.09
26°-28° and 50°-52°	$mv(\%) = 1.67 \sigma_{dB}(\theta_{low}) + 0.55 \sigma_{dB}(\theta_{high}) + 38.22$	0.69	1.65	2.46	2.91

201 the sum of two functions that describe the dependence of the
 202 radar signal on soil moisture (f : linear) and surface roughness
 203 (g : exponential) (e.g., [1] and [4])

$$\sigma_{dB}^{\circ} = f(mv, \theta)_{dB} + g(rms, \theta)_{dB} = \delta, mv + \mu, e^{-krms} + \tau \quad (3)$$

204 where k is the radar wavenumber ($\sim 2 \text{ cm}^{-1}$ for TerraSAR-X).
 205 This equation neglects the effect of the correlation length
 206 L on the backscattering coefficient. To take account of the
 207 correlation length, Zribi and Deschambre [1] proposed a new
 208 roughness parameter Z_s , defined by rms^2/L , which is the
 209 product of the rms surface height and the slope of the soil
 210 surface (rms/L). Thus, the empirical model linking σ° and Z_s
 211 could be written as $\sigma_{dB}^{\circ} = \delta mv + \eta e^{-kZ_s} + \psi$.

212 In the case of one SAR image characterized by one inci-
 213 dence ($\theta = 26^{\circ}-28^{\circ}$ or $50^{\circ}-52^{\circ}$), inversion model is written as
 214 follows:

$$mv = \alpha \sigma^{\circ}(\theta) + \beta. \quad (4)$$

215 The use of two incidence angles eliminates the effects of
 216 roughness and thus allows linking the backscattering coefficient
 217 to the soil moisture only. For two images acquired with low
 218 and high incidence angles, the estimate of soil moisture can
 219 be obtained by solving (3) for two incidences (substituting the
 220 e^{-krms} of $\sigma^{\circ}(\theta_{low})$ into $\sigma^{\circ}(\theta_{high})$)

$$mv = \alpha \sigma^{\circ}(\theta_{low}) + \beta \sigma^{\circ}(\theta_{high}) + \gamma. \quad (5)$$

221 α and β depend on δ and μ , whereas γ is a function of δ , μ ,
 222 and τ (in both incidence angles).

223 The form of (5) should be the same if the Z_s parameter was
 224 used.

225 The empirical models given in (4) and (5) were then fitted to
 226 experimental data acquired in 2008 and 2009 by using the least
 227 squares method (cf. Table II). The validation of these models
 228 was tested in using the data set of 2010 (13 points for each of
 229 the two configurations HH26° and HH50°). The inputs are the
 230 mean backscattering coefficients in decibels calculated for each
 231 reference field.

IV. RESULTS AND DISCUSSION

232
 233 The inversion procedures were applied in order to retrieve
 234 soil moisture. The results obtained in the validation phase
 235 with one low incidence show inversion errors in the estimation

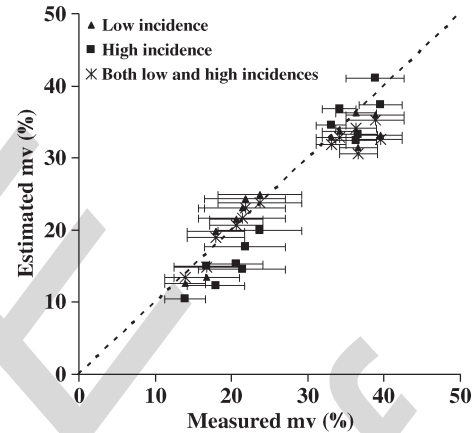


Fig. 4. Comparison between the estimated mv values and those measured. The error bars on the measured soil moisture values correspond to one standard deviation.

of mv of about 3% for incidence angles. The use of high
 236 incidences ($50^{\circ}-52^{\circ}$) gives slightly poorer results with an rmse
 237 of about 4%. The accuracy of the soil moisture estimate remains
 238 unchanged by using TerraSAR-X multi-incidence data (both
 239 low and high incidence angles) with an rmse of about 3%
 240 (Table II). Fig. 4 shows the good agreement between estimated
 241 and measured mv values.

242
 243 In contrast, large errors in the retrieved soil moisture were
 244 observed at C-band for a single incidence angle (rmse of about
 245 6% for 20° and 9% for 40°) [4]. This is due to the fact that the
 246 radar signal is much more sensitive to surface roughness at high
 247 radar wavelength. The accuracy is strongly improved with the
 248 use of both low and high incidences (rmse of about 3.5%) (e.g.,
 249 [1], [2], and [4]).

250 The dependence of the radar signal at X-band on surface
 251 roughness in agricultural areas was described as weak by
 252 several works ([8], [14], and [17]). Results of these studies
 253 show that the influence of surface roughness on the radar signal
 254 increases with increasing radar wavelength. Moreover, this
 255 dependence is mainly significant for low levels of roughness.
 256 At X-band, Baghdadi *et al.* [4], [8] showed that the sensitivity
 257 of σ° to surface roughness becomes weak for $rms > 1 \text{ cm}$.
 258 Thus, the effect of surface roughness on radar signal becomes
 259 weak in X-band, which improves the estimates of soil moisture,
 260 particularly for $rms > 1 \text{ cm}$. Moreover, the multi-incidence
 261 approaches become less effective because the effect of surface
 262 roughness that we try to eliminate is relatively weak at X-band
 263 compared to C-band.

TABLE III
 TERRASAR-X COVERAGE SIMULATION FOR ORGEVAL SITE BETWEEN
 SEPTEMBER 2 AND 12, 2010 (ORBIT CYCLE)

Time	02 sep.	03 sep.	04 sep.	05 sep.	06 sep.	07 sep.	08 sep.	09 sep.	10 sep.	11 sep.	12 sep.
θ (°)	-	39	58	50	26	-	26	50	58	39	-

264

V. CONCLUSION

265 This study examined the potential of TerraSAR-X data for
 266 estimating soil moisture (mv) over bare soils. TerraSAR-X
 267 images collected between 2008 and 2010 over two study sites in
 268 France were used. SAR images were acquired at HH polariza-
 269 tion and for incidence angles of 26° , 28° , 50° , and 52° . The goal
 270 of this work was to compare estimates of mv obtained from
 271 various incidence configurations and to find the best sensor
 272 configuration in incidence angle for measuring the bare soil
 273 moisture.

274 This study tested empirical models for soil moisture inver-
 275 sion from one incidence (low or high) and multi-incidence
 276 TerraSAR-X data (both low and high incidences). The results
 277 of this study may be summarized as follows.

278 1) For a single incidence, the retrieval algorithm performed
 279 very well for low and high incidence angles. The rmses
 280 for the soil moisture estimate are about 3% for 26° – 28°
 281 and 4% for 50° – 52° .

282 2) The accuracy of the soil moisture estimate does not
 283 improve when two incidence angles (rmse is about 3%)
 284 are used.

285 These results appear promising for the development of sim-
 286 plified algorithms for retrieving soil moisture from TerraSAR-
 287 X data and for monitoring temporal moisture changes. Table III
 288 lists the different observation possibilities for the Orgeval study
 289 site within one orbit cycle (11 days). This site could be imaged 8
 290 times within 11 days (two images for each following incidence:
 291 $\sim 26^\circ$, 39° , 50° , and 58°) and 24 times within one month.
 292 The soil moisture mapping frequency with low incidence angle
 293 (26°) or with both low and high incidence angles (26° and 50°)
 294 is possible six times within one month. The incidence of 39° can
 295 also be used, which would increase to 12 the TerraSAR-X scene
 296 number within one month. This very short revisit time makes
 297 TerraSAR-X a very useful source for the soil moisture mapping.
 298 Moreover, the increase in the acquisition frequency is much
 299 awaited for the soil moisture data assimilation in hydrological
 300 modeling.

301 In addition, the very high spatial resolution (metric) of the
 302 TerraSAR-X sensor is also very promising for local estimation
 303 of soil moisture at the within agricultural field scale. It offers a
 304 great potential in terms of improving the quality of soil moisture
 305 mapping for catchment areas where the parcels are of small
 306 size.

307

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314

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AQ11

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AQ1 = “In” was changed to “by.” Please check if the original thought was retained.

AQ2 = Please provide the expanded form of the acronym “COSMO-SkyMed.”

AQ3 = Please provide the expanded form of the acronym “ORFEO.”

AQ4 = “French Space Study Center” was changed to “National Space Study Center.” Please check if appropriate.

AQ5 = Please provide the expanded form of the acronym “UMR TETIS.”

AQ6 = The acronyms “CESBIO” and “IRD” were defined as “Centre d’Etudes Spatiales de la BIOSphère” and “Institut de Recherche pour le Développement,” respectively. Please check if appropriate.

AQ7 = Please provide the expanded form of the acronym “PALSAR.”

AQ8 = All occurrences of “ $2.2e^{-16}$ ” were changed to “ $< 2.2 \times 10^{-16}$.” Please check if appropriate.

AQ9 = Please provide the expanded forms of the acronyms “ERS,” “RADARSAT,” and “ASAR.”

AQ10 = This sentence was reworded for clarity. Please check if the original thought was retained.

AQ11 = Please check the URL provided in Ref. [10]. Page was not found.

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