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7 Soil moisture retrieval over irrigated grassland using 8 X-band SAR data

9

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19 **Abstract:** The aim of this study was to develop an inversion approach to estimate surface soil
20 moisture from X-band SAR data over irrigated grassland areas. This approach simulates a
21 coupling scenario between Synthetic Aperture Radar (SAR) and optical images through the
22 Water Cloud Model (WCM). A time series of SAR (TerraSAR-X and COSMO-SkyMed) and

23 optical (SPOT 4/5 and LANDSAT 7/8) images were acquired over an irrigated grassland region
24 in southeastern France.

25 An inversion technique based on multi-layer perceptron neural networks (NNs) was used to
26 invert the Water Cloud Model (WCM) for soil moisture estimation. Three inversion
27 configurations based on SAR and optical images were defined: (1) HH polarization, (2) HV
28 polarization, and (3) both HH and HV polarizations, all with one vegetation descriptor derived
29 from optical data. The investigated vegetation descriptors were the Normalized Difference
30 Vegetation Index "NDVI", Leaf Area Index "LAI", Fraction of Absorbed Photosynthetically
31 Active Radiation "FAPAR", and the Fractional vegetation COVER "FCOVER". These
32 vegetation descriptors were derived from optical images. For the three inversion configurations,
33 the NNs were trained and validated using a noisy synthetic dataset generated by the WCM for a
34 wide range of soil moisture and vegetation descriptor values. The trained NNs were then
35 validated from a real dataset composed of X-band SAR backscattering coefficients and
36 vegetation descriptor derived from optical images. The use of X-band SAR measurements in HH
37 polarization (in addition to one vegetation descriptor derived from optical images) yields more
38 precise results on soil moisture (M_v) estimates. In the case of NDVI derived from optical images
39 as the vegetation descriptor, the Root Mean Square Error on M_v estimates was 3.6 Vol.% for
40 NDVI values between 0.45 and 0.75, and 6.1 Vol.% for NDVI between 0.75 and 0.90. Similar
41 results were obtained regardless of the other vegetation descriptor used.

42 **Keywords:** grassland; TerraSAR-X; COSMO-SkyMED; neural networks; inversion; soil
43 moisture; vegetation indices

44 **1. Introduction**

45 Monitoring the spatio-temporal evolution of soil moisture over irrigated grassland areas is of
46 crucial importance for effective irrigation and crop management (Allen et al., 1998; Brereton and
47 Hope-Cawdery, 1988; Hong et al., 2013; Leenhardt et al., 2004; Merot et al., 2008). In situ
48 sensors to measure soil moisture are costly and provide only local information. Thus, these
49 sensors are not sufficient for monitoring the soil moisture in huge irrigated grassland areas
50 because the soil moisture presents large heterogeneities due to environmental characteristics and
51 irrigation practices. SAR (Synthetic Aperture Radar) data have shown great potential to provide
52 spatially distributed surface soil moisture measurements over bare and vegetated soil (Aubert et
53 al., 2011; Baghdadi et al., 2012a; Gherboudj et al., 2011; Paloscia et al., 2008, 2013; Prevot et
54 al., 1993; Santi et al., 2013). Due to their ability to operate in all weather conditions, SAR
55 sensors offer the opportunity to monitor and quantify the surface soil moisture at a large scale
56 with high spatial and temporal resolution.

57 SAR remote sensing was widely and primarily used to estimate the soil moisture and surface
58 roughness. Over bare soil (or soil with little vegetation cover) the estimation of soil moisture was
59 performed using either a physical (e.g the Integral Equation Model, Fung et al., 1992) or
60 statistical (e.g Dubois and Oh models, Dubois et al., 1995; Oh, 2004) model in an inversion
61 scheme. In contrast to physical models, statistical models need to be calibrated using in situ
62 measurement and SAR observation acquired over the study area. Moreover, the use of statistical
63 models is limited to the ranges of data variation used for calibration. Most of the studies used
64 radar data in the X- and C-bands to estimate the soil moisture of bare soil and have shown good
65 results, with an accuracy between 3 and 6 Vol.% (Aubert et al., 2011; Baghdadi et al., 2012a;
66 Srivastava et al., 2003, 2009; Zribi et al., 2005).

67 The presence of vegetation cover complicates soil moisture retrieval from SAR data because
68 vegetation canopy not only introduces two-way attenuation in SAR backscatter from soil, but
69 also contributes its own backscatter (He et al., 2014; Srivastava et al., 2011). Most studies used
70 the Water Cloud Model (WCM) in an inversion scheme for soil moisture estimation over areas
71 with vegetated cover. In the WCM the total reflected radar signal is modeled as a function of the
72 vegetation and soil contribution. The vegetation contribution, direct scattering and attenuation, is
73 computed mainly using one biophysical parameter representing the vegetation effect. This
74 biophysical parameter could be estimated from optical data. Therefore, it is important to combine
75 SAR and optical data for operational mapping of soil moisture over areas covered by vegetation
76 (Fieuzal et al., 2011; He et al., 2014; Hosseini and Saradjian, 2011; Notarnicola et al., 2006;
77 Prakash et al., 2012). Currently, the high temporal repetitiveness of X-band (at least one day in
78 case of TSX and CSK) and optical (between 16 and 26 days for Landsat-7/8 and SPOT-4/5 data,
79 respectively) data makes the combined use of SAR and optical data for soil and vegetation
80 parameter monitoring more reliable in near real time.

81 Optical data have shown a great potential to estimate biophysical parameters of vegetation.
82 These parameters can be derived from optical data using physical and statistical models. Physical
83 models (e.g PROSAIL, and SAFY) invert the vegetation spectral reflectance and estimate the
84 biophysical parameters of the vegetation (Botha et al., 2010; Ceccato et al., 2001; Darvishzadeh
85 et al., 2008; Fieuzal et al., 2011). Most statistical models are based on direct relationships
86 between the Normalized Differential Vegetation Index (NDVI) and the measured biophysical
87 parameters of vegetation, such as the LAI of wheat, grasslands, maize, corn and rice (Baret and
88 Guerif, 2006; Baret et al., 2007; Bsaibes et al., 2009; Courault et al., 2008, 2010)

89 The possibility of retrieving soil parameters from vegetated surfaces was widely investigated
90 using C-band configurations, whereas few studies were carried out using X-band data. Hajj *et al.*
91 (2014) showed that the radar signal penetration depth in the X-band (incidence about 30°) is
92 high, even in dense grass cover (HVE "Vegetation Height" about 1m, BIO "Biomass" up to 3.9
93 kg/m²). These results encourage the use of X-band with medium angle (about 30°) in both HH
94 and HV polarizations for soil moisture estimates over grassland. For C and X-bands SAR data,
95 studies showed that it is possible to estimate the soil moisture with accuracy from 2 to 8 Vol.%
96 (RMSE "Root Mean Square Error") (Gherboudj *et al.*, 2011; He *et al.*, 2014; Notarnicola *et al.*,
97 2006; Prévot *et al.*, 1993; Sikdar and Cumming, 2004; Wang *et al.*, 2011; Yang *et al.*, 2012; Yu
98 and Zhao, 2011; Zribi *et al.*, 2011).

99 The aim of this study is to evaluate the potential of X-band SAR data combined with optical
100 data to estimate soil moisture over irrigated grassland areas located in southeastern France. An
101 approach based on the inversion of the WCM using multi-layer neural networks (NNs) was
102 developed. This approach relies on four main steps: (1) parameterize the WCM, (2) simulate
103 learning the SAR synthetic dataset, (3) train the neural networks according to three inversion
104 configurations using a part of the synthetic dataset, and finally (4) apply the trained NNs on
105 synthetic and real datasets to validate the inversion approach. In this paper, section 2 presents the
106 study areas and the ground-truth measurements performed in situ. Section 3 describes the
107 methodology. The results are shown in section 4. Finally, section 5 presents the principal
108 conclusions.

109 **2. Study area and in situ measurements**

110 2.1 Study area

111 The study area, named "Domaine de Merle", is an experimental farm located in southeastern
112 France (centered at 43.64° N, 5.00° E). Its extent is approximately 400 hectares, among which
113 150 hectares are irrigated grassland for hay production (Figure 1). The produced hay is high-
114 value with a Certified Origin Product label (COP) thanks to the specific environmental
115 conditions and conventional irrigation guidelines.

116 The climate is Mediterranean with a rainy season between September and November. The
117 average cumulative rainfall collected at the study site reached 457.5 mm in 2013, and in general
118 varies between 350 mm and 800 mm over the past 20 years (Courault et al., 2010). The mean air
119 temperature is approximately 8°C and 24°C during winter and summer, respectively (Courault et
120 al., 2010). The in situ measured evaporation rate (potential evapotranspiration) can reach 10
121 mm/day during the summer due to high temperatures associated with dry and windy conditions.
122 Meteorological instruments installed in the study area allow for recording hourly temperature
123 and precipitation.

124 The topsoil texture of irrigated plots is stony loam (15% to 20% pebbles) with the depth
125 varying from 30 cm to 80 cm, depending on the plot age (between 10 years and 3 centuries)
126 (Bottraud et al., 1984; Mérot, 2007). The soil is always very smooth thanks to regular irrigation
127 (approximately every 10 days) by gravity. Moreover, the soil has a moderate retention capacity,
128 with concentrated vegetation roots in the upper 30 cm (Merot et al., 2008).

129 Plots were leveled with a very gentle slope to allow irrigation by gravity (border irrigation).
130 Irrigation is applied by means of canals which bring water to the highest extremities of the plots.

131 Each plot is irrigated every 10 days on average from April to September. Plots are harvested
132 three times a year, in May, July, and September.



133

134 **Figure 1.** Location of the study site (Domaine du Merle). Black polygons delineate training
135 irrigated grassland plots where ground measurements were made.

136 2.2 SAR Images

137 Twenty three X-band SAR images were acquired by the COSMO-SkyMed (CSK) and
138 TerraSAR-X (TSX) sensors between April and October 2013. All SAR images are in dual-
139 polarization mode (HH and HV) with incidence angles between 28.3° and 32.5° (Table 1).
140 Moreover, TSX and CSK images are in Stripmap (pixel spacing of 3 m) and Stripmap Pingpong
141 (pixel spacing of 8 m) imaging modes, respectively.

142 Radiometric calibration of SAR images was performed using algorithms developed by the
143 German Aerospace Center (DLR) and the Italian Space Agency (ASI). The radiometric
144 calibration transforms the digital number of each pixel (DN_i) to a radar backscattering coefficient

145 (σ_i°). For the seven TSX MGD (Multi Look Ground Range Detected), the radiometric
146 calibrations were performed according to the following equation (Eineder et al., 2008):

$$\sigma_i^\circ = K_s \cdot DN_i^2 \cdot \sin(\theta) - NESZ \quad (\text{Eq. 1})$$

147 where K_s is the calibration constant, θ is the reference incidence angle, and NESZ is the Noise
148 Equivalent Sigma Zero.

149 For the sixteen CSK images, σ_i° was computed from the DN_i using the following equation:

$$\sigma_i^\circ = DN_i^2 \cdot \frac{1}{K \cdot F^2} \cdot \sin(\theta) R_{\text{ref}}^{2 \cdot R_{\text{exp}}} \quad (\text{Eq. 2})$$

151 where R_{ref} is the reference slant range, R_{exp} is the reference slant range exponent, K is the
152 calibration constant, and F is the rescaling factor.

153 Values of parameters given in Equations 1 and 2 are given in the metadata associated with
154 each TSX and CSK image. The σ_i° were then averaged for each grassland plot and converted to
155 the decibel scale according to the following equation:

$$\sigma_{\text{dB}}^\circ = 10 \cdot \log_{10}(\sum \sigma_i^\circ) \quad (\text{Eq. 3})$$

156 The number of looks used to generate a pixel spacing of 3 m x 3 m is one look in both the
157 range and the azimuth. However, to generate a pixel spacing of 8 m x 8 m, the number of looks
158 is one look in the range and four in the azimuth. The radar image pixel count in the training plots
159 is between 521 and 1686 pixels for the CSK images, and between 3425 and 11320 for the TSX
160 images.

161 For training plots, a comparison was performed between the backscattering coefficients (in
162 both HH and HV polarizations) derived from one TSX and one CSK image, both acquired on the
163 same day (08/07/2013) with about 40 minutes time interval. For such time interval the soil and
164 vegetation conditions remain unchanged. For both HH and HV polarizations, results showed
165 unbiased comparison with low Root Mean Square Error (RMSE ~ 0.4 dB), low Mean Absolute
166 Percentage Error (MAPE < 5 %) and high correlation coefficient ($R^2 \sim 0.9$).

167 2.3 Optical Images

168 Thirty optical images were acquired by SPOT-4, SPOT-5, LANDSAT-7 and LANDSAT-8
169 between April and October 2013 at dates very close to the SAR images (Table 1). The
170 calibration of optical images includes correction for atmospheric effects and ortho-rectification.
171 SPOT-4 images were calibrated by the CESBIO (Centre d'Etudes Spatiales de la BIOSphère) in
172 the framework of the Take 5 experiment (<http://www.cesbio.ups-tlse.fr/>). Atmospheric correction
173 of SPOT-4 images was performed according to the method described in the study of Hagolle *et*
174 *al.* (2008). SPOT-5 and LANDSAT-8 were corrected for atmospheric effects using the
175 Simplified Method of Atmospheric Correction (SMAC) (Rahman and Dedieu, 1994). The
176 SMAC model transforms the TOA reflectance (Top Of Atmosphere) to an atmospherically
177 corrected reflectance. Input data to the SMAC model, the Aerosol Optical Thickness (AOT) at
178 550 nm, the water vapor content (g/m^2), and Ozone, were obtained from the AERONET
179 (Aerosol Robotic NETwork) website (<http://aeronet.gsfc.nasa.gov/>). LANDSAT-7 images,
180 already corrected for atmospheric effects, were downloaded directly from the website of the
181 USGS (<http://earthexplorer.usgs.gov/>). The atmospheric correction of LANDSAT-7 images
182 were carried out by NASA (National Aeronautics and Space Administration) by applying the 6S
183 (Second Simulation of a Satellite Signal in the Solar Spectrum) radiative transfer model data as

184 described by Masek et al. (2013) . Finally, LANDSAT-7/8 images were already ortho-rectified,
185 whereas SPOT-5 images were ortho-rectified using the terrain correction module implemented in
186 the ERDAS imaging software. The optical image pixel count in the training plots is between 39
187 and 108 for LANDSAT images, and between 79 and 223 for SPOT images.

188 The NDVI was computed from the optical images. Then, NDVI pixel values were averaged
189 for each plot. For all training plots, a comparison was performed between NDVI derived from
190 images acquired by different sensors (LANDSAT-7/8, SPOT-4/5) with time interval less than
191 four days. Results showed unbiased comparison with low RMSE (≤ 0.04), low MAPE ($< 5\%$),
192 and good correlation coefficient (R^2 between 0.70 and 0.98). Thus, NDVI derived from different
193 sensors were comparable.

194

195 **Table 1.** Acquisition dates of SAR and optical images (in 2013). Ground measurements are soil
 196 moisture and roughness, LAI, FAPAR, FCOVER, BIO, VWC, and HVE (described in section
 197 below).

| | April | | | | | | May | | | | | | Jun | | | | | | | | | | July | | | | | | | | | | | |
|----------------------------|-------|----|----|----|----|----|-----|----|----|----|----|----|-----|----|----|----|----|----|----|----|----|----|------|----|----|----|----|----|----|----|----|----|----|---|
| | 14 | 17 | 19 | 24 | 25 | 30 | 03 | 04 | 11 | 14 | 22 | 27 | 03 | 04 | 06 | 10 | 11 | 12 | 13 | 14 | 18 | 26 | 28 | 30 | 05 | 08 | 12 | 14 | 16 | 19 | 22 | 29 | 30 | |
| TSX | | | X | | | X | | | | X | X | | | | | | | | | | | | | | | X | | | | | | | X | |
| CSK | | | | | | | | | | | | | | X | X | X | | | | X | | X | | | | X | X | | | X | | | | |
| SPOT-4 & 5 | X | | | X | | | | X | | X | | | | | X | | | X | | X | | | | | X | X | | | | | | | | |
| LANDSAT-7 & 8 | | X | | X | | X | | X | | | X | | X | | | | X | | | | | | X | | | | | X | | | X | | X | |
| In situ measurement | | X | | | X | X | | | X | X | | X | | X | X | X | | | X | | X | | X | | | X | X | | | X | X | | X | X |

| | August | | | | | | | | | | | September | | | | | | | | October | | | | |
|----------------------------|--------|----|----|----|----|----|----|----|----|----|----|-----------|----|----|----|----|----|----|----|---------|----|----|----|--|
| | 01 | 09 | 13 | 15 | 20 | 21 | 22 | 23 | 26 | 29 | 31 | 02 | 03 | 04 | 10 | 16 | 22 | 24 | 01 | 04 | 06 | 11 | 16 | |
| TSX | | | | | | | | | | | | | | | | | | | X | | | | | |
| CSK | X | X | | | | | | | X | X | X | | | X | | | | | X | | | | X | |
| SPOT-4 & 5 | X | | | | X | | | | | | | | | | | | X | | | | X | X | | |
| LANDSAT-7 & 8 | | | | X | | | X | | | X | | | | | | X | | X | | | | | | |
| In situ measurement | X | X | X | X | | X | X | | X | X | X | X | X | X | | | | | X | X | X | | X | |

198 2.4 In situ measurements

199 In situ campaigns were conducted simultaneously with SAR acquisitions to collect ground-
 200 truthed measurements of soil and vegetation parameters in twelve training plots (plots

201 completely flooded or under harvest were not considered). These plots are well levelled and have
202 enough size to be considered as sampling unit (Patel and Srivastava, 2013). The dimension of
203 sampled plot ranges between 2.9 ha and 8.80 ha.

204 2.4.1 Soil moisture and roughness

205 Due to the high irrigation frequency and evapotranspiration rates, soil moisture measurements
206 were performed close in time (within a window of 2 hours) to the satellite overpass. For each
207 training plot, twenty five to thirty measurements of volumetric soil moisture approximately
208 evenly distributed in space (on average every 20 m) were conducted in the top 5 cm of soil by
209 means of a calibrated TDR (Time Domain Reflectometry) probe. Soil moisture was measured in
210 the top 5 cm of soil because the radar penetration depth is assumed to be a few centimeters in the
211 X-band (Ulaby et al., 1986). The soil moisture of each plot was represented by the mean of all
212 soil moisture measurements performed in that plot, except when high spatial variability of soil
213 moisture was observed. This variability is the result to current or recent (few hours before)
214 irrigation events. In this case, many homogenous sub-plots were defined using hand-held GPS
215 (brand: GARMIN, model: OREGON 550, location precision < 2m). The soil moisture was
216 approximately 12 Vol.% when the plot was not supplied by water (irrigation or rainfalls) for 10
217 days during the summer, and it reached approximately 45 Vol.% approximately 10 hours after
218 irrigation ended. The standard deviation of soil moisture measurements within a plot was
219 between 1 and 5 Vol.%.

220 Soil roughness measurements were conducted only once because soil roughness remains
221 stable, using a needle profile-meter (total length of 1 m, and needle spacing of 2 cm). Ten
222 roughness profiles (five parallels and five perpendiculars to SAR's line of sight) were recorded
223 for each plot couple of days after the third harvest, when the vegetation was very short. The root

224 mean square height (*Hrms*) which represents the vertical scale of roughness, and the correlation
225 length (*L*), representing the horizontal scale, were derived by processing the roughness profile.
226 The individual autocorrelation functions are averaged, to produce a mean autocorrelation
227 function representing each training plot (exponential function). Then, this mean autocorrelation
228 function was used to derive *Hrms* and *L*. The *Hrms* values varied between 0.35 and 0.55 cm, and
229 the correlation length (*L*) ranged from 2.00 to 4.60 cm.

230 2.4.2 Vegetation parameters




231 Additionally, in situ measurement of vegetation parameters were performed to estimate the
232 fresh Biomass (BIO), Vegetation Water Content (VWC), Vegetation Height (HVE), leaf area
233 index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), and Fractional
234 vegetation COVER (FCOVER). The vegetation characteristics within each plot are relatively
235 homogeneous. To determine the BIO, two vegetation samples over a 50 cm x 50 cm square were
236 clipped using shears at the center of each plot, and then weighed (wet biomass). Later, these
237 samples were dried at 70°C for three days to calculate the VWC (VWC = wet biomass – dry
238 biomass). The VWC is well correlated to the BIO (VWC = 0.80 BIO, $R^2=0.99$), it increases as
239 BIO increases (i.e. growing season progresses). A poor correlation was found between VWC and
240 soil moisture. Twenty measurements of vegetation heights were performed for each plot (the
241 standard deviation of HVE measurements within a plot was between 5 and 10 cm). Finally,
242 twenty to thirty hemispherical images were acquired for each plot by means of a fish eye lens.
243 These photos were processed using CanEye software (<http://www6.paca.inra.fr/can-eye>) to
244 estimate the LAI, FAPAR and FCOVER. Figure 2 showed photos for plots at different
245 vegetation growth stage. For HVE, LAI, FAPAR, and FCOVER the measurements location
246 within each plot were approximately evenly distributed in space (on average every 20 m). All

247 vegetation measurements within each plot were averaged to provide a mean value for each plot.

248 Figure 2 showed photos for plots at different vegetation growth stage.

249 In our study site, HVE reaches a value between 80 cm and 120 cm (BIO ~ 4.2 kg/m², LAI ~ 5
250 m²/m²) five to seven days before harvest. About ten days after harvest, the HVE reaches a value
251 of about 30 cm (BIO ~0.80 kg/m², LAI ~2.5 m²/m²).

252

| | |
|---|--|
|  | Training plot 2e (Jun 10, 2013) BIO= 0.89 kg/m ² HVE = 0.25 m LAI = 1.01 m ² /m ² |
|  | Training plot 1l (April 19, 2013) BIO= 1.90 kg/m ² HVE = 0.50 cm LAI = 3.98 m ² /m ² |
|  | Training plot 1m (May 14, 2013) BIO= 3.56 kg/m ² HVE = 1.13 m LAI = 4.71 m ² /m ² |

253 **Figure 2.** Ground-based photographs of study sites illustrating variations in grass growth stages
254 along with in situ measurements.

255

256 The *in situ* campaigns, frequently performed along each of the three growth cycles, capture
 257 full range of soil moisture and vegetation conditions (Table 2). Table 2 shows the number of
 258 sampled plots that correspond to soil and vegetation conditions.

259 **Table 2 :** The number of sampled plots for each soil moisture and vegetation conditions

| | Low (HVE \leq 25 cm) | Medium (25 < HVE \leq 60 cm) | High (HVE > 60 cm) |
|--------------------------------------|--|---|--|
| Low ($M_v \leq 20$ Vol.%) | 10 | 17 | 13 |
| Medium (20 < $M_v \leq 30$ Vol.%) | 19 | 40 | 20 |
| High ($M_v > 30$ Vol.%) | 20 | 21 | 18 |
| | | | |
| | Low (VWC \leq 0.7 kg/m ²) | Medium (0.7 < VWC \leq 1.3 kg/m ²) | High (VWC > 1.3 kg/m ²) |
| Low ($M_v \leq 20$ Vol.%) | 12 | 13 | 15 |
| Medium (20 < $M_v \leq 30$ Vol.%) | 30 | 26 | 23 |
| High ($M_v > 30$ Vol.%) | 20 | 22 | 17 |

260

261 3. Methods

262 3.1 Radar signal modeling

263 In this study, the Water Cloud model (WCM), developed by Attema and Ulaby (1978), was
 264 used for modeling the total backscattered radar signal according to soil moisture and vegetation
 265 parameters. This semi-empirical model is widely used over soil with vegetation cover because it
 266 can be easily performed in an inversion scheme to estimate soil moisture and vegetation
 267 parameters (Gherboudj et al., 2011; Prevot et al., 1993; De Roo et al., 2001; Sikdar and
 268 Cumming, 2004; Soon-Koo Kweon et al., 2012; Wang et al., 2011; Yang et al., 2012; Yu and
 269 Zhao, 2011; Zribi et al., 2011). The significant variables in the WCM are the medium height and

270 dielectric cylinder density (Attema and Ulaby, 1978). The latter was assumed to be proportional
 271 to the volumetric water content of the canopy. Very few studies have compared different
 272 vegetation parameters to define the optimal one for use in the WCM. Champion (1991) and
 273 Champion and Guyot (1991) found that the LAI (m²/m²) better represents the wheat canopy in
 274 the WCM than the VWC per unit volume (kg/m³). Said *et al.* (2012) compared the use of LAI
 275 (m²/m²), VWC (kg/m²), and HVE and found that the use of LAI as the vegetation descriptor
 276 allows the accurate simulation of the vegetation volume contribution (sugarcane, cherry, rice,
 277 and grassland).

278 In this context, the WCM represents the total backscattered radar signal (σ^0_{tot}) in linear scale
 279 as a sum of the direct vegetation contribution (σ^0_{veg}) and soil contribution attenuated by the
 280 vegetation volume ($T^2 \sigma^0_{sol}$).

$$\sigma^0_{tot} = \sigma^0_{veg} + T^2 \sigma^0_{sol} \quad (\text{Eq. 4})$$

$$\sigma^0_{veg} = A.V_1.\cos \theta (1 - T^2) \quad (\text{Eq. 5})$$

$$T^2 = \text{Exp} (-2.B.V_2.\sec \theta) \quad (\text{Eq. 6})$$

$$\sigma^0_{sol} = C(\theta) \exp (D.M_v) \quad (\text{Eq. 7})$$

281

282

283 Where:

- 284 • V_1 and V_2 are vegetation descriptors (BIO (kg/m^2), VWC (kg/m^2), HVE (m), LAI
285 (m^2/m^2), FAPAR, FCOVER, and NDVI)
- 286 • θ is the radar incidence angle
- 287 • A and B are parameters that depend on the canopy descriptors and radar
288 configurations
- 289 • T^2 is the two way attenuation
- 290 • C is dependent on the roughness and incidence angle
- 291 • D is the sensitivity of the radar signal to volumetric soil moisture in the case of
292 bare soils, which is dependent on radar configurations
- 293 • M_v is the volumetric soil moisture (expressed in Vol.%).

294

295 3.2 Soil moisture retrieval

296 In this study, soil moisture was estimated by means of multi-layer perceptron neural networks
297 (NNs). The Levenberg-Marquardt optimization algorithm (Marquardt, 1963) was used to train
298 the NNs. The NNs architecture is composed of three layers: input, one hidden, and output. The
299 NNs have a two dimensional input vector when using one polarization (HH or HV) in addition to
300 one vegetation descriptor. Using two polarizations (HH and HV) in addition to one vegetation
301 descriptor, the NNs have a three dimensional input vector. The one dimensional output vector
302 contains soil moisture. The numbers of neurons associated with the hidden layer was determined
303 by training the NNs using different numbers of neurons. 20 hidden neurons provided accurate
304 estimates of reference parameters (Baghdadi et al., 2012a; Chai et al., 2009). Sigmoidal and
305 linear transfer functions were associated with the hidden and output layer, respectively. These

306 functions allow non-linear transformations from input to output (Del Frate and Solimini, 2004;
307 Del Frate et al., 2003; Paloscia et al., 2008). To study the performance of the inversion approach,
308 the NNs were trained and validated on the synthetic datasets.

309 A Synthetic dataset of SAR backscatter data was generated from the parameterized WCM to
310 be used in the procedures leading to the estimation of soil moisture by means of the neural
311 networks (NNs) technique. The parameterized WCM is able to simulate the backscattering
312 coefficients at both HH and HV polarizations using the volumetric soil moisture, one vegetation
313 descriptor, and incidence angle values as input variables. Only parameters easily estimated from
314 optical images such as NDVI, LAI, FAPAR and FCOVER were considered in the synthetic
315 datasets generation. Indeed, only few studies showed that the optical data could be used for
316 estimating the biomass, vegetation water content, and the vegetation height. Four synthetic
317 datasets have thus been generated using NDVI, LAI, FAPAR and FCOVER as vegetation
318 descriptors (V1 and V2 in equations 4 and 5) to evaluate the most adequate vegetation descriptor
319 for vegetation layer characterization in the WCM, and to open a perspective for future works
320 based on SAR and optical data coupling. Indeed, several studies have developed methods to
321 correct atmospheric effects in optical images, allowing the accurate estimation of the NDVI
322 (Agapiou et al., 2011; Masek et al., 2013; Rahman and Dedieu, 1994; Saastamoinen, 1972;
323 Vermote et al., 2002). Regarding the other vegetation descriptors, many studies have developed
324 methods to estimate LAI, FAPAR, and FCOVER from optical images (Baret and Guyot, 1991;
325 Bsaibes et al., 2009; Carlson and Ripley, 1997; Carlson et al., 1994; Claverie et al., 2013;
326 Courault et al., 2008; Darvishzadeh et al., 2008b; Duveiller et al., 2011; Fensholt et al., 2004;
327 Guerschman et al., 2009; Li et al., 2014; North, 2002). In addition, in the framework of our
328 study, LAI, FAPAR, and FCOVER of our studied grassland were derived from optical images

329 (SPOT-4, SPOT-5, LANDSAT-7, LANDSAT-8) using the BV-NNET (Biophysical Variables
 330 Neural NETWORK) tool developed based on algorithms proposed by Baret *et al.* (2007) and then
 331 optimized through the SIRRIMED project (<http://www.sirrimed.org/index.php>). A comparison
 332 was performed between the LAI, FAPAR and FCOVER derived from BV-NNET (using optical
 333 images) and those derived from hemispherical photos. Results showed unbiased estimations of
 334 LAI, FAPAR, and FCOVER by the BV-NNET. Moreover, the BV-NNET estimates the LAI
 335 with an RMSE of 0.66 m²/m² and an RRMSE (as well as MAPE) around 29%. For FAPAR and
 336 FCOVER, an RMSE around 0.13 and an RRMSE (as well as MAPE) around 19% were obtained.

337 The synthetic dataset based on NDVI as the vegetation descriptor comprises 80 elements (8 x
 338 10, Table 3). Each element of the dataset contains radar signals in HH and HV polarizations for a
 339 given NDVI and volumetric soil moisture (Table 3). Moreover, synthetic dataset based on LAI
 340 and FAPAR (as well as FCOVER) comprised 248 (8 x 31, table 3) and 168 (8 x 21, table 3)
 341 elements, respectively.

342 **Table 3.** The minimum, maximum, and step values of WCM inputs.

| Parameter | Min value | Max value | Step | Total elements |
|--|------------------|------------------|-------------|-----------------------|
| NDVI | 0.45 | 0.90 | 0.05 | 10 |
| LAI (m²/m²) | 0.0001 | 6 | 0.20 | 31 |
| FAPAR | 0.0001 | 1 | 0.05 | 21 |
| FCOVER | 0.0001 | 1 | 0.05 | 21 |
| M_v (Vol.%) | 10 | 45 | 5 | 8 |

343 To make WCM simulations more realistic, uncertainties of SAR measurements were added to
344 the simulated radar response. The uncertainties range is between 0.6 and 1 dB for CSK and TSX
345 sensors (Agenzia Spaziale Italiana, 2007; Coletta et al., 2007; Iorio et al., 2010; Schwerdt et al.,
346 2008; Torre et al., 2011). Thus, we considered two absolute uncertainties values (± 0.75 , and
347 ± 1.00 dB) to be added to the simulated radar response. Moreover, relative uncertainties were
348 added on our reference vegetation descriptor values (NDVI, LAI, FAPAR, and FCOVER) to
349 handle the associated uncertainty. For NDVI, Simoniello *et al.* (2004) reported a relative
350 uncertainty of approximately 8% on NDVI values estimated from AVHRR (Advanced Very
351 High Resolution Radiometer) calibrated data over pasture and cultivated areas. El Hajj *et al.*
352 (2008) found that the relative uncertainty on NDVI computed from SPOT-5 surface reflectance
353 data over sugarcane fields is approximately 13%. For the other vegetation descriptors, studies
354 showed for crop canopies (corn, grass, sunflower, maize, wheat, rapeseed and sunflower) relative
355 uncertainty between 10% and 30% for LAI, and between 5% and 20% for FAPAR and FCOVER
356 (Bsaibes et al., 2009; Claverie et al., 2013; Courault et al., 2008; Duveiller et al., 2011; North,
357 2002). In addition, the uncertainty on the vegetation descriptor estimates depends on crop type
358 (Bsaibes et al., 2009; Claverie et al., 2013). Moreover, the comparison between derived LAI,
359 FAPAR, and FCOVER from our optical images with ground-truthed measurements yields a
360 relative RMSE (Root Mean Square Error) of 29.12, 19.24, and 18.14%, respectively. Therefore,
361 in our study we considered a relative additive noise of 15, 30, and 20% on the NDVI, LAI, and
362 FAPAR (as well as FCOVER), respectively.

363 Zero-mean Gaussian noise with a standard deviation equal to absolute and relative
364 uncertainties were added to the radar signal simulated by the WCM and reference vegetation
365 descriptors, respectively. Finally, to obtain statistically significant datasets, 500 random

366 samplings of zero-mean Gaussian noise was added to each simulated radar response and each
367 vegetation descriptor value.

368 Three case studies to estimate soil moisture using X-band SAR data were evaluated:

- 369 • Case 1: Noisy radar signal at HH polarization and noisy vegetation descriptor as the
370 inputs to NNs, and soil moisture as the target.
- 371 • Case 2: Noisy radar signal at HV polarization and noisy vegetation descriptor as the
372 inputs to NNs, and soil moisture as the target.
- 373 • Case 3: Noisy radar signal at HH and HV polarizations and noisy vegetation descriptor as
374 the inputs to NNs, and soil moisture as the target.

375 Finally, the calibrated NNs were used to invert real SAR measurements for estimation of the
376 soil moisture. The inversion was performed according to the configurations above, but using
377 SAR and a vegetation descriptor (LAI, FAPAR, and FCOVER) derived from optical images
378 instead of the noisy radar signal and vegetation descriptors.

379 **4. Results and discussions**

380 4.1 Water Cloud Model parameterization, and modelling results

381 This section presents the results of the Water Cloud Model (WCM) parameterization, and shows
382 the radar signal modelling results as a function of soil and vegetation parameters.

383 4.1.1 Water Cloud Model parameterization

384 The real dataset composed of SAR data and measurements of soil moisture and vegetation
385 descriptors was divided into two sub-datasets. The first sub-dataset (training dataset) was used to
386 fit the WCM model, whereas the second (validation dataset) was used to validate the soil

387 moisture estimation of the WCM model. The training dataset contains the SAR and the ground-
 388 truthed data obtained during the three cycles for the half of training plots, whereas the validation
 389 dataset comprises the data collected for other half of plots. These two real sub-datasets contain a
 390 wide range of soil moisture (M_v) and vegetation descriptor values measured in situ (BIO, VWC,
 391 HVE, LAI, FAPAR, FCOVER) and derived from optical images (NDVI, LAI, FAPAR, and
 392 FCOVER) (Table 4). The two real sub-datasets have almost the same ranges of variation.

393

394

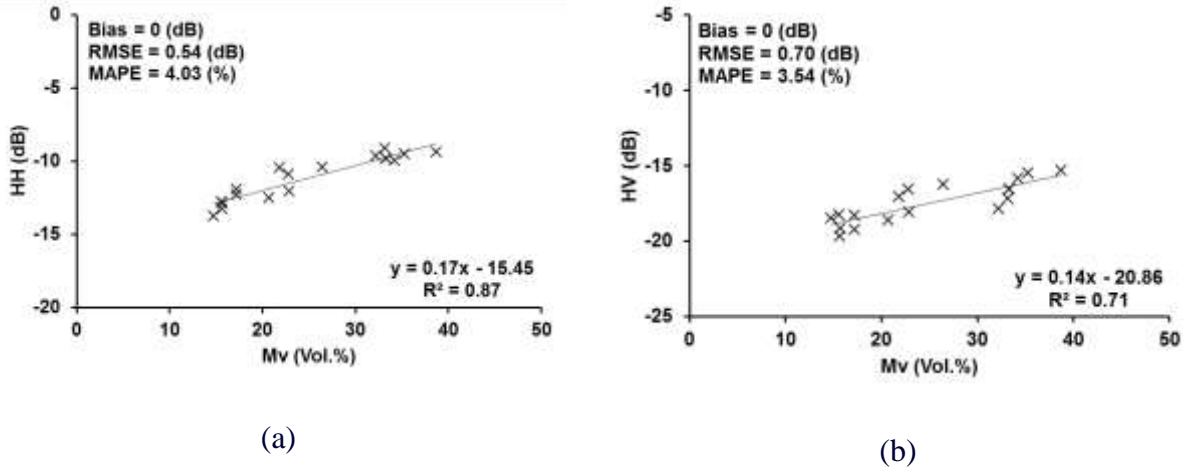
Table 4: ranges of variation of real training and validation datasets

| | | | | | |
|-------------------------|------------------|------|------|------|--------------------------------|
| Real training dataset | | Min | Mean | MAX | Unit |
| | Mv | 10.9 | 25.6 | 39.0 | Vol.% |
| | In situ BIO | 0.28 | 1.41 | 4.14 | Kg/m ² |
| | In situ VWC | 0.15 | 1.12 | 3.35 | Kg/m ² |
| | In situ HVE | 0.08 | 0.48 | 1.20 | m |
| | In situ LAI | 0.10 | 2.64 | 5.88 | m ² /m ² |
| | In situ FAPAR | 0.20 | 0.79 | 1.00 | - |
| | In situ FCOVER | 0.12 | 0.63 | 0.96 | - |
| | LAI (BV-NNET) | 0.20 | 2.63 | 5.04 | m ² /m ² |
| | FAPAR (BV-NNET) | 0.16 | 0.77 | 0.98 | - |
| | FCOVER (BV-NNET) | 0.16 | 0.66 | 0.96 | - |
| | NDVI | 0.47 | 0.73 | 0.88 | - |
| Real validation dataset | | | | | |
| | Mv | 14.1 | 27.0 | 47.0 | Vol.% |
| | In situ BIO | 0.30 | 1.31 | 3.46 | Kg/m ² |
| | In situ VWC | 0.03 | 1.02 | 2.87 | Kg/m ² |
| | In situ HVE | 0.08 | 0.45 | 1.15 | m |
| | In situ LAI | 0.26 | 2.23 | 4.00 | m ² /m ² |
| | In situ FAPAR | 0.20 | 0.73 | 0.93 | - |
| | In situ FCOVER | 0.09 | 0.57 | 0.88 | - |
| | LAI (BV-NNET) | 0.26 | 2.16 | 5.10 | m ² /m ² |
| | FAPAR (BV-NNET) | 0.09 | 0.69 | 0.98 | - |
| | FCOVER (BV-NNET) | 0.09 | 0.58 | 0.94 | - |
| | NDVI | 0.48 | 0.69 | 0.87 | - |

395 WCM parameterization consists of first estimating the sensitivity parameter D before fitting
396 the model against ground-truthed measurements to estimate parameters A, B, and C (equations 4,
397 5, and 6).

398 • To estimate parameter D, SAR backscattering coefficients in HH and HV
399 polarizations (dB scale) were linearly related to soil moisture (Vol.%) for 18 plots
400 recently harvested (vegetation very short), to have the minimum vegetation effect on
401 the backscattering coefficients (Figure 3). The slopes of these linear regressions
402 represent the sensitivity of the backscattered radar signal to volumetric soil moisture
403 on the dB scale (Figure 3). Results showed a good correlation between radar signal
404 and volumetric soil moisture ($R^2 = 0.87$ and 0.71 for HH and HV, respectively).
405 Moreover, results showed that the HH polarization is slightly more sensitive (0.172
406 dB/Vol.%) to volumetric soil moisture rather than HV (0.135 dB/Vol.%) polarization
407 (Figure 3). In the WCM model, the sensitivity parameter D is represented on a linear
408 scale. In linear unit, these sensitivities D_{HH} and D_{HV} are 0.03971 [m^2/m^2]/[Vol.%] and
409 0.03116 [m^2/m^2]/[Vol.%] for HH and HV polarizations, respectively

410 • A, B and C parameters were then estimated for each radar polarization and each
411 vegetation descriptor (NDVI and ground-truthed BIO, VWC, HVE, LAI, FAPAR, and
412 FCOVER) by minimizing the sum of squares of the differences between the simulated
413 and measured radar signal. Therefore, the WCM was parameterized according to
414 seven vegetation descriptors (Table 5). With A, B and C parameters, it becomes
415 possible to predict WCM components (σ_{veg}^0 , T^2 , and σ_{sol}^0) and consequently the total
416 backscattering coefficient (σ_{tot}^0) using one vegetation descriptor and the soil moisture
417 values as inputs in the WCM.



418 **Figure 3.** Sensitivity of radar signal in both HH and HV polarization to volumetric soil moisture.

419

420 To validate the fitted WCM, a comparison was performed between the radar backscattering
 421 coefficients predicted by the mean of the parameterized WCM (using the soil moisture and
 422 ground-truthed vegetation descriptors of the real validation dataset) and the observed
 423 backscattering coefficients of the real validation dataset. Results showed that the fit of the WCM
 424 was slightly better in HH polarization than in HV polarization (Table 5). The limited correlation
 425 coefficient (R^2) is not due to difficulty of model to simulate radar data but particularly to limited
 426 range of radar data dynamic for different moisture and vegetation conditions. In addition, the
 427 quality of the fit is approximately the same for all the used vegetation descriptors with the RMSE
 428 (Root Mean Square Error) on the predicted backscattering coefficients between 0.76 and 0.86 dB
 429 in HH, and between 0.85 and 0.94 dB in HV polarization, depending on the used vegetation
 430 descriptor. Water cloud model is considered adequately fitted because the RMSE on simulated
 431 radar signal in both HH and HV polarizations is less than 1 dB, which is the same magnitude as
 432 the CSK and TSX sensors precision (Agenzia Spaziale Italiana, 2007; Coletta et al., 2007; Iorio
 433 et al., 2010; Schwerdt et al., 2008; Torre et al., 2011). Several studies used the WCM model to
 434 predict radar backscattering coefficients (Attema and Ulaby, 1978; Gherboudj et al., 2011;

435 Prevot et al., 1993; Ulaby et al., 1984). Attema and Ulaby, (1978) simulated the X-band
436 backscattering coefficients for crops fields (alfalfa, corn, milo, and wheat) in HH and VV
437 polarizations for a wide range of incidence angles (0° - 70°) with a RMSE of simulated
438 backscattering coefficients ranging between 1.5 and 2 dB, depending on the crop type. Ulaby *et*
439 *al.*, (1984) simulated the radar backscattering coefficients in the X-band (VV polarization and 50°
440 incidence angle) for wheat fields with a RMSE of 1.6 dB. Prevot *et al.* (1993) obtained a RMSE
441 for wheat fields on the simulated backscattering coefficients of 1.24 and 0.72 dB in the C-band
442 (HH, 20°) and X-band (VV, 40°), respectively. Gherboudj et al. (2012) predicted the
443 backscattering coefficients in the C-band, in quad-polarization mode with a 30° incidence angle
444 for wheat and pea fields. The RMSE on the predicted backscattering coefficients in HH and VV
445 polarizations was approximately 1 (for wheat) and 0.7 dB (for peas), respectively. In cross
446 polarization, the backscattering coefficient was simulated with a RMSE of 1.2 and 0.2 dB for
447 wheat and pea fields, respectively.

448

Table 5. Fit of WCM parameters for HH and HV polarizations (real validation dataset).

| V1=V2 | A_{HH} | B_{HH} | C_{HH} | D_{HH} | A_{HV} | B_{HV} | C_{HV} | D_{HV} | R²_{HH} (R²_{HV}) | RMSE_{HH} (RMSE_{HV}) (dB) |
|----------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|--|---|
| Ground-truthed BIO | 0.0345 | 0.0995 | 0.0334 | 0.03971 | 0.0068 | 0.1850 | 0.0093 | 0.03116 | 0.49 (0.39) | 0.85 (0.86) |
| Ground-truthed VWC | 0.0438 | 0.1047 | 0.0324 | 0.039711 | 0.0084 | 0.1927 | 0.0088 | 0.03116 | 0.49 (0.39) | 0.86 (0.86) |
| Ground-truthed HVE | 0.1045 | 0.4314 | 0.0357 | 0.03971 | 0.0207 | 0.7882 | 0.0105 | 0.03116 | 0.52 (0.40) | 0.79 (0.85) |
| Ground-truthed LAI | 0.0205 | 0.0613 | 0.0338 | 0.03971 | 0.0041 | 0.0856 | 0.0088 | 0.03116 | 0.48 (0.29) | 0.86 (0.95) |
| Ground-truthed FAPAR | 0.0911 | 0.3275 | 0.0354 | 0.03971 | 0.0177 | 0.4662 | 0.0096 | 0.03116 | 0.47 (0.25) | 0.80 (0.93) |
| Ground-truthed FCOVER | 0.1021 | 0.3696 | 0.0355 | 0.03971 | 0.0203 | 0.5212 | 0.0095 | 0.03116 | 0.48 (0.27) | 0.82 (0.94) |
| NDVI | 0.0767 | 0.7944 | 0.0644 | 0.03971 | 0.016474 | 1.134 | 0.0221 | 0.03116 | 0.51 (0.33) | 0.76 (0.93) |

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4.1.2 Modelling results

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Modelling results obtained by using the NDVI as the vegetation descriptor in the WCM model will be presented first because (i) the best fit of water cloud model was obtained with NDVI as vegetation descriptor, and (ii) it is easier to derive NDVI from optical data than LAI, FAPAR, and FCOVER. Next, results with the LAI, FAPAR, FCOVER, BIO, VWC, and HVE as vegetation descriptors will be briefly discussed.

457 The WCM components ($T^2\sigma_{sol}^\circ$ and σ_{veg}°) were simulated for wide ranges of soil moisture
458 (M_v) and NDVI values using the WCM with the NDVI as the vegetation descriptor. For both HH
459 and HV polarizations, the vegetation contribution (σ_{veg}°), soil contribution (σ_{sol}°), two-way
460 attenuation (T^2), and consequently, the total backscattered signal (σ_{tot}°) were generated in a linear
461 scale using the parameterized equations (3) to (6). NDVI values ranging from 0.45 to 0.90 were
462 used to simulate the vegetation contribution and the two-way attenuation ($V1=V2=NDVI$ in
463 equations 4 and 5). In addition, the soil contribution was simulated using M_v -values ranging from
464 10 to 45 Vol.% (equation 6). The maximum values of NDVI and M_v correspond to the highest
465 values derived from optical images and measured in situ, respectively.

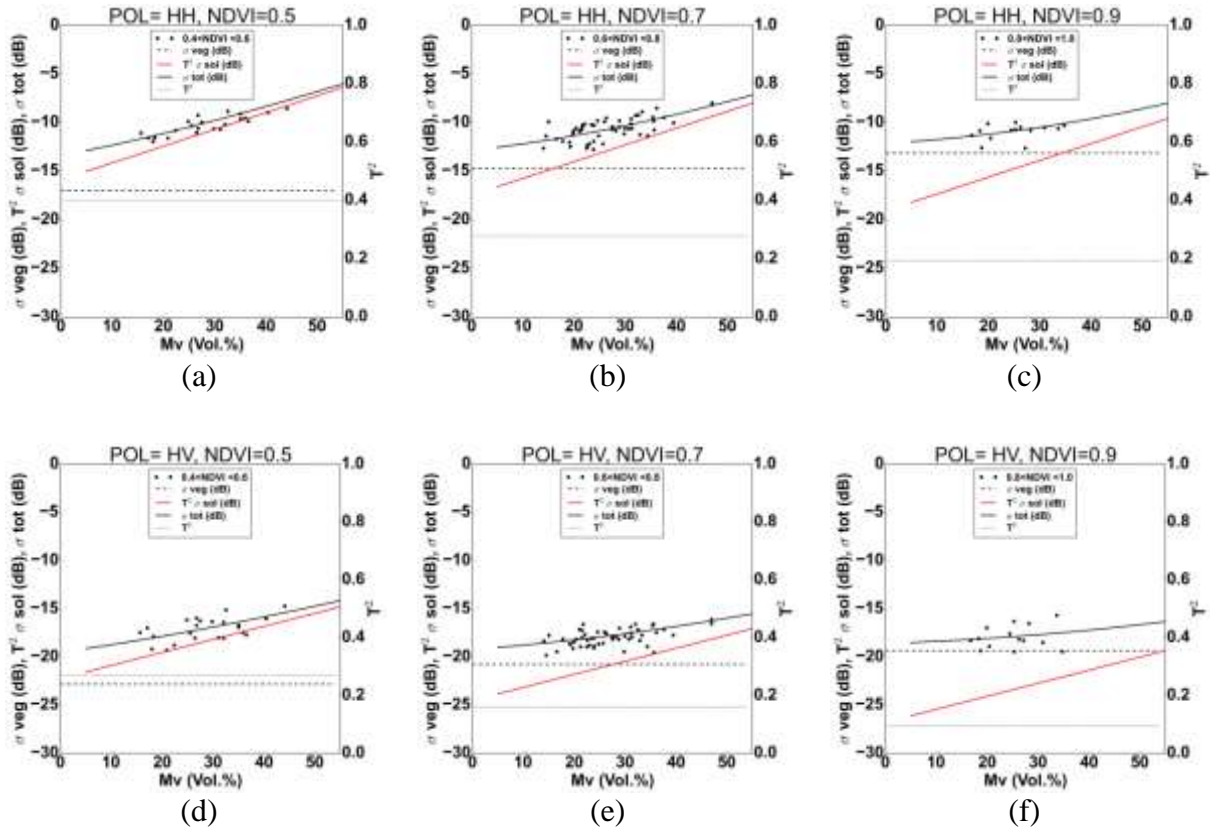
466 Figure 4 shows the modelled σ_{veg}° , $T^2\sigma_{sol}^\circ$ and σ_{tot}° in dB units as a function of M_v using
467 different values of NDVI (0.5, 0.7, and 0.9). In addition, the modelled σ_{veg}° , $T^2\sigma_{sol}^\circ$ and σ_{tot}°
468 were also plotted according to NDVI for M_v values of 15, 20, 30 and 40 Vol.% (Figure 5).

469 Figure 4 shows that σ_{tot}° in both HH and HV polarizations are always sensitive to soil
470 moisture even for high NDVI values. The sensitivity of σ_{tot}° to soil moisture decreases with the
471 NDVI for NDVI between 0.45 and 0.90. For NDVI value equal to 0.50 this sensitivity is about
472 0.14 dB/% and 0.10dB/% for HH and HV, respectively. Moreover, for a NDVI value equal to
473 0.9, this sensitivity is approximately 0.08 and 0.04 dB/Vol.% in HH and HV, respectively. For
474 each case in figure 4 statistical index were provided in table 6. Results showed that the WCM
475 adequately simulates SAR real validation dataset observations ($0 < Bias < 0.3$, $RMSE < 1dB$,
476 $RRMSE$ and $MAPE < 7\%$).

477 Figure 5 shows that σ_{tot}° in both HH and HV polarization is slightly sensitive to the NDVI (for
478 NDVI between 0.45 and 0.90). Indeed, as the vegetation grows, the decreasing soil contribution
479 is similar to the increasing vegetation contribution. σ_{tot}° shows slight decreases with increases in

480 the NDVI until reaching a minimum, and starts to slightly increase. In both HH and HV
481 polarizations, $\sigma_{\text{tot}}^{\circ}$ decreases with NDVI for a NDVI lower than 0.60, 0.75, and 0.90 for M_v of
482 15, 20, and 30 Vol.%, respectively. However, the $\sigma_{\text{tot}}^{\circ}$ in both HH and HV polarizations always
483 decreases with NDVI (NDVI between 0.45 and 0.90) for M_v equal to 40 Vol.% due to the high
484 soil contribution (Figures 5 d and h). This decrease of $\sigma_{\text{tot}}^{\circ}$ with the NDVI is related to an
485 increase in the attenuation of the soil contribution (T^2), which is more important than the
486 enhanced contribution from the vegetation canopy (Balenzano et al., 2011; Brown et al., 2003;
487 Mattia et al., 2003). Beyond these values of NDVI thresholds, $\sigma_{\text{tot}}^{\circ}$ increases slightly with NDVI
488 for M_v values between 15 and 30 Vol.%. This increase of $\sigma_{\text{tot}}^{\circ}$ with NDVI results in the increase
489 of the vegetation contribution combined with the decrease in the soil contribution. Moreover, the
490 decrease and increase of $\sigma_{\text{tot}}^{\circ}$ according to the NDVI are slightly more pronounced in HV than in
491 HH polarization. Regarding vegetation contribution ($\sigma_{\text{veg}}^{\circ}$), results showed that the modelled
492 $\sigma_{\text{veg}}^{\circ}$ in HH polarization increases from -17.7 dB for NDVI of 0.45 to -13.2 dB for NDVI of 0.90.
493 For HV polarization, $\sigma_{\text{veg}}^{\circ}$ increases from -23.5 dB to -18.8 dB for NDVI between 0.45 and 0.90.
494 For each case in figure 5, statistical index were provided in table 7. Results showed that the
495 WCM adequately simulates SAR real validation dataset observations ($0 < \text{Bias} < 0.7$, $\text{RMSE} \leq$
496 1dB , RRMSE and $\text{MAPE} < 8\%$).

497

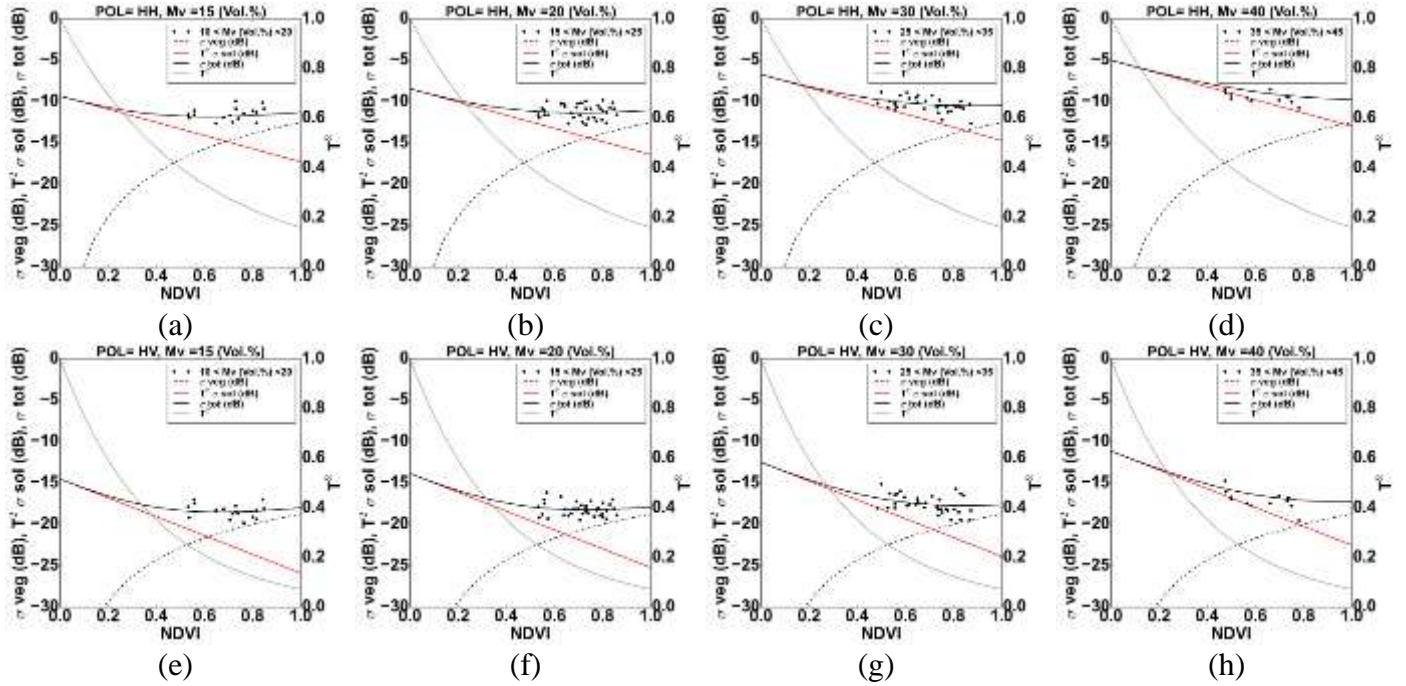


498 **Figure 4.** Behavior of WCM components (σ°_{veg} , $T^2\sigma^{\circ}_{sol}$, and σ°_{tot}) in both HH and HV
 499 polarizations according to M_v . Black points represent the SAR data (σ°_{tot} : real validation dataset)
 500 associated with NDVI measurements within ± 0.1 of the NDVI used in the modelling.

501 **Table 6:** Statistical index for each case in figure 4

| Case | Polarization | NDVI | Bias (dB) | RMSE (dB) | RRMSE (dB) | MAPE (dB) | R^2 | Nb |
|-----------|--------------|------|-----------|-----------|------------|-----------|-------|----|
| Figure 4a | HH | 0.50 | 0.3 | 0.6 | 6.0 | 5.4 | 0.71 | 23 |
| Figure 4b | HH | 0.70 | 0.0 | 0.9 | 8.0 | 6.7 | 0.45 | 52 |
| Figure 4c | HH | 0.90 | 0.1 | 0.8 | 7.0 | 4.8 | 0.12 | 14 |
| Figure 4d | HV | 0.50 | 0.1 | 1.0 | 5.7 | 5.1 | 0.30 | 23 |
| Figure 4e | HV | 0.70 | 0.2 | 0.8 | 4.3 | 3.3 | 0.26 | 52 |
| Figure 4f | HV | 0.90 | 0.1 | 1.1 | 6.4 | 5.5 | 0.03 | 14 |

502



503 **Figure 5.** Behavior of WCM components (σ_{veg}° , $T^2\sigma_{sol}^{\circ}$, and σ_{tot}°) in both HH and HV
 504 polarizations according to NDVI. Black points represent the SAR data (σ_{tot}° : real validation
 505 dataset) associated with M_v measurements within ± 5 vol. % of the M_v used in the modelling.

506 **Table 7:** Statistical index for each case in figure 5

| Case | Polarization | M_v (Vol.%) | Bias (dB) | RMSE (dB) | RRMSE (%) | MAPE (%) | R^2 | Nb |
|-----------|--------------|---------------|-----------|-----------|-----------|----------|-------|----|
| Figure 5a | HH | 15 | -0.3 | 0.8 | 6.8 | 5.6 | 0.13 | 17 |
| Figure 5b | HH | 20 | -0.1 | 0.9 | 7.7 | 6.7 | 0.00 | 36 |
| Figure 5c | HH | 30 | 0.1 | 0.7 | 7.1 | 5.4 | 0.16 | 37 |
| Figure 5d | HH | 40 | 0.6 | 0.8 | 8.7 | 7.6 | 0.32 | 12 |
| | | | | | | | | |
| Figure 5e | HV | 15 | -0.1 | 0.8 | 4.3 | 3.6 | 0.05 | 17 |
| Figure 5f | HV | 20 | 0.0 | 0.8 | 4.5 | 3.7 | 0.01 | 36 |
| Figure 5g | HV | 30 | 0.1 | 1.0 | 5.5 | 4.7 | 0.18 | 37 |
| Figure 5h | HV | 40 | 0.6 | 1.1 | 6.3 | 5.0 | 0.41 | 12 |

507 Table 8 shows NDVI thresholds from which the $T^2\sigma_{sol}^{\circ}$ is dominated by σ_{veg}° ($T^2\sigma_{sol}^{\circ} < \sigma_{veg}^{\circ}$).
 508 In HH polarization, these thresholds are approximately 0.69, 0.74, 0.85, 0.97 for soil moisture of

509 15, 20, 30 and 40 Vol.%, respectively. In HV polarizations and for M_v values of 15, 20, 30 and
 510 40 Vol.%, σ°_{veg} dominates $T^2\sigma^{\circ}_{sol}$ for NDVI values greater than 0.62, 0.65, 0.71, and 0.79,
 511 respectively. Thus, for a given soil moisture value, the thresholds of NDVI for which the
 512 vegetation contribution dominates the soil contribution are lower in HV than in HH (Table 8).

513 **Table 8.** Threshold values of vegetation descriptors at which σ°_{veg} dominates $T^2\sigma^{\circ}_{sol}$ at both HH
 514 and HV polarizations. Dash symbols mean that the σ°_{veg} is always dominated by $T^2\sigma^{\circ}_{sol}$.

| M_v (Vol.%) | HH polarization | | | | HV polarization | | | |
|--|-----------------|------|------|------|-----------------|------|------|------|
| | 15 | 20 | 30 | 40 | 15 | 20 | 30 | 40 |
| NDVI | 0.69 | 0.74 | 0.85 | 0.97 | 0.62 | 0.65 | 0.71 | 0.79 |
| LAI (m²/m²) | 4.22 | 4.60 | 5.43 | - | 3.69 | 3.94 | 4.47 | 5.05 |
| FAPAR | 0.87 | 0.95 | - | - | 0.77 | 0.82 | 0.93 | - |
| FCOVER | 0.78 | 0.84 | 0.99 | - | 0.68 | 0.72 | 0.82 | 0.92 |
| BIO (kg/m²) | 2.55 | 2.77 | 3.28 | 3.85 | 1.95 | 2.07 | 2.34 | 2.64 |
| VWC (kg/m²) | 2.20 | 2.40 | 2.84 | 3.35 | 1.70 | 1.82 | 2.06 | 2.32 |
| HVE (m) | 0.70 | 0.76 | 0.90 | - | 0.55 | 0.58 | 0.65 | 0.73 |

515 WCM components were also modelled using the LAI, FAPAR, FCOVER, BIO, VWC and
 516 HVE as vegetation descriptors. Similar results on the behavior of modelled total backscattered
 517 radar signal (σ°_{tot}) were obtained with all vegetation descriptors. Table 8 shows the values of the
 518 vegetation descriptors at which σ°_{veg} dominates $T^2\sigma^{\circ}_{sol}$. As an example, for soil moisture of 20
 519 Vol.%, σ°_{veg} in HH polarization dominates $T^2\sigma^{\circ}_{sol}$ for LAI values higher than 4.60 m²/m². In
 520 addition, for some soil moisture and vegetation descriptor conditions, the vegetation contribution
 521 is always dominated by the soil contribution (dash symbol in Table 8). As an example, for soil

522 moisture of 40 Vol.%, the vegetation contribution in HH polarization is always dominated by the
523 soil contribution for HVE values between 0 and 1.2 m (maximum value of HVE obtained by
524 ground-truthed measurements and used in modelling). In addition, Table 8 shows that the
525 vegetation contribution in HV polarization dominates the soil contribution at threshold values of
526 vegetation descriptors which are lower than those observed in HH polarization.

527 4.2 Soil moisture retrieval

528 Synthetic and real datasets were used to estimate the soil moisture for the three inversion
529 configurations defined in section 3.2: (1) using the radar signal in HH and one vegetation
530 descriptor, (2) using the radar signal in HV and one vegetation descriptor, and (3) using the radar
531 signal in both HH and HV and one vegetation descriptor. The estimated soil moistures were
532 compared to reference soil moisture values to evaluate the accuracy of the soil moisture
533 estimates of each inversion configuration.

534 Before the use of neural networks for soil moisture estimation, the WCM model was
535 numerically inverted. For some points of the synthetic and real datasets where the SAR
536 backscattering coefficient is lower than the vegetation contribution simulated by the WCM, the
537 direct inversion of the WCM is not numerically possible (about 10% of the datasets). Such
538 limitation is overcome when using the NNs for both synthetic and real datasets. In addition, the
539 Root Mean Square Error on M_v estimates was better with the NNs than using the direct inversion
540 of the WCM (precision on M_v two times better). For these reasons, the neural networks inversion
541 technique for soil moisture estimation was considered.

542 To estimate the soil moisture, neural networks were built for each inversion configuration
543 using a part of the synthetic dataset. The quality of inversion approaches were studied using both
544 the other part of the synthetic dataset and the real validation dataset.

545 4.2.1 Synthetic dataset

546 The synthetic dataset was composed of $2 \cdot 10^7$ elements (10 NDVI values x 8 M_v values x 500
547 random sampling values of the NDVI x 500 random sampling values of the simulated radar
548 signal). According to the radiometric accuracy of the TerraSAR-X and COSMO-SkyMed
549 signals, the radar signal simulated by the WCM model was noised using an additive Gaussian
550 noise with zero mean and a standard deviation of 0.75 and 1 dB. The synthetic dataset was
551 randomly divided into 80% training and 20% validation data samples. The prediction error based
552 on a 5-fold cross-validation was estimated for each inversion configuration to assess the
553 performance of the neural networks. Analysis of the results obtained with NDVI as the
554 vegetation descriptor will be provided in detail whereas the results based on LAI, FAPAR, and
555 FCOVER as the vegetation descriptors will be briefly described.

556 The Root Mean Square Error (RMSE), the Relative Root Mean Square Error (RRMSE), the
557 Mean Absolute Percentage Error (MAPE), the associated mean deviation (bias = estimated M_v -
558 reference M_v), and the correlation coefficient (R^2) were used to evaluate the performance of each
559 inversion configuration. Table 9 presents statistical indexes (RMSE, RRMSE, MAPE, bias, and
560 R^2) on M_v estimates computed from the validation dataset for reference M_v between 10 and 45
561 Vol.% and NDVI values between 0.45 and 0.90. Table 9 shows that the RMSE (as well as
562 RRMSE, and MAPE) on M_v estimates is lower with HH polarization than with HV polarization
563 (configuration 1 in comparison to configuration 2, Table 9). For a noise condition on the radar
564 signal of ± 0.75 dB, the RMSE is 4.5 Vol.% (RRMSE and MAPE about 17 %) with HH

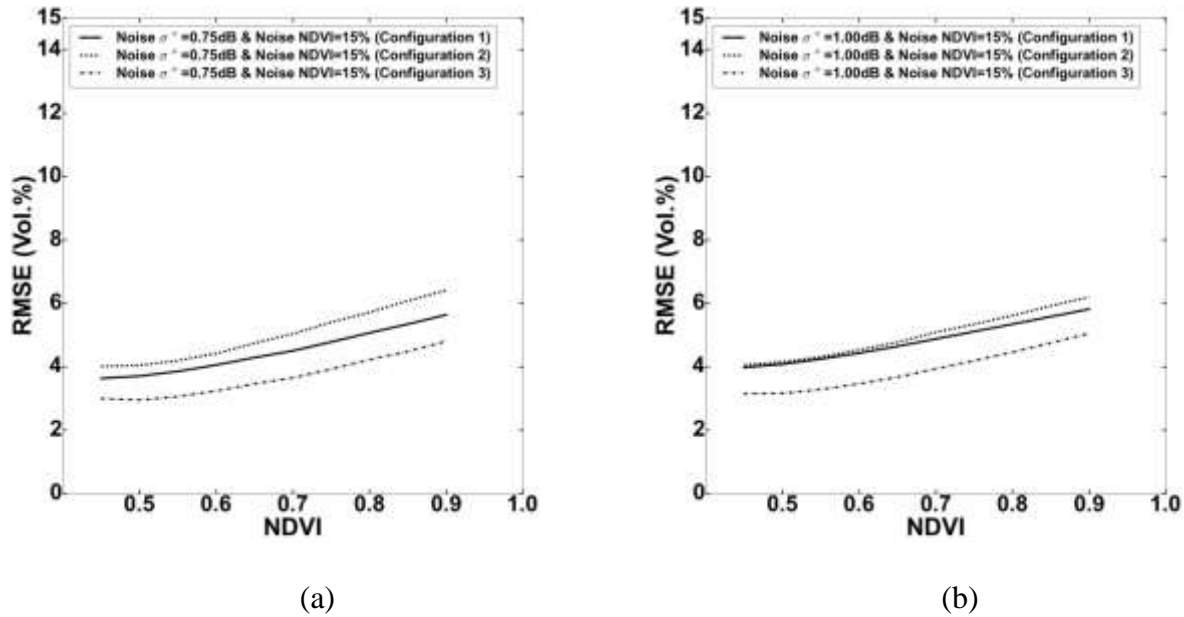
565 compared to 5.1 Vol.% (RRMSE and MAPE 19 %) with HV. In addition, results showed that the
 566 use of both HH and HV (in addition to the NDVI, configuration 3) slightly decreases the RMSE
 567 on M_v estimates (lower than 1 Vol.%). With configuration 3, the RMSE on M_v estimates reaches
 568 3.7 Vol.% (RRMSE and MAPE about 14%) for a noise on the modeled radar signal of ± 0.75
 569 (Table 9). Table 9 also shows that the RMSE on M_v increases when the noise added to the
 570 modeled radar signal increases. This increase is approximately 1 Vol.% when the noise on the
 571 radar signal increases from ± 0.75 dB to ± 1.00 dB (Table 9). Finally, Table 9 also shows that the
 572 three inversion configurations provide un-biased M_v estimates and significant correlation
 573 coefficient (R^2 between 0.77 and 0.90).

574 **Table 9.** Statistical indexes on M_v estimates according to the three inversion configurations
 575 (RMSE (Vol.%) | RRMSE (%) | MAPE (%) | bias (Vol.%) | R^2). Configuration 1 uses HH and
 576 NDVI, configuration 2 uses HV and NDVI, and configuration 3 uses HH, HV and NDVI.
 577 Relative noise of the NDVI=15%.

| | Noise on σ_{tot}^0 : ± 0.75 dB | Noise on σ_{tot}^0 : ± 1.00 dB |
|--|--|--|
| Configuration 1 (HH and NDVI) | 4.5 16.5 17.1 0.0 0.85 | 5.5 19.8 21.0 0.0 0.78 |
| Configuration 2 (HV and NDVI) | 5.1 18.5 19.2 0.0 0.81 | 5.7 20.7 21.8 0.0 0.77 |
| Configuration 3 (HH, HV and NDVI) | 3.7 13.6 13.7 0.0 0.90 | 4.5 16.2 16.7 0.0 0.85 |

578 Figure 6 illustrates the RMSE evolution of M_v estimates as a function of NDVI for values
 579 between 0.45 and 0.90 for each inversion configuration. For each value of NDVI, statistics were
 580 calculated using all M_v values. The results showed that the RMSE of M_v estimates increases with
 581 NDVI for all inversion configurations. As an example, in configuration 3 (HH, HV and NDVI),

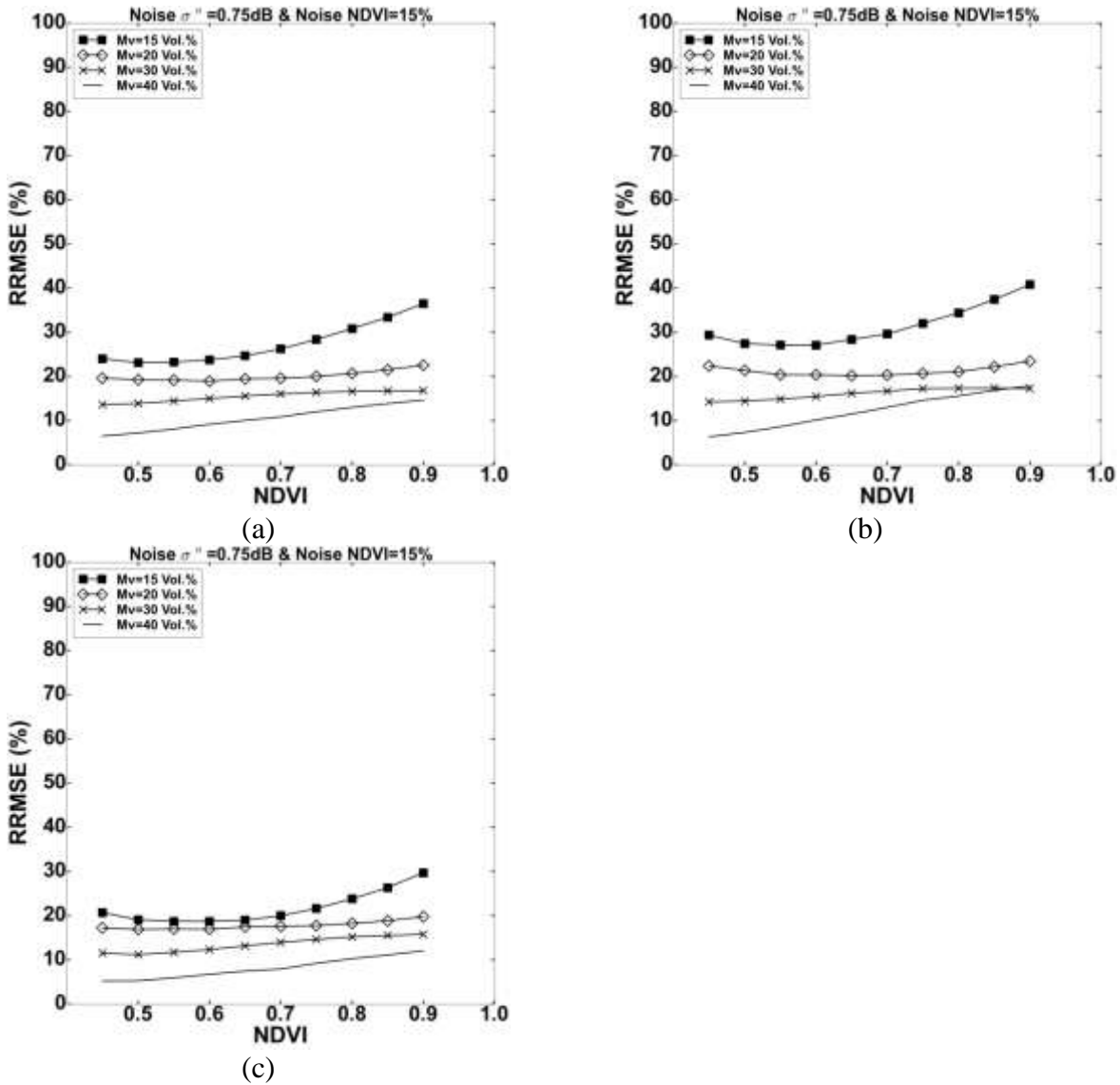
582 the RMSE of soil moisture estimates increases from 3.0 Vol.% for NDVI of 0.45 to 4.8 Vol.%
 583 for a NDVI of 0.9 for a noise condition on the radar signal of ± 0.75 dB (Figure 6a). The results
 584 showed that for a given NDVI value between 0.45 and 0.90, the RMSE is in same order in
 585 configurations 1 and 2 (configuration 1 is slightly better than configuration 2) (Figure 6). In
 586 addition, results obtained with HH were worse than those obtained with HH and HV.



587 **Figure 6.** Evolution of RMSE of M_v estimates according to the three inversion configurations as
 588 a function of NDVI for noise conditions on the modeled radar signal of ± 0.75 dB (a), and ± 1 dB
 589 (b).

590 Moreover, the performances of neural networks for estimating soil moisture were analyzed
 591 according to NDVI for given M_v values (Figure 7). The results showed that the relative RMSE
 592 ($RRMSE = RMSE / M_v$) of M_v estimates increases with the NDVI for the three inversion
 593 configurations. Indeed, as the vegetation grows (i.e., increasing NDVI values) the soil
 594 contribution decreases and the backscattering coefficients become less sensitive to soil moisture.

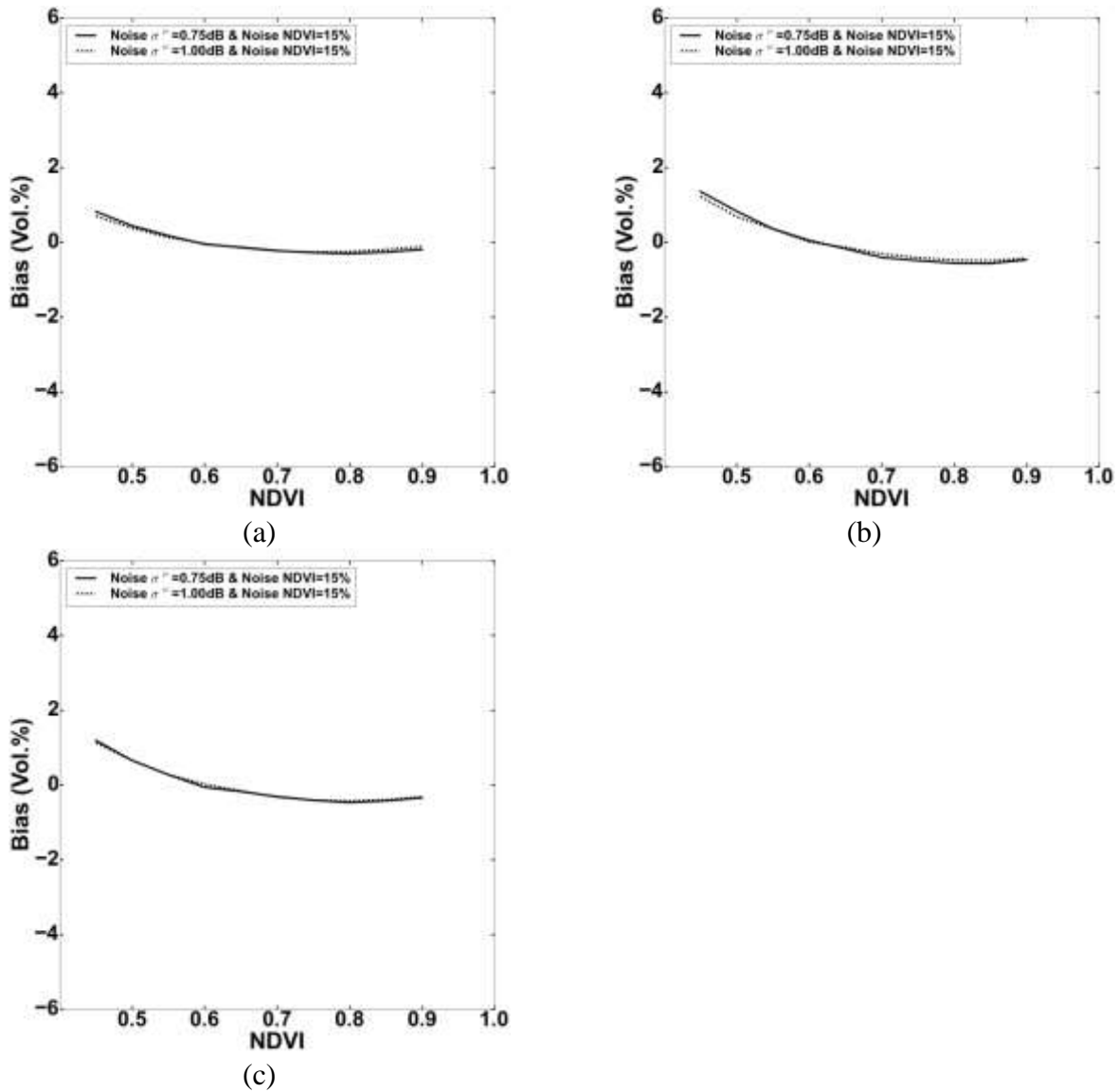
595 In addition, for a given NDVI between 0.45 and 0.90 the RRMSE decreases when M_v increases
596 (Figure 7) because for a given NDVI value the soil contribution is more important for high than
597 for low soil moisture conditions, and consequently, the errors on M_v estimates decrease when M_v
598 increases. As an example, in configuration 1 (HH and NDVI), for a NDVI of 0.75 (LAI about 3
599 m^2/m^2), the RRMSE values are approximately 28.3, 20.0, 16.3, and 12.0% for reference M_v of
600 15, 20, 30 and 40 Vol.%, respectively. For low M_v (lower than 20 Vol.%), the RRMSE increases
601 significantly with NDVI for high NDVI values (higher than 0.75, LAI about 3 m^2/m^2) in
602 comparison to the RRMSE observed for higher M_v values (higher than 20 Vol.%). As an
603 example, in configuration 3 (HH, HV and NDVI), the RRMSE on M_v estimates increases for M_v
604 of 15 Vol.% and noise condition on the simulated radar signal of 0.75 dB from approximately
605 21% for NDVI=0.45 to 30% for NDVI=0.90. This increase in the RRMSE is only approximately
606 5% for M_v of 30 Vol.% (RRMSE increases from approximately 11% for NDVI=0.45 to 16% for
607 NDVI=0.90) (Figure 7).



608 **Figure 7.** Evolution of the relative RMSE (in percent) of M_v estimates ($RRMSE=RMSE/ M_v$)
 609 according to NDVI and M_v . (a) configuration 1: HH and NDVI, (b) configuration 2: HV and
 610 NDVI, and (c) configuration 3: HH, HV and NDVI.

611 The difference between the estimated and reference M_v were also analyzed as a function of
 612 NDVI using for each NDVI and all M_v values (Figure 8). For a given NDVI between 0.45 and
 613 0.90, the bias on M_v estimates is similar for radar signal noise of ± 0.75 and ± 1 dB. The results
 614 showed a slight underestimation (lower than approximately 1 Vol.%) of M_v estimates for NDVI

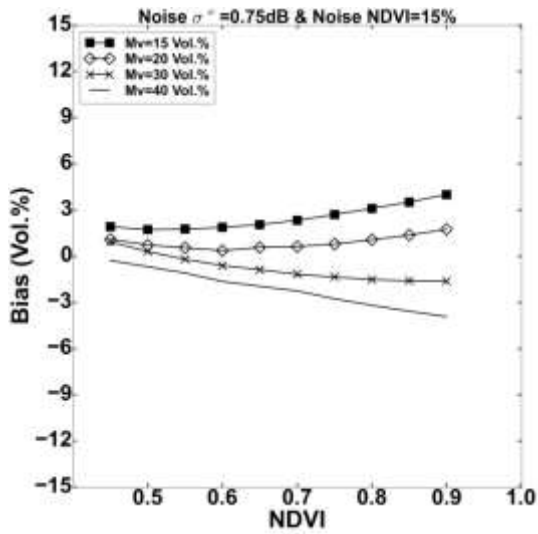
615 values between 0.60 (LAI about $1\text{ m}^2/\text{m}^2$) and 0.90 (LAI about $6\text{ m}^2/\text{m}^2$). In addition, a slight
 616 overestimation of M_v is observed for a NDVI lower than 0.60 (lower than approximately 1 Vol.
 617 %).



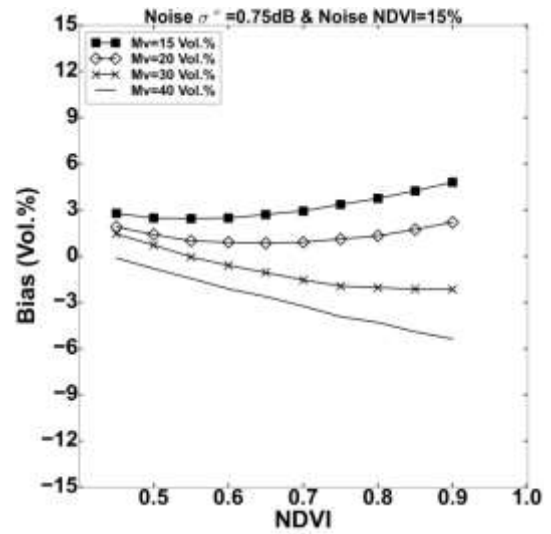
618 **Figure 8.** Evolution of the bias (estimated M_v – reference M_v) of M_v estimates according to
 619 NDVI values. (a) Inversion configuration 1, (b) inversion configuration 2, and (c) inversion
 620 configuration 3.

621 Figure 9 shows the evolution of bias on M_v estimates obtained for the three inversion
622 configurations as a function of the NDVI for some M_v values (15, 20, 30 and 40 Vol.%). For
623 NDVI values lower than approximately 0.65 (LAI about $1.5 \text{ m}^2/\text{m}^2$), the bias on M_v estimates is
624 lower than 1.5 Vol.% for M_v between 15 and 40 Vol.%, in the case of configurations 1 and 3. For
625 the inversion configuration 2, the bias reaches 5.4 Vol.% (for $M_v= 40 \text{ Vol.}\%$). In addition, results
626 showed that the bias increased when the NDVI increased, regardless of the M_v values. This
627 increase was mainly observed when the NDVI was greater than 0.75 (LAI about $3 \text{ m}^2/\text{m}^2$) for
628 low M_v values (Figure 9). An overestimation of M_v estimates is mainly observed for M_v values
629 lower than 20 Vol.%, while an underestimation is mainly observed for M_v values higher than 30
630 Vol.%. Figure 9 also showed that for a given M_v , the bias is lower for configurations 1 and 3.
631 The bias reaches 3.5 Vol.% for configurations 1 and 3 compared to 5 Vol.% for configuration 2
632 for NDVI = 0.9 and $M_v = 15 \text{ Vol.}\%$. Figure 10 shows an example of box plots calculated for the
633 inversion of configuration 3 and some NDVI values (0.6, 0.7, 0.8 and 0.9).

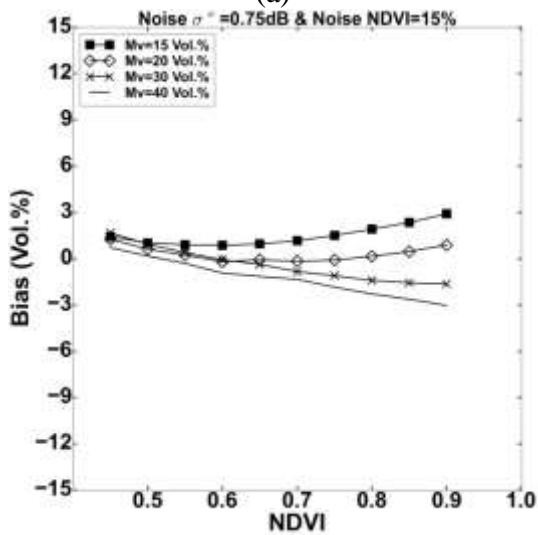
634



(a)

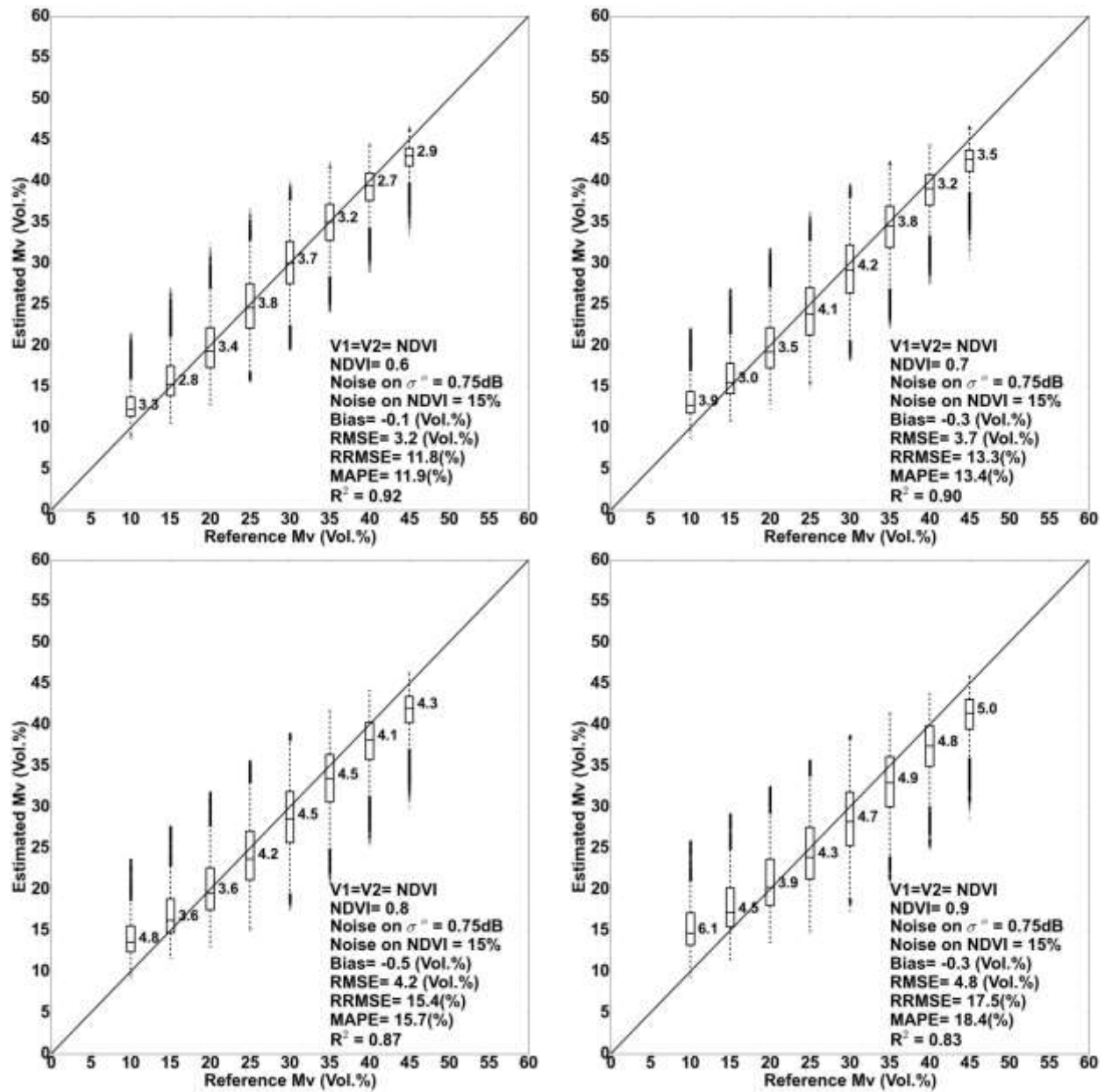


(b)



(c)

635 **Figure 9.** Evolution of the **bias** (estimated M_v – reference M_v) on M_v estimates according to
 636 NDVI and M_v values for noise on the modeled radar signal of 0.75 dB. (a) configuration 1, (b)
 637 configuration 2, and (c) configuration 3.



638 **Figure 10.** Box plots of M_v estimates retrieved from the synthetic dataset. Neural networks were
 639 trained and validated according to configuration 3 (using HH, HV and NDVI). Noise on the
 640 modeled radar signal is ± 0.75 dB, and noise on NDVI is 15% of the NDVI value. Values to the
 641 right of the box plots represent the RMSE on M_v estimates for a given reference M_v .

642 Moreover, 5-fold cross-validation was used to predict errors on M_v estimates for each
643 inversion configuration performed using the synthetic dataset with LAI, FAPAR, and FCOVER
644 as vegetation descriptors. Table 10 shows statistics (RMSE, RRMSE, MAPE, bias, and R^2) on
645 M_v estimates computed from the validation dataset for reference M_v values between 10 and 45
646 Vol.% and a LAI between 0 and 6 and FAPAR (as well as FCOVER) between 0 and 1. The results
647 show that regardless of the vegetation descriptor used, the RMSE on M_v estimates is lower using
648 HH compared to HV polarization (configuration 1 in comparison to configuration 2). In addition,
649 the use of HH and HV polarizations slightly decreases the RMSE on M_v estimates. Table 10 also
650 shows that the RMSE on M_v estimates increases approximately 1 Vol.% when noise added to the
651 radar signal increases. For each inversion configuration and for a given noise condition on the
652 modeled radar signal, the RMSE on M_v estimates is in the same order with the use of NDVI,
653 LAI, FAPAR, or FCOVER as a vegetation descriptor (Table 10). Finally, the results showed that
654 whatever the vegetation descriptor used, the three inversion configurations provide un-biased M_v
655 estimates.

656 **Table 10.** RMSE and Bias on M_v estimates according to the three inversion configurations
 657 (RMSE (Vol.%) | RRMSE (%) | MAPE (%) | bias (Vol.%) | R^2). Configuration 1 uses HH and
 658 vegetation descriptor, configuration 2 uses HV and vegetation descriptor, and configuration 3
 659 uses HH, HV and vegetation descriptor.

| | Noise on σ_{tot}^0 : ± 0.75 dB | Noise on σ_{tot}^0 : ± 1.00 dB |
|---------------------------------------|--|--|
| V1=V2=NDVI Relative noise = 15 % | | |
| Configuration 1 | 4.5 16.5 17.1 0.0 0.85 | 5.5 19.8 21.0 0.0 0.78 |
| Configuration 2 | 5.1 18.5 19.2 0.0 0.81 | 5.7 20.7 21.8 0.0 0.77 |
| Configuration 3 | 3.7 13.6 13.7 0.0 0.90 | 4.5 16.2 16.7 0.0 0.85 |
| V1=V2=LAI Relative noise = 30 % | | |
| Configuration 1 | 5.6 20.5 20.6 0.0 0.76 | 6.7 24.5 25.4 0.0 0.65 |
| Configuration 2 | 7.1 26.0 26.9 0.0 0.61 | 8.1 29.3 31.2 0.0 0.50 |
| Configuration 3 | 5.2 0.0 18.9 18.8 0.79 | 5.8 21.1 21.3 0.0 0.74 |
| V1=V2=FAPAR Relative noise = 20 % | | |
| Configuration 1 | 5.2 18.9 18.8 0.0 0.79 | 6.4 23.1 24.1 0.0 0.69 |
| Configuration 2 | 6.3 22.8 23.3 0.0 0.70 | 7.3 26.7 28.0 0.0 0.59 |
| Configuration 3 | 4.4 16.0 15.7 0.0 0.85 | 5.4 19.7 19.9 0.0 0.78 |
| V1=V2=FCOVER Relative noise = 20 % | | |
| Configuration 1 | 5.2 18.7 18.8 0.0 0.80 | 6.5 23.8 24.4 0.0 0.67 |
| Configuration 2 | 7.1 25.7 26.7 0.0 0.62 | 7.8 28.3 30.0 0.0 0.54 |
| Configuration 3 | 4.7 16.9 16.8 0.0 0.84 | 5.7 20.7 20.9 0.0 0.75 |

660 4.2.2 Real dataset

661 The capacity of the developed Neural Networks (NNs) to correctly estimate the soil moisture
662 was then tested using the real dataset. The NNs applied to the real validation dataset are those
663 which have been trained and validated using the synthetic dataset. NDVI, LAI, FAPAR and
664 FCOVER derived from optical images were used as the input vegetation descriptors for the
665 trained NNs. Inversion results obtained with the NDVI derived from optical images as the
666 vegetation descriptor will be provided in detail, whereas the results based on the LAI, FAPAR,
667 FCOVER derived from optical images as the vegetation descriptor will be briefly described.

668 First, statistics (RMSE, RRMSE, MAPE, bias, R^2) on M_v estimates were also computed for
669 all NDVI observations (Table 11). Slightly better statistics were observed with the noise on a
670 modeled radar signal of ± 1.00 dB. With the noise of ± 1.00 dB, the RMSE is 4.5, 6.0 and 5.5
671 Vol.% in configuration 1, 2 and 3, respectively. Moreover, a slight underestimation (about -0.1
672 Vol.%) was observed in configuration 1 for the noise conditions of ± 0.75 dB and ± 1.00 dB. For
673 configurations 2 and 3, an underestimation of M_v estimates was observed (about -1.4 Vol.% in
674 configuration 2 and -1 Vol.% in configuration 3).

675 **Table 11.** statistics on M_v estimates according to the three inversion configurations (RMSE
676 (Vol.%) | RRMSE (%) | MAPE (%) | bias Vol.% | R^2 | samples). Configuration 1 uses HH and
677 NDVI, configuration 2 uses HV and NDVI, and configuration 3 uses HH, HV and NDVI.
678 Relative noise on the NDVI=15%. Real SAR measurements and the LAI derived from optical
679 images were used to estimate M_v .

| | Noise on $\sigma_{tot}^0 : \pm 0.75$ dB | Noise on $\sigma_{tot}^0 : \pm 1.00$ dB |
|--|---|---|
| | NDVI = [0.45-0.90] | NDVI = [0.45-0.90] |
| Configuration 1 (HH and NDVI) | 4.9 18.4 16.4 -0.1 0.60 93 | 4.5 17.0 15.5 -0.1 0.63 93 |
| Configuration 2 (HV and NDVI) | 6.8 25.7 23.1 -1.3 0.37 93 | 6.0 22.6 19.8 -1.3 0.42 93 |
| Configuration 3 (HH, HV and NDVI) | 6.2 23.5 21.2 -0.8 0.49 93 | 5.5 20.5 18.0 -0.9 0.53 93 |

680 Next, the statistics were computed from the real dataset of validation for NDVI classes of 0.05
681 (NDVI was derived from optical images are between 0.45 and 0.9). The results showed that the
682 RMSE on M_v estimates was in the same order for NDVI classes between 0.45 and 0.75 (LAI
683 about $3\text{m}^2/\text{m}^2$) on the one hand (difference lower than 1 Vol.%), and on the other hand for NDVI
684 classes between 0.75 (LAI about $3\text{m}^2/\text{m}^2$) and 0.90 (LAI about $6\text{m}^2/\text{m}^2$). Therefore, the results
685 of M_v estimates were presented for two classes of NDVI: NDVI lower and higher than 0.75
686 (Table 12). The comparison between estimated M_v and M_v ground-truthed measurements is
687 given in Figures 11 and 12. RMSE and bias on M_v estimates are lower with the noise condition
688 on the modeled radar signal of ± 1 dB.

689 RMSE of 3.6 (RRMSE and MAPE about 12%), 5.4 (RRMSE and MAPE about 18%), and 4.4
690 (RRMSE and MAPE about 15%) Vol.% were observed for configurations 1, 2 and 3,
691 respectively, in the case of a NDVI lower than 0.75 and for modeled radar signal noise of ± 1 dB

692 (Table 12, Figure 11). For a NDVI higher than 0.75, the RMSE on M_v estimates is 6.1 (RRMSE
693 and MAPE about 24%), 7.1 (RRMSE and MAPE about 28%) and 7.3 (RRMSE and MAPE
694 about 29%) Vol.%, respectively, for configurations 1, 2 and 3 and for the noise on the modeled
695 radar signal of ± 1 dB (Table 12, Figure 11). Moreover, results showed that for a NDVI < 0.75
696 the trained NNs provide M_v estimates with slight bias (0.2, -1.7, and -0.9 Vol.% in
697 configurations 1, 2 and 3, respectively) (Table 12, Figure 11). For a NDVI > 0.75 , an slight bias
698 (between -1 and 0.1 Vol.%) was observed for the noise on the radar signal of ± 1 dB, with the
699 lower value for the inversion using HH and NDVI (0.1 Vol.%) (Table 12, Figure 11).

700 **Table 12.** RMSE and bias on M_v estimates according to the three inversion configurations
701 (RMSE (Vol.%) | RRMSE (%) | MAPE (%) | bias Vol.% | R^2 | samples). Configuration 1 uses
702 HH and NDVI, configuration 2 uses HV and NDVI, and configuration 3 uses HH, HV and
703 NDVI. Relative noise on the NDVI=15%. Real SAR measurements and NDVI derived from
704 optical images were used to estimate M_v .

| | Noise on $\sigma_{tot}^0 : \pm 0.75$ dB | | Noise on $\sigma_{tot}^0 : \pm 1.00$ dB | |
|------------------------|---|--------------------------------|---|--------------------------------|
| | NDVI < 0.75 | NDVI > 0.75 | NDVI < 0.75 | NDVI > 0.75 |
| Configuration 1 | 3.8 13.9 12.4 0.0 0.77 64 | 6.6 27.3 25.3 -0.3 0.07 29 | 3.6 13.1 11.8 -0.2 0.79 64 | 6.1 24.9 23.5 0.1 0.10 29 |
| Configuration 2 | 6.0 21.7 19.8 -1.5 0.52 64 | 8.4 34.5 30.6 -0.8 0.04 29 | 5.4 19.7 17.0 -1.7 0.56 64 | 7.1 29.2 26.1 -0.5 0.07 29 |
| Configuration 3 | 5.0 18.2 16.8 -0.7 0.67 64 | 8.3 34.2 30.9 -1.1 0.04 29 | 4.4 15.8 13.9 -0.9 0.71 64 | 7.3 30.1 26.9 -1.0 0.06 29 |

705 Moreover, the SAR real validation dataset was inverted to estimate soil moisture by means of
706 trained NNs with the use of each of the vegetation descriptors derived from optical images LAI,

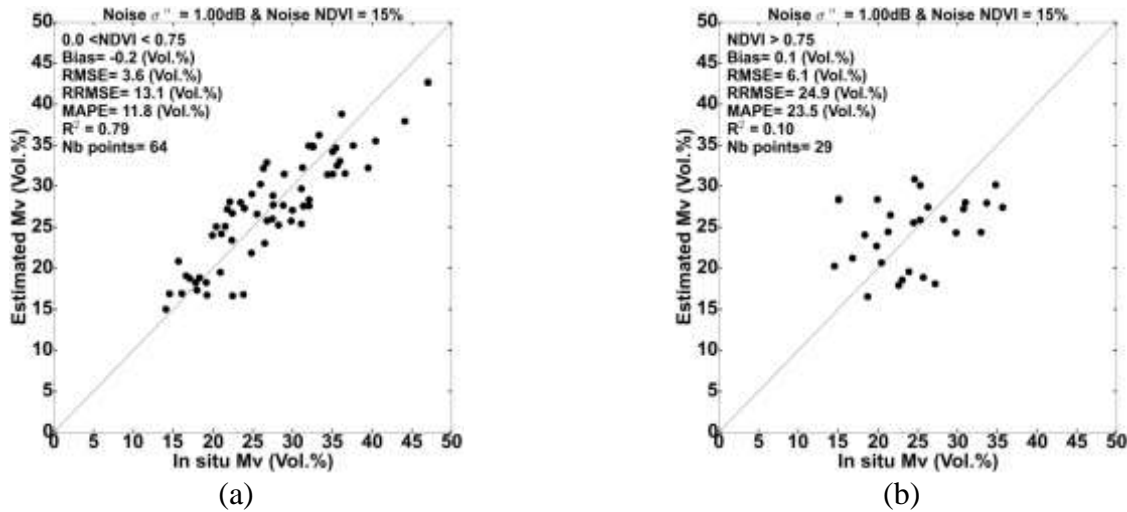
707 FAPAR, and FCOVER). Table 13 shows the (RMSE, RRMSE, MAPE, bias, R^2) on M_v
708 estimates in the three inversion configurations for two classes of NDVI: NDVI lower and higher
709 than 0.75 (LAI about $3\text{m}^2/\text{m}^2$). The results showed that the RMSE (as well as RRMSE, MAPE)
710 on M_v estimates are almost similar, regardless of which vegetation descriptors derived from
711 optical images were used (NDVI, LAI, FAPAR, or FCOVER) (Table 13).

712 In conclusion, the use of HH polarization in addition to a vegetation descriptor derived from
713 optical images (Configuration 1) provides a better estimation of the soil moisture with a RMSE
714 approximately 4.5 and 7.0 Vol.% for a NDVI lower and higher than 0.75 (LAI about $3\text{m}^2/\text{m}^2$),
715 respectively. The use of HV in addition to HH slightly lowers the precision of M_v estimates.

716

717 **Table 13.** Statics on M_v estimates according to the three inversion configurations (RMSE
718 (Vol.%) | RRMSE (%) | MAPE (%) | bias Vol.% | R^2 | samples). Configuration 1 uses HH and
719 NDVI, configuration 2 uses HV and NDVI, and configuration 3 uses HH, HV and NDVI. Real
720 SAR measurements, and NDVI, LAI, FAPAR and FCOVER derived from optical images were
721 used to estimate M_v .

| | Noise on $\sigma_{tot}^0 : \pm 0.75$ dB | | Noise on $\sigma_{tot}^0 : \pm 1.00$ dB | |
|-----------------------|---|---------------------------------|---|--------------------------------|
| | NDVI < 0.75 | NDVI > 0.75 | NDVI < 0.75 | NDVI > 0.75 |
| V1=V2=NDVI | | | | |
| Relative noise = 15 % | | | | |
| Configuration 1 | 3.8 13.9 12.4 0.0 0.77 64 | 6.6 27.3 25.3 -0.3 0.07 29 | 3.6 13.1 11.8 -0.2 0.79 64 | 6.1 24.9 23.5 0.1 0.10 29 |
| Configuration 2 | 6.0 21.7 19.8 -1.5 0.52 64 | 8.4 34.5 30.6 -0.8 0.04 29 | 5.4 19.7 17.0 -1.7 0.56 64 | 7.1 29.2 26.1 -0.5 0.07 29 |
| Configuration 3 | 5.0 18.2 16.8 -0.7 0.67 64 | 8.3 34.2 30.9 -1.1 0.04 29 | 4.4 15.8 13.9 -0.9 0.71 64 | 7.3 30.1 26.9 -1.0 0.06 29 |
| V1=V2=LAI | | | | |
| Relative noise = 30 % | | | | |
| Configuration 1 | 4.7 17.1 15.9 -0.0 0.65 64 | 7.3 29.7 27.2 -1.5 0.02 29 | 4.5 16.3 15.3 0.6 0.67 64 | 7.5 30.6 28.9 0.3 0.00 29 |
| Configuration 2 | 7.5 27.1 23.8 -1.1 0.36 64 | 10.0 41.0 34.9 -3.2 0.00 29 | 7.1 25.8 22.2 -1.1 0.35 64 | 9.0 36.8 31.4 -2.5 0.00 29 |
| Configuration 3 | 5.6 20.1 17.3 -0.9 0.57 64 | 8.4 34.5 30.5 -2.5 0.00 29 | 5.7 20.7 17.7 -0.5 0.55 64 | 8.7 35.7 31.1 -2.2 0.00 29 |
| V1=V2=FAPAR | | | | |
| Relative noise = 20 % | | | | |
| Configuration 1 | 5.0 18.1 16.2 0.5 0.63 64 | 7.9 32.6 30.3 -0.7 0.00 29 | 4.9 17.8 16.6 1.2 0.63 64 | 7.4 30.4 29.0 0.7 0.00 29 |
| Configuration 2 | 8.1 29.2 25.8 -0.0 0.34 64 | 10.9 44.6 39.3 -3.1 0.00 29 | 7.2 26.2 22.4 -0.1 0.34 64 | 9.1 37.2 32.5 -1.7 0.00 29 |
| Configuration 3 | 6.4 23.3 20.5 0.4 0.52 64 | 9.5 38.9 34.2 -2.4 0.00 29 | 6.2 22.4 19.5 0.9 0.51 64 | 8.8 36.1 32.4 -1.3 0.01 29 |
| V1=V2=FCOVER | | | | |
| Relative noise = 20 % | | | | |
| Configuration 1 | 5.1 18.6 16.5 0.8 0.62 64 | 8.0 33.0 30.7 -0.7 0.01 29 | 5.0 18.3 17.1 0.9 0.62 64 | 6.8 27.5 25.2 -0.4 0.03 29 |
| Configuration 2 | 7.6 27.5 23.7 -0.6 0.34 64 | 10.0 40.9 35.1 -3.3 0.01 29 | 7.2 25.9 21.8 -0.7 0.34 64 | 9.1 37.2 31.9 -2.5 0.01 29 |
| Configuration 3 | 6.0 21.6 19.0 0.3 0.55 64 | 9.2 37.6 32.7 -2.5 0.01 29 | 5.9 21.4 18.2 0.2 0.54 64 | 8.4 34.5 30.1 -1.9 0.01 29 |



723 **Figure 11.** Retrieved soil moisture using configuration 1 versus ground-truthed measurements
 724 for NDVI lower and higher than 0.75 (a, and b respectively). Noise on radar signal = ± 1 dB. Bias
 725 = estimated M_v - reference M_v .
 726

727 **5. Conclusion**

728 Inversion results of the synthetic dataset showed that the best M_v estimates were obtained
 729 with the use of the X-band radar signal in HH polarization or in using both HH and HV
 730 polarizations, in addition to one vegetation descriptor derived from optical images. However, the
 731 use of HV in addition to one vegetation descriptor derived from optical images degrades the
 732 precision on M_v estimates. Moreover, results showed that the RMSE on M_v estimates is slightly
 733 sensitive to additive noise on the modelled radar signal. The RMSE increases approximately 1
 734 Vol.% when the noise of the radar signal increases from ± 0.75 dB to ± 1.00 dB. For all NDVI
 735 values, the RMSE on M_v estimates (M_v between 10 and 45 Vol.%) was approximately 5.0 Vol.%
 736 (RRMSE and MAPE about 19 %) in configurations 1 and 3. Similar values of the RMSE (as well
 737 as RRMSE and MAPE) on M_v estimates were obtained with the use of LAI, FAPAR, and
 738 FCOVER as the vegetation descriptor. The accuracy of M_v estimates degrades (i.e., an increase
 739 in the RMSE, RRMSE, and MAPE) with vegetation growth (i.e., an increase in the NDVI). As
 740 an example, in configuration 3 (HH, HV and NDVI), the RMSE on M_v estimates increases from

741 3.6 Vol.% (RRMSE about 13%) for NDVI of 0.45 to 5.7 Vol.% (RRMSE about 21 %) for a
742 NDVI of 0.9.

743 From the real validation dataset (53% of the real dataset), the soil moisture estimation using
744 the X-band SAR data in addition to one vegetation descriptor derived from optical images allows
745 better results with HH polarization than with HV or both HH and HV. With HH and NDVI
746 information derived from optical images, the accuracy on the soil moisture estimation was 3.6
747 Vol.% (RRMSE and MAPE about 13%) for NDVI between 0 and 0.75 (LAI about 3 m²/m²) and
748 6.1 Vol.% (RRMSE and MAPE about 25%) when the NDVI of the grassland was between 0.75
749 and 0.9 (LAI about 6 m²/m²). Similar results were obtained regardless the vegetation descriptor
750 used.

751 With the arrival of new satellites, such as SENTINEL-1A (launched on 3 April 2014), in
752 addition to future satellites SENTINEL-1B, SENTINEL-2A (optical sensor), and SENTINEL-
753 2B, it will be possible to obtain SAR (C-band) and optical remote sensing data covering global
754 areas with high spatial and temporal resolutions (2 days with 2 SENTINEL-1 satellites, and 5
755 days for 2 SENTINEL-2 satellites at 10 m spatial resolution). Combining SENTINEL-1 data
756 with optical images (SENTINEL-2, LANDSAT-7/8) will allow more precise estimation of M_v
757 because the radar signal penetration depth into vegetation cover is higher in the C-band
758 compared to the X-band. This work is in the context of preparing for SENTINEL 1 and 2
759 missions.

760 This study demonstrated that the use of NNs technique to invert X-band SAR backscattering
761 coefficients allows the estimation of soil moisture with acceptable accuracy (RMSE of 3.6 Vol.%
762 for a NDVI lower than 0.75). Current remote sensing sensors (optical and SAR) and those
763 available in the near future (spatial resolution better than 10 m) will allow the estimation of soil

764 moisture at a field scale with high temporal resolution (better than weekly). Vegetation
765 biophysical parameters (i.e., LAI) and soil moisture that can be derived from optical and SAR
766 images could be useful to calibrate crop models for better irrigation management and crop
767 growth monitoring. Indeed, combining optical and SAR data would enhance the relevance of
768 remote sensing data for water and crop monitoring.

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781

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