Soil Parameter Retrievals Over Bare Agricultural Fields Using Multiangular RADARSAT-2 Dataset

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***Abstract*—The objective of this study is to evaluate the potential of multi-angular SAR data at C-band for soil parameters discrimination over bare agricultural fields. In order to exploit the incidence angle diversity to enhance the soil parameter retrievals, the conventional multi-angular roughness descriptor Δ_{HH} formulated originally as the backscattering difference between two specific incidence angles is adapted to take into account a general incidence angle effect. Moreover, a new angular coherence SAR descriptor γ_{HH} is proposed by using a pair of low and high incidence angle SAR data. The adapted Δ_{HH} and the proposed γ_{HH} are applied to the RADARSAT-2 data with three different incidence angles. The results indicate that the proposed γ_{HH} is more sensitive to surface roughness than the adapted Δ_{HH}. Thus, the γ_{HH} is selected to retrieve the surface roughness, and then the retrieved surface roughness is substituted into a low incidence angle data to retrieve the soil moisture. The RMSE of 6.1-8.5 m^3/m^3 is obtained for soil moisture retrieval.**

***Index Terms*—Multi-angular, RADARSAT-2, surface roughness, soil moisture, agricultural field.**

I. Introduction

SOIL moisture and surface roughness are essential parameters in several physical processes (such as water conservation, soil erosion and surface runoff) over agricultural fields. Compared with the conventional soil moisture acquisitions by point sampling (time and labour consumption), Synthetic Aperture Radar (SAR) has the potential to extract surface information with high spatial and temporal resolution. Nevertheless, the contributions of surface roughness and soil moisture are coherently superimposed in the measured SAR signature, leading to the complexity of soil parameter retrieval problem.

To solve this issue of soil parameters characterization and retrievals from SAR measurements, extensive studies have been implemented in the past decades [1]–[4]. Theoretical surface backscattering models such as the Integral Equation Model (IEM) [5], [6] are developed to simulate the microwave propagation and interaction with the soils, however, the complicated formulation of such models limits the direct retrieval of soil parameters. In contrary, the empirical models [2] with simple formulations offer an alternative approach for soil features retrievals, although the empirical models are site-dependent.

Furthermore, recent techniques using multi-dimensional measurements (include multi-polarization, multi-frequency and multi-angular modes) are applied with encouraging potentials to separate the contributions of surface roughness and soil moisture on the backscattering signature [7]. Multi-polarization approaches are investigated in the past [3], [8], [9]. Moreover, multi-frequency approach is investigated in [9], [10] using polarimetric SAR data to improve the robustness of soil parameters retrievals.

The potentials of multi-angular SAR acquisitions to improve the robustness of soil parameter retrievals are demonstrated in a commonly used semi-empirical model [2]. Moreover, the advantages of multi-angular and multi-polarization approaches are compared in [11], indicating that multi-angular configuration is more sensitive to bare soil characteristics variation than multi-polarization configuration. A method using two images acquired at small and large incidence angle is proposed to extract the roughness effect from the full SAR signature [12]. An original surface roughness descriptor developed to combine the horizontal and vertical statistical roughness is estimated from the backscattering difference between SAR data acquired with two incidence angles [7], [13]. Furthermore, an additional image measured under quite dry condition is suggested in [14] to estimate the horizontal and vertical roughness separately. The study in [15] demonstrates that large incidence angle image is more suitable to retrieve surface roughness, while the small incidence angle image is more sensitive to soil moisture variation.

Within this context, the objective of this paper is to investigate the potentials of multi-angular SAR data at C-band for soil parameter retrievals over bare agricultural fields. Most of previous mentioned studies are focused on the L-band and single angular mode. As the missions in C band (e.g. ERS-2/SAR, Envisat/ASAR, RADARSAT-2) are developed, more efforts should be devoted to evaluate the advantages of incidence angle diversity. The section II describes the multi-angular RADARSAT-2 dataset acquisitions and ground truth campaign used in this paper. A new surface roughness characterization method based on the multi-angular SAR acquisition is proposed in section III. The results are analyzed in section IV, and the main discussion and conclusion are finally presented in section V.

II. Study site and dataset

A. Study site

The study site is located in the region of Pleine-Fougères, near the Mont-St-Michel (N $48^\circ 38^{'}$, E$1^\circ 30^{'}$) in Brittany, France (Fig. 1). Over this area, several researches are conducted in the framework of the French national program "ZA Armorique" [16]. This area is characterized by a moderate oceanic climate influenced by gulf stream, with an annual

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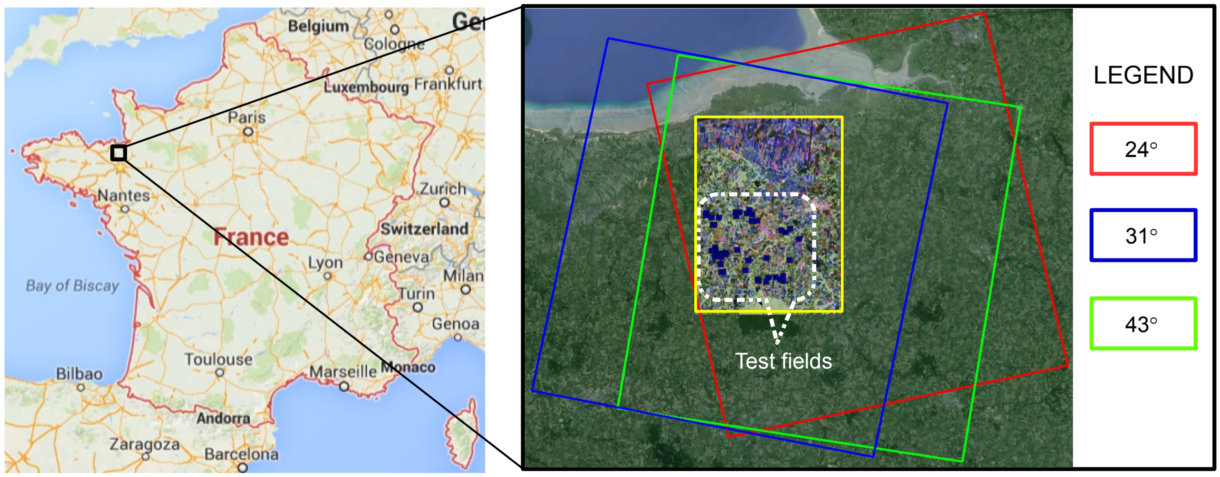


Fig. 1. Study site and the multi-angular RADARSAT-2 image swaths.

temperature around 11.2 °C. There are significant rainfalls throughout the year with average annual precipitation of 735 mm (http://en.climate-data.org/location/700011/), resulting in high soil moisture in some experimental data acquisitions.

B. RADARSAT-2 data and processing

Multi-angular polarimetric RADARSAT-2 data presented in Table I are acquired during April 2013 in Ascending (A) and Descending (D) orbits in fine quad-polarization mode (Single look complex - SLC products) with spatial resolution 5.2 m in range and 7.6 m in azimuth. The incidence angle varies from 24° to 43° (Fig. 1 and Table I). These data are firstly extracted as a coherence matrix T3 using PolSARpro4.2 [8]. Then, a boxcar filter with 7×7 window [4] is applied to reduce speckle effect. The polarimetric images are ortho-rectified and transformed from slant range geometry to ground range using NEST (ESA SAR toolbox). As the test fields are flat, no compensation of terrain slope is applied to the SAR images. The images are co-registered with an average accuracy of 0.8 pixel, which is the achievable co-registration accuracy in NEST.

TABLE I
MULTI-ANGULAR RADARSAT-2 DATASETS

Date (2013)	Beam mode	Incidence angle (°)	images Orbit (Asc/Des)
23/04	FQ5	24	A
23/04	FQ11	31	D
20/04	FQ24	43	D

The temporal variation of rainfall is obtained from the nearest meteorological survey station, providing essential information to analyze the SAR signature with respect to soil characteristics. As shown in Fig. 2, the time evolution of rainfall is in agreement with the measured soil moisture. The significant rainfall on 10/04/2013, leads to the increased soil moisture.

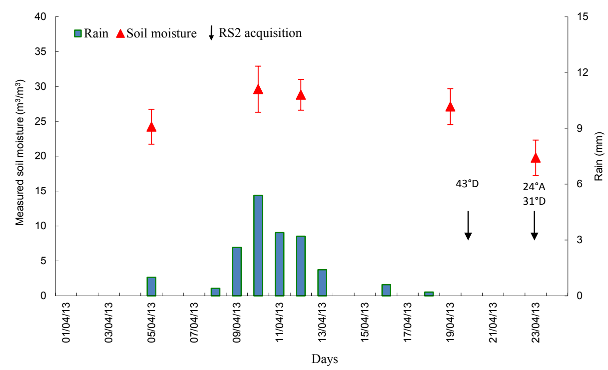


Fig. 2. Temporal evolution of the mean measured volumetric soil moisture (with standard deviation) along with daily precipitation amount and the availability of RADARSAT-2 acquisitions.

In order to locate the bare agricultural fields during the ground campaign of April 2013, the land cover information is collected in collaboration with the COSTEL laboratory from University of Rennes 2 (Climat et Occupation du Sol par TELdtection). 34 bare fields have been selected, considering their size and their distributions over the common section of multi-angular RADARSAT-2 swaths. Over the bare fields, the surface roughness and soil moisture are measured respectively as described in the following section.

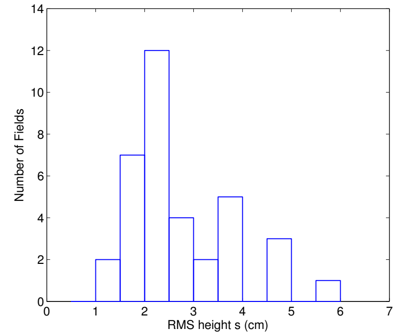
C. Ground truth measurements

The ground measurements of *in situ* surface roughness and soil moisture are conducted in coincidence with RADARSAT-2 data acquisitions.

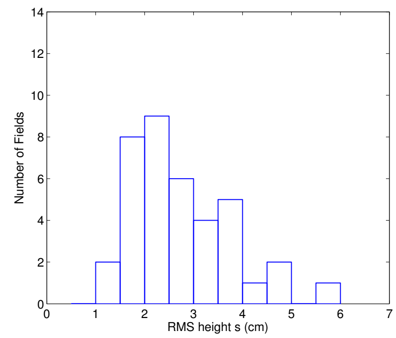
1) Surface roughness: Surface roughness is commonly quantified by the standard deviation of the surface height, also named Random Roughness Factor s. Several methods for surface roughness measurements have been developed in the past decades [17] by using i) vertical movable steel needles; ii) a laser profiler to measure high resolution surface roughness. Nevertheless, over a mass of agricultural fields, the application of these two approaches are time and labor

(a) (b)

Fig. 3. Ground *in situ* measurement of surface roughness profile over two sites by laser instrument.



(a)



(b)

Fig. 4. The distribution of surface roughness s on (a) 19/04/2013; (b) 23/04/2013.

consuming. In our study, the original chain method proposed by Saleh [18] is adopted as an alternative simpler and faster approach to measure surface roughness. The chain method is based on the principle that as a chain of a given length L_1 is placed across a surface, the covered horizontal distance L_2 decreases as surface roughness increases. Therefore, the roughness descriptor called Saleh Roughness Factor (SRF) is defined as: $\mathrm{SRF} = 100(1 - \mathrm{L}_2/\mathrm{L}_1)$.

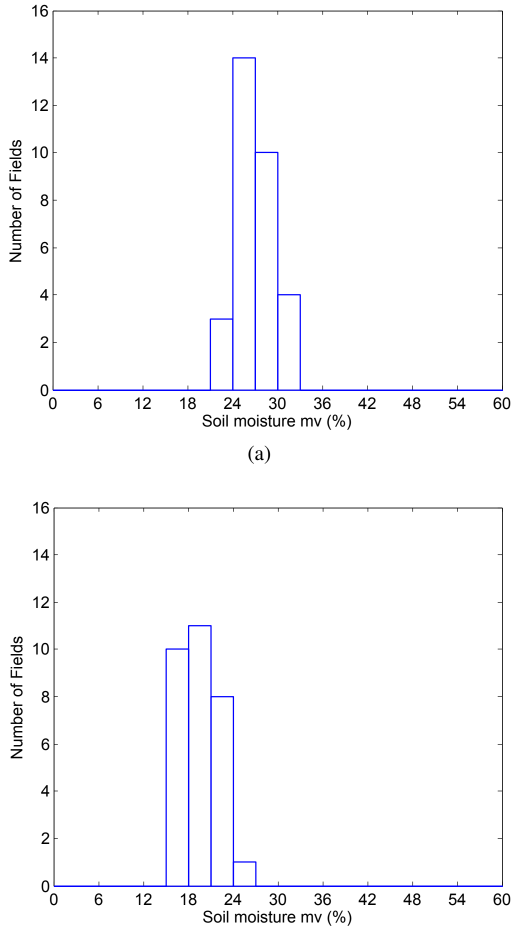
The ground measurements are implemented using a chain of length $\mathrm{L}_1 = 146.5$ cm and with a 2.2 cm linkage length. A conversion relationship by using a laser (2.8 m length and 596 sampling points) is established in this study to transform the SRF measurements to surface RMS height. Several laser profiles are generated over different soil surfaces (Fig. 3) which are also measured by chain method. Indeed, SRF is related to both the RMS height s and the correlation length l. Nevertheless, the influence of l is not considered in our study, as large statistical uncertainties are associated with l when obtained from the finite length profiles [19] (146.5 cm in our case). In addition, the l is linearly related to s [20], thus the relationship proposed in our study is expected to cover some information of l. This explain partially why the effect of correlation length on the relationships between SRF and s is not considered in [21]. The relationship between SRF and s is based on a regression model [21], derived as $s = a.\mathrm{SRF}^b$, where s is given in cm and the coefficient a and b are in function of rainfall amount [21]. In our study, based on the regression between the laser measurements and synchronous chain sampling data (Fig. 3), the coefficients for roughness scale transformation are $a = 0.5072$ and $b = 0.7867$. These two coefficients differ from those in [21] due to the difference in linkage length. This is expected, as it is reported in [22] that the linkage length greatly affects the SRF values.

On each field, the SRF is measured 10 times uniformly in two perpendicular directions so as to represent the entire field. Then, using the developed conversion model, the SRF measurements are transformed into s. Fig. 4 shows the roughness values for the ground campaigns conducted in April 2013. The values ranged from 1.0 cm to 6.0 cm, and are quasi-invariant during the multi-angular RADARSAT-2 data acquisitions. The careful repeating measurements of surface roughness make it reliable to interpret the synchronous multi-angular RADARSAT-2 data. In this study, the soil characteristics are assumed to be quasi-invariant during the multi-angular SAR acquisitions. However, as the previous description in section II-B, RADARSAT-2 data were acquired in both ascending and descending orbits, thus the observed surface roughness which is perpendicular to the SAR look direction may vary if the soil anisotropy is presented. Fortunately, the measurements of soil parameters were operated either just before or just after the RADARSAT-2 path (around several hours). Furthermore, the surface roughness was measured in two orthogonal directions to obtain the representative surface roughness. Considering the resolution cell and the size of each field, we are able to say the fields in this study are globally isotropic, and therefore the effect of ascending/descending orbit is not taken into account.

In addition to surface roughness, another important soil parameter is the soil moisture which determines the permittivity of soil mixture.

2) Soil moisture: The electromagnetic wave traveling speed between two rods installed in TDR instrument depends on the permittivity of the mixture (in our study, the natural soil) which is located between these two rods. The ground soil moisture are measured at 3.8 cm depth (probe length) over the bare agricultural fields. For each field, the TDR measurements are implemented on 25 samples distributed homogeneously on that field so as to represent the general soil moisture status. For the ground campaign in April 2013, the soil moisture distributions on 19/04/2013 and on 23/04/2014 are compared in Fig. 5(a)-(b). The soil moisture is ranged from 23% to 32% on 19/04/2013, and from 15% to 24% on 23/04/2013.

Considering all these ground truth measurements, we are consequently able to develop the empirical models by analyz-



(b)

Fig. 5. The distribution of soil moisture mv on (a) 19/04/2013; (b) 23/04/2013.

ing the sensitivity of multi-angular RADARSAT-2 data with respect to the surface roughness and soil moisture respectively.

III. Methodology of multi-angular SAR

Multi-angular SAR observations are demonstrated to be around ten times more sensitive to surface roughness than multi-polarization measurements [23]. Thus, the incidence angle diversity is assumed to improve the retrieval robustness of soil characteristics by exploiting the complementary information dimension. In this section, two methods for surface roughness retrieval from multi-angular SAR data are proposed. Then the retrieved surface roughness is applied to a low incidence angle SAR data to inverse the soil moisture. The horizontal polarization is selected in this study, as the radar signature is more sensitive to bare soil characteristics than in other channels [7], [24].

A. Geometric configuration

The SAR geometric configuration presented in Fig. 6 (same ground position but different orbits) is used for satellite platform [25]. There exists a temporal interval between the multi-angular SAR data acquisitions, limiting the rigorous soil parameter retrieval when the change of soil status is significant during the acquisition interval. Nevertheless, in our study, the distribution of surface roughness values is quasi-invariant during the three incidence angle acquisitions, as illustrated in Fig. 4 for two repeating measurements.

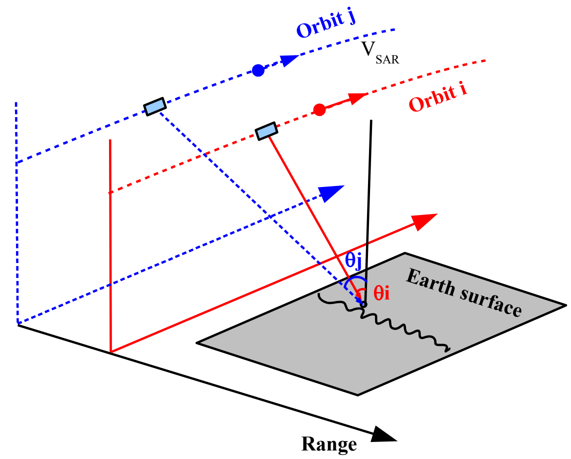


Fig. 6. Multi-angular SAR configuration.

B. Surface roughness

The SAR descriptors derived from multi-angular measurements are assumed to be dominated more by surface roughness than soil moisture [7], as the change of SAR observing geometric configuration (multi-angle) mainly relates to soil geometric features, e.g surface roughness for bare agricultural soils. Two approaches are proposed in this study. On one hand, the SAR parameter based on backscattering difference reported by [7] is analyzed and adapted to our incidence angle diversity. On the other hand, a new soil roughness descriptor based on the correlation of dual incidence SAR measurements is proposed and compared with the behaviors of [7].

1) Difference of SAR backscattering: Under the hypothesis of quasi-invariant soil characteristics (surface roughness and soil moisture) during multi-angular SAR acquisition, the backscattering difference (ratio in linear scale) between dual-angular measurements [7] is defined in dB as:

$$\Delta_{HH}(\text{dB}) = \sigma^0_{HH}(\theta_1) - \sigma^0_{HH}(\theta_2) \tag{1}$$

This parameter is assumed to be sensitive to surface roughness ks (wave number k and root mean square height s).

To parameterize Δ_{HH} in term of surface roughness ks, several solutions are published. For example, the exponential function [7] and a cubic polynomial function [13] are proposed to quantify the surface roughness effect. Nevertheless, it is obvious that Δ_{HH} depends not only on surface roughness, but also on the multi-incidence angle combination. This indicates that the magnitude of Δ_{HH} is dependent on the values of the selected incidence angles for the angular combination. For a single incidence angle acquisition, the cosine function is used to simulate the decreasing trend of backscattering coefficient in term of incidence angle. Thus, the difference of two cosine functions accounts for the incidence angle effect on Δ_{HH}. Therefore, our study proposes a new empirical relationship to

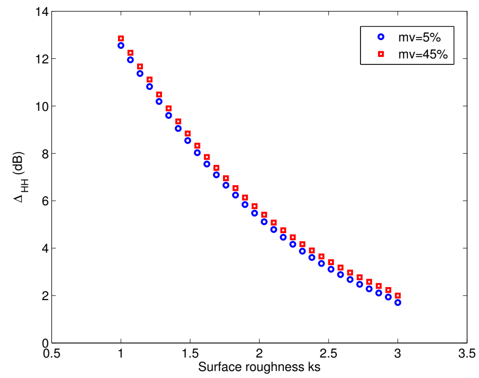


Fig. 7. IEM model simulation for the dependence of multi-angular descriptor Δ_{HH} on surface roughness.

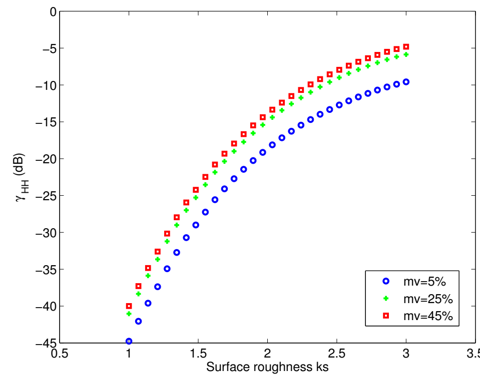


Fig. 8. IEM model simulation for the dependence of multi-angular descriptor γ_{HH} on surface roughness.

take into account the incidence angle effect:

$$\Delta_{HH}(\text{dB}) = m_1(\cos\theta_1 - \cos\theta_2)\exp(n_1 \cdot ks) \tag{2}$$

The empirical constants m_1 and n_1 are determined by using iterative Levenberg-Marquardt method [26] with respect to the SAR data and ground measurements. The two involved incidence angles satisfy $\theta_1 < \theta_2$, and the incidence angle absolute difference $\Delta\theta = |\theta_1 - \theta_2|$ is assumed to be more than 5° to generate a significant backscattering difference [7].

In order to verify the potential of Δ_{HH} for surface roughness characterization, the Integral Equation Model (IEM) model [5] is simulated to analyze the Δ_{HH} behavior. The IEM model is a physically based radar backscatter model for bare soil, and this model quantifies the strength of backscattering in function of soil moisture, surface roughness and the radar configuration. Considering its wide application range over bare soil, the IEM model is used to simulate the behaviors of Δ_{HH} in terms of surface roughness (vertical RMS height $ks = 1 \sim 3$, horizontal correlation length $kl = 13$ and Gaussian surface spectrum) and soil moisture ($mv = 5\% \sim 45\%$) with incidence angle 24° and 31°. Looking on the simulation in Fig. 7, the soil moisture effect on Δ_{HH} is weak, and 40% soil moisture difference only results in less than 0.4 dB difference in Δ_{HH}, indicating the potential use of this multi-angular descriptor for surface roughness retrieval.

Furthermore, considering the similar concept as [7], another new multi-angular SAR descriptor is proposed to retrieve the surface roughness.

2) Coherence of SAR backscattering: Following the assumption that the soil characteristics (surface roughness and soil moisture) are quasi-invariant during multi-angular SAR acquisitions, the two received signatures from the same bare soils are given by [27]:

$$\begin{aligned} s_1(HH) &= A_1 \exp(i\phi_1) \\ s_2(HH) &= A_2 \exp(i\phi_2) \end{aligned} \tag{3}$$

with amplitude A_1 and A_2, phase ϕ_1 and ϕ_2. To combine the measured two signatures under different incidence angles, the strength of coherence in horizontal polarization γ_{HH} is initially defined as:

$$\begin{aligned} \gamma_{HH} &= |s_1 s_2^*| = A_1 \cdot A_2 = \sqrt{\sigma_{HH}(\theta_1) \times \sigma_{HH}(\theta_2)} \\ \text{and } \gamma_{HH}(\text{dB}) &= \frac{\sigma_{HH}(\theta_1, dB) + \sigma_{HH}(\theta_2, dB)}{2} \end{aligned} \tag{4}$$

For γ_{HH} parameterization, the soil moisture effect is neglected, as the multi-angular observation is approximately independent on non-geometric soil parameters such as soil moisture [7]. In contrary, the roughness effect is modeled by an exponential function which is a common form to describe roughness influence on backscattering coefficient [28]. Moreover, the combination choice of two incidence angles (considering the availability of incidence angles in the dataset) also affects the magnitude of γ_{HH}. As cosine function is used to account for the incidence angle effect on backscattering coefficient of single acquisition, the addition of two cosine functions is consequently included to interpret the incidence angle effect on γ_{HH}. Therefore, in our study, the parameterization of γ_{HH} is proposed in dB as:

$$\gamma_{HH}(\text{dB}) = m_2(\cos\theta_1 + \cos\theta_2)\exp(n_2 \cdot ks) \tag{5}$$

where m_2, n_2 are the empirical constants determined by using iterative Levenberg-Marquardt method [26] on the multi-angular RADARSAT-2 dataset.

To understand the behaviors of γ_{HH}, the IEM model [5] simulated γ_{HH} is shown in Fig. 8. The γ_{HH} parameter is dominated by surface roughness effect. The soil moisture difference of 40% leads to around 4.9 dB difference in γ_{HH} for the whole roughness range. In contrast, the surface roughness ks difference of 2.0 results in 35 dB difference in γ_{HH}. Thus, compared with the great effect of surface roughness on the new parameter γ_{HH}, the soil moisture disturbance can be neglected. For soil moisture more than 25%, the γ_{HH} is ideally quasi-independent of soil moisture.

After removing the roughness effect from backscattering signature, the method for soil moisture characterization is proposed in the next part.

C. Soil moisture

As it is reported in [29] that the backscattering coefficient is more dominated by soil moisture than surface roughness at

TABLE II
PEARSON CORRELATION BETWEEN MULTI-ANGULAR DESCRIPTORS AND SURFACE ROUGHNESS

Descriptors	24° and 31° (A, D) (23/04) and (23/04)	24° and 43° (A, D) (23/04) and (20/04)	31°and 43° (D, D) (23/04) and (20/04)
Δ_{HH}	**-0.50***	-0.35	-0.15
γ_{HH}	**0.54****	**0.67****	**0.75****

Note: '$*$' denotes $p < 0.05$, '$**$' denotes $p < 0.01$ and '$--$' no correlation.
The significant correlation is denoted by bold characters, and the same in the following.

low incidence angle. Thus, the low incidence angle (e.g $\leq 31°$) is supposed to be optimal for soil moisture characterization. The soil moisture retrieval is consequently based on the backscattering coefficient σ^0_{HH} at low incidence angle.

The simple empirical model is proposed for soil moisture, as this study is dedicated to demonstrate the advantage of multi-angular SAR. The proposed empirical σ^0_{HH} (in dB) parameterization has the following form in Eq. (6): the term $a_1\, mv$ quantifies the linear relation between σ^0_{HH} and soil moisture [1], [29], [30]; the term $b_1 \exp(c_1 \cdot ks)$ models the exponential relation between σ^0_{HH} and surface roughness [15], [29], [31]; and the last term $d_1 \cos\theta$ quantifies the incidence angle effect on σ^0_{HH} [30].

$$\sigma^0_{HH}(\theta \leq 31°) = a_1\, mv + b_1\, \exp(c_1 \cdot ks) + d_1\, \cos\theta \quad (6)$$

where a_1, b_1, c_1 and d_1 are empirical constants determined by Levenberg-Marquardt method [26] using the multi-angular RADARSAT-2 dataset.

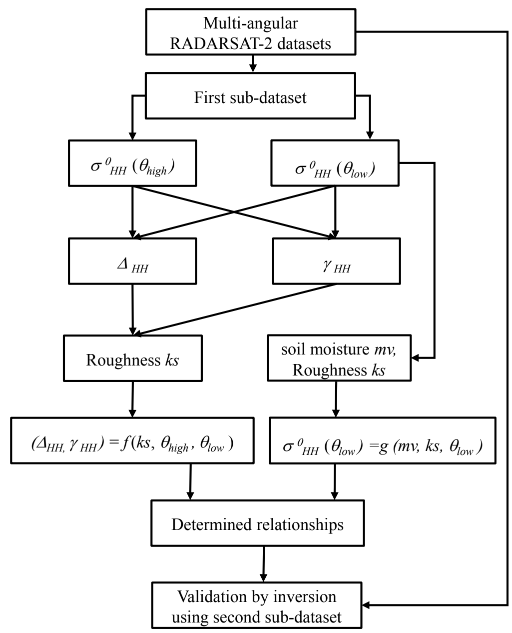


Fig. 9. The flowchart of empirical model development.

D. Implementation procedure

Based on the previous analysis, Fig. 9 presents the implementation procedures conducted in this paper.

- First, the multi-angular parameters Δ_{HH} and γ_{HH} are calculated by using a low incidence angle and a high incidence angle;
- Then, these multi-angular parameters are correlated to surface roughness, and the coefficients in Eq. (2) and Eq. (5) are determined by fitting to the first sub-dataset;
- Meanwhile, the σ^0_{HH} at low incidence angle is related to soil moisture and surface roughness, and the coefficients in Eq. (6) are determined for soil moisture characterization;
- The determined relationships are validated by inversion the surface roughness and soil moisture using the second sub-dataset.

The next section justifies the advantages and limitations of the proposed multi-angular approaches by applying them to the multi-angular RADARSAT-2 data and the ground truth measurements for soil parameters characterization.

IV. RESULTS

This section evaluates the potential of the proposed approach (see Fig. 9) for soil parameters characterization and retrievals using the RADARSAT-2 dataset. Half of the pixels over the bare fields are randomly selected for the correlation analysis (section IV-A) and forward empirical model establishment (section IV-B), and the remaining pixels are used for the retrieval process validation (section IV-C). In this section, the correlation between SAR derived descriptors and soil variables are studied first. Then, the coefficients of the empirical relationships are properly determined to relate the SAR derived parameters with the measured soil variables. Finally, the surface roughness and soil moisture are retrieved and evaluated in term of ground *in situ* campaign.

A. Correlation analysis

Pearson product moment correlation coefficient [24], [32] is used to quantify to correlation between the measured soil characteristic X and RADARSAT-2 data derived descriptor Y. It is based on both the statistical significance p ($p < 0.01$ indicates extreme significant; $p < 0.05$ represents significant), and the Pearson correlation strength r given as:

$$r = \frac{\sum_{i=1}^{N}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{N}(Y_i - \bar{Y})^2}} \quad (7)$$

TABLE III
PEARSON CORRELATION BETWEEN BACKSCATTERING COEFFICIENT AND SOIL MOISTURE

Descriptors	24° (A) (23/04)	31° (D) (23/04)	43° (D) (20/04)
σ^0_{HH}	**0.43***	0.35	0.09

with the field index i, the mean value of soil variable $\bar{X}$, the mean value of RADARSAT-2 derived descriptor $\bar{Y}$, and total number of fields N in the assessment.

The Pearson correlations obtained between multi-angular SAR descriptors (Δ_{HH}, γ_{HH}) and surface roughness are shown in Table II. For different multi-angular configuration, the correlation for γ_{HH} is higher than for Δ_{HH}, whatever the roughness and the satellite configuration. For γ_{HH}, the correlation reaches to the level of extreme significant ($p < 0.01$). By including a high incidence angle 43° in γ_{HH}, the correlation is further improved. It can be explained by the fact that the backscattering is essentially dominated by soil moisture at low incidence angle condition (e.g. $\leq$ 31°), and dominated by surface roughness at high incidence angle (e.g. $>$ 40°) [12]. For Δ_{HH}, only one configuration (24° and 31°) shows significant correlation ($p < 0.05$), as the soil moisture is the same during these two incidence angle acquisitions.

The same correlation analysis is led between soil moisture and the horizontal backscattering coefficient σ^0_{HH}. The results are shown in Table III for different incidence angle values. The soil moisture is only significantly correlated to horizontal polarization signature at small incidence angle (24°) with $r = 0.4279$. As the incidence angle increases to 31°, the correlation coefficient decreases. For incidence angle greater than 31°, no correlation has been found. This result was expected, as the two RADARSAT-2 data ($\theta = 24°$ and $\theta = 31°$) were acquired at low soil moisture condition (Fig. 5(b)). In this case, the microwave penetrating depth is deep, resulting in enhanced correlation with soil moisture. As a comparison, the studies in [28], [33], [34] also demonstrate that σ^0_{HH} has higher correlation with soil moisture at low incidence angle (normally less than 31°) than at high incidence angle. The results of [24] verify that the σ^0_{HH} is much more sensitive to soil moisture than other polarimetric descriptors.

Therefore, the correlation study demonstrates that the multi-angular SAR acquisition is very sensitive to surface roughness, and the SAR signature at a single low incidence angle is highly sensitive to soil moisture. Then, the coefficients for Eq. (2) (Δ_{HH}), Eq. (5) (γ_{HH}) and Eq. (6) ($\sigma_{HH}(\theta \leq 31°)$) can be determined.

B. Empirical relationships between SAR derived descriptors and soil characteristics

Based on the multi-angular RADARSAT-2 data, this part determines the coefficients of the empirical relationships for surface roughness (Eq. (2) and Eq. (5)) and for soil moisture (Eq. (6)) respectively. The performances of the determined empirical relationships are evaluated using Root Mean Square Error (RMSE) and bias:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \tag{8}$$

$$\text{bias} = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \tag{9}$$

where the index i describes the field number, P_i the simulated value from empirical approaches, O_i the extracted value from RADARSAT-2, and N the total number of fields used for the assessment. The RMSE quantifies the magnitude of average modeling error for each empirical model, while the bias describes deviation tendency of the model.

1) Surface roughness: For surface roughness characterization, the parameters Δ_{HH} and γ_{HH} are discussed separately.

Δ_{HH} with respect to roughness: Through the previous correlation analysis, we found that Δ_{HH} is only related to surface roughness for two incidence angle combination conditions: (24° with 31°) and (24° with 43°). Hence, based on 47 points extracted from these two angle combination cases jointly, the coefficients of Eq. (2) are obtained in Table IV by the minimization method of Levenberg-Marquardt [26] for decreasing the deviation of model prediction from RADARSAT-2 data.

The matching between RADARSAT-2 derived Δ_{HH} and our determined empirical Δ_{HH} model (Eq. (2)) is shown in Fig. 10 for two cases of incidence angle combination. The Δ_{HH} decreases with surface roughness, in accordance with the study in [7]. Moreover, the soil moisture effects on Δ_{HH} are not presented, in agreement with the IEM simulation (section III). Nevertheless, the Δ_{HH} is sensitive to both the RMS height ks and auto correlation length kl [7]. However, the kl is reported to be statistically uncertain when measured over a finite profile [19], and is therefore not considered in this study. Consequently, the sensitivity of Δ_{HH} is only evaluated in term of ks, and neglecting the kl explains partially the under-performance of Δ_{HH} in Fig. 10. Furthermore, the Δ_{HH} derived from incidence angle pair (24° with 31°) in Fig. 10(a) is with less RMSE (to match the Δ_{HH} model under overall soil moisture status in this study) than the combination of (24° and 43°) in Fig. 10(b). This is due to the fact that the RADARSAT-2 data of (24° and 31°) are acquired on the same day 23/04/2013, thus, the corresponding surface roughness and soil moisture are the same, which exactly respects the assumption of Δ_{HH} method. In contrary, the soil conditions in case of Fig. 10(b) might be disturbed during the 3 days time span (from 20/04 to 23/04/2013), leading to high RMSE of Δ_{HH}. On the other hand, as the incidence angle gap $\Delta\theta$ of the combination pair (24° and 43°) is greater than the gap of (24° and 31°), the induced dynamic range of Δ_{HH} is correspondingly large.

In contrary, the unfavorable performance of other incidence angle combinations (e.g. 31° and 43°) for Δ_{HH} indicates the strict requirement of quasi-invariant soil moisture for application of Δ_{HH} to characterize surface roughness. Nevertheless, this strict application condition is rarely satisfied, as the soil moisture is a very dynamic parameter which vary continuously

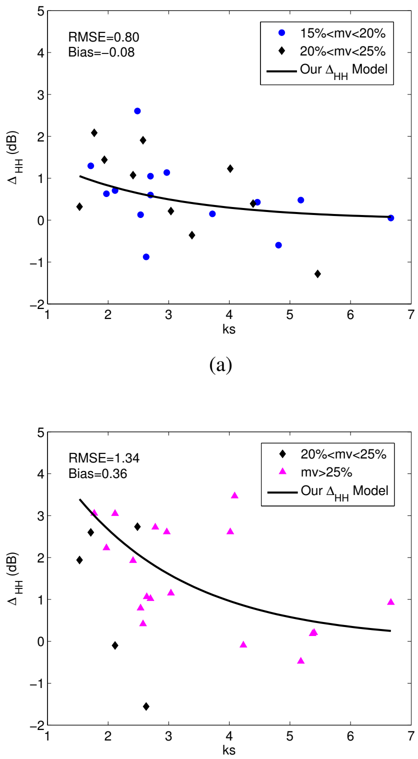


Fig. 10. Δ_{HH} in function of ks for incidence angle combination of (a) 24° and 31°; (b) 24° and 43°.

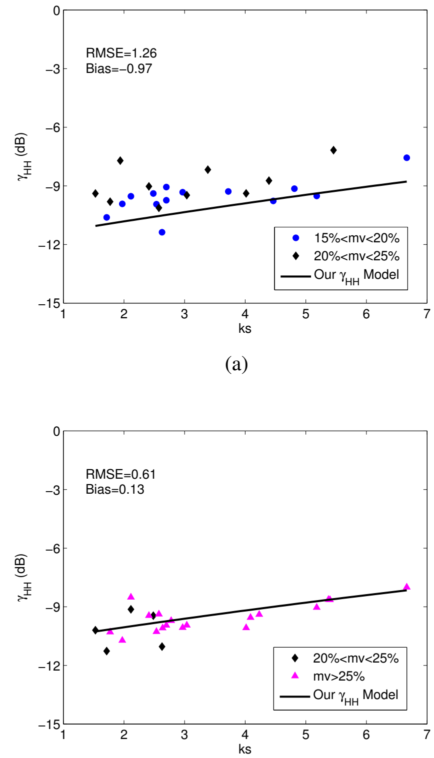


Fig. 11. γ_{HH} in function of ks for incidence angle combination of (a) 24° and 31°; (b) 24° and 43°.

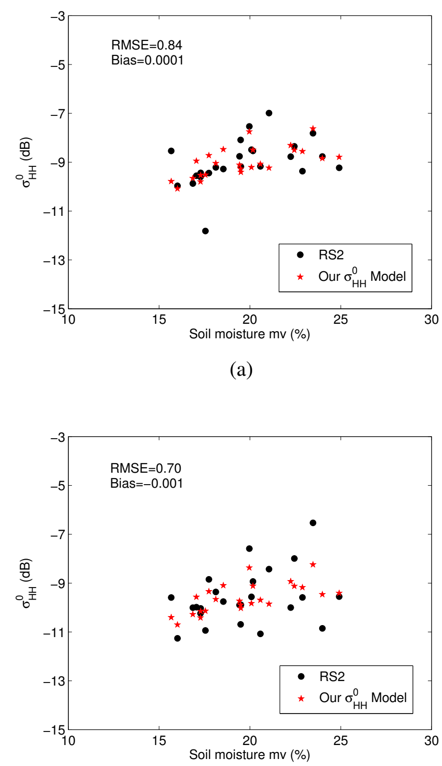


Fig. 12. σ^0_{HH} against soil moisture for incidence angle (a) 24°; (b) 31°.

due to water evaporation, infiltration and disturbance from air humidity variation.

γ_{HH} with respect to roughness: From the previous correlation analysis, γ_{HH} is found to be sensitive to surface roughness for all angle combination. Three possible incidence angle combinations among 24°, 31° and 43° are achieved, leading to 71 data points. Thus, the coefficients for Eq. (5) are determined in Table IV by fitting these data points jointly.

The simulation using the determined empirical γ_{HH} relationship (Eq. (5)) is compared with γ_{HH} extracted from RADARSAT-2 data in Fig. 11. As the incidence angle gap ($\Delta\theta$ between the two angle pairs) increases to more than 16°, the RMSE of γ_{HH} decreases, indicating an enhanced sensitivity to surface roughness. Thus, the best results are obtained for an angle combination of 24° and 43° (Fig. 11(b)). Furthermore, the soil moisture effect in γ_{HH} is not observed, in accordance with the theoretical IEM simulation (Fig. 8).

To this step, we have demonstrated the potential of multi-angular RADARSAT-2 to characterize the surface roughness by using Δ_{HH} and γ_{HH} . The following part is dedicated to characterize the soil moisture by using low incidence angle RADARSAT-2 data.

2) Soil moisture: For soil moisture characterization, the backscattering coefficient is assumed to be function of surface roughness, soil moisture and incidence angle under low incidence angle condition. As seen in the previous section, σ^0_{HH} is sensitive to soil moisture for $\theta = 24°$ and $\theta = 31°$ (Fig. 12), verifying the phenomenon that soil moisture domi-

TABLE IV

OBTAINED COEFFICIENTS OF THE EMPIRICAL MODELS

Δ_{HH}	m_1	n_1	γ_{HH}	m_2	n_2
	40.5921	-0.5094		-6.6817	-0.0447
σ^0_{HH}	a_1	b_1	c_1	d_1	
	0.10542	-22.7527	-0.0188	11.4829	

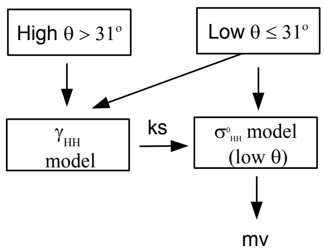


Fig. 13. Multi-angular SAR approach for soil parameter retrievals.

nates the backscattering signature at low incidence angle, e.g. $\leq 31°$, in accordance with [12], [15]. Thus, the coefficients of σ^0_{HH} expression (Eq. (6)) are determined in Table IV using RADARSAT-2 data acquired at $\theta = 24°$ and $\theta = 31°$ jointly (48 points).

Comparing the RMSE and bias between Fig. 12(a) and Fig. 12(b), we observed that the monotonic increase of backscattering signature with soil moisture is more confident at lowest incidence angle $\theta = 24°$ than $\theta = 31°$. This behavior is in agreement with [28], justifying that the backscattering signature at small incidence angle is more sensitive to soil moisture than large incidence angle. Nevertheless, a limitation of this study to analyze the SAR signature sensitivity to soil moisture lies in the fact that the measured soil moisture are relatively homogenous among different agricultural fields during the ground campaign, resulting in the low dynamic range of soil moisture in the analysis.

The following section is dedicated to retrieve surface roughness and soil moisture by applying the developed empirical relationships to the second half of the pixels selected randomly over bare fields.

C. Retrievals of soil parameters

In order to validate the established empirical relationships, the remaining 50% of the randomly selected pixels are analyzed in this section for the retrieval procedure.

1) Retrieval strategy: Based on the previous studies, the soil parameter retrieval algorithm is proposed in Fig. 13. Surface roughness is retrieved from γ_{HH} using a low and a high incidence angle by solving Eq. (5):

$$ks = -22.3714 \log \left(\frac{\gamma_{HH_1}(\text{dB})}{-6.6817\,(\cos\theta_1 + \cos\theta_2)} \right) \quad (10)$$

It should be mentioned that Δ_{HH} parameter is not used in the retrieval strategy, as its correlation with roughness is less than γ_{HH}. Consequently, the retrieved surface roughness ks is then substituted into Eq. (11) (obtained by solving Eq. (6)) to infer the corresponding soil moisture mv from a low incidence angle RADARSAT-2 data.

$$mv = 9.4859\,\sigma^0_{HH}(\text{dB}) + 215.8291\,\exp(-0.0188 \cdot ks) \\ -108.9253\,\cos\theta \quad (11)$$

Considering the incidence angle diversity of RADARSAT-2 data, the performance of the retrieval is also assessed using RMSE and bias (between the retrieved soil parameters and ground truth measurements).

2) Surface roughness: The quantitative comparison between the retrieved surface roughness and the ground truth measurement is shown in Fig. 14 for different incidence angle combination. The optimal retrieval (with lowest RMSE and bias) are obtained by using incidence angle combination of 24° and 43° (Fig. 14(c)). This is due to the large incidence angle gap of 19°, improving the sensitivity of γ_{HH} against roughness. However, the surface roughness of two fields is seriously overestimated, and this can be explained by the presence of significant ridge on these fields as a result of tillage. Moreover, for the combination of two low incidence angles with small angle difference of 7° in Fig. 14(a), the surface roughness is overestimated. In contrary, for another combination of two high incidence angle with angle gap of 12° in Fig. 14(b), the surface roughness is underestimated.

3) Soil moisture: For soil moisture, the field-level comparison with the ground truth measurement is shown in Fig. 15. Most of the retrieval values (around 95%) are located within the $\pm 10\%$ error tolerance region (dot line). Depending on the accuracy of surface roughness retrieval, the incidence angle combination of 24° and 43° insures the best results in Fig. 15(c) with lowest bias of -0.86%. This over-performance is expected, as the previous multi-angular retrieval procedure provides the best surface roughness values (with lowest RMSE and bias). Thus, the robust retrieval of surface roughness causes the best retrieval of soil moisture (with incidence angle 24°). In contrary, the soil moisture retrieval results in Fig. 15(a) are slight underestimated, while the results in Fig. 15(b) are overestimated due to the previous retrieval bias of surface roughness. This is understandable since the overestimation of roughness causes the underestimation of soil moisture, and vice versa.

Therefore, the incidence angle selection should be taken care when using the multi-angular parameters γ_{HH}. The optimal angle combination should include a low incidence angle ($\leq 31°$) and a high incidence angle ($> 31°$), and the incidence angle gap should more than a threshold (such as $12° < \Delta\theta < 19°$ in our study). In this way, the derived γ_{HH} is more sensitive to surface roughness than the case of little incidence angle gap e.g. $\Delta\theta < 7°$, and the robust retrieval of surface roughness is the precondition to improve the accuracy of soil moisture inversion.

V. DISCUSSION AND CONCLUSION

The objective of this study is to evaluate the potential of multi-angular RADARSAT-2 data for separation the soil surface roughness from the backscattering signature. On one hand, the sensitivity of the SAR derived parameter Δ_{HH} [7]

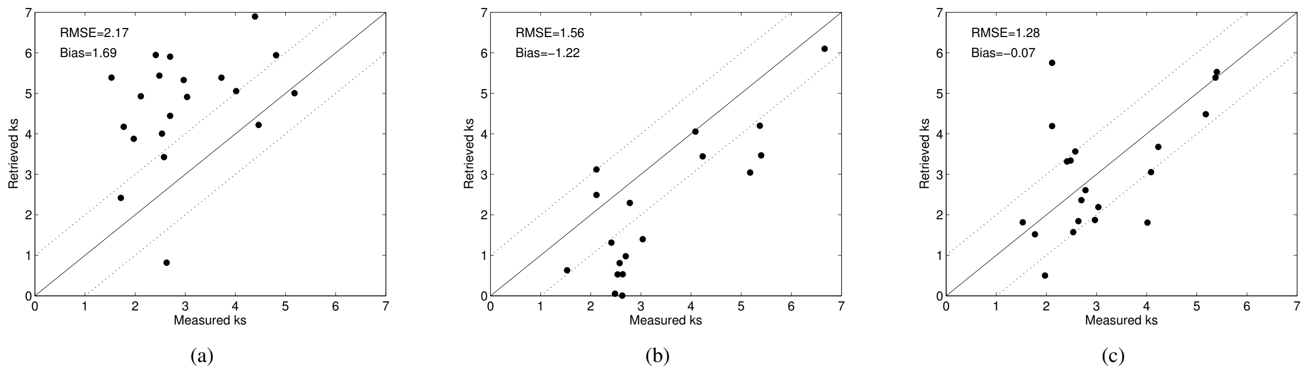


Fig. 14. Comparison between ground *in situ* measured and retrieved surface roughness using γ_{HH} (a) $24°$ and $31°$; (b) $31°$ and $43°$; (c) $24°$ and $43°$.

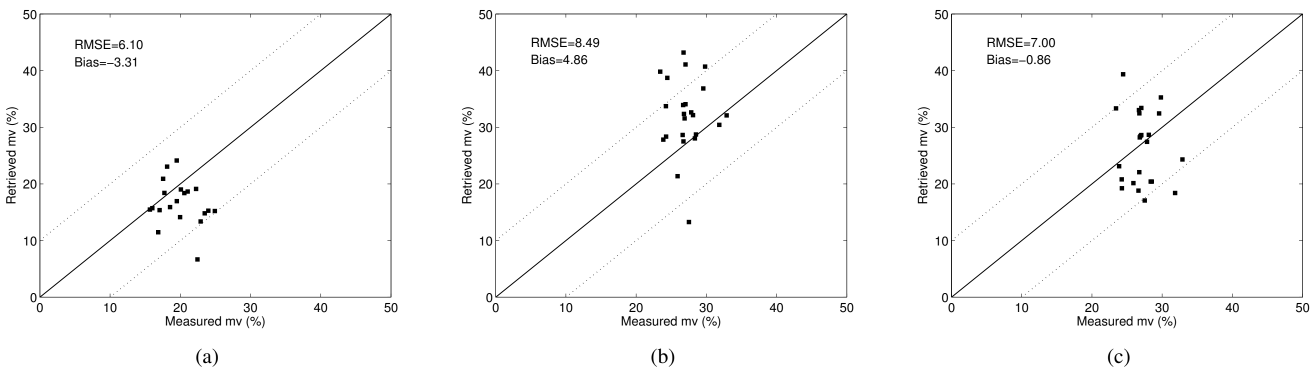


Fig. 15. Comparison between ground *in situ* measured and retrieved soil moisture (a) $24°$ (and $31°$ for roughness); (b) $31°$ (and $43°$ for roughness); (c) $24°$ (and $43°$ for roughness).

is analyzed against surface roughness, and its parameterization in term of soil roughness is adapted to include the incidence angle effect. On the other hand, a new SAR derived descriptor γ_{HH} is proposed to improve the robustness of soil roughness characterization by using multi-angular RADARSAT-2 data. In addition, the low incidence angle data ($\leq 31°$) is proposed to characterize the corresponding soil moisture. Furthermore, the empirical relationships are established to retrieve surface roughness and soil moisture respectively from multi-angular SAR acquisitions.

This study indicates that both the multi-angular parameters Δ_{HH} and γ_{HH} are predominated by surface roughness, in agreement with IEM scattering model. Nevertheless, the γ_{HH} is found to be more sensitive to surface roughness than Δ_{HH}. This can be caused by several reasons: the Δ_{HH} is initially related to s^2/l in [7], however, our study lacks the l measurements which may lead to the decreased sensitivity. Moreover, the potential errors in the ground truth measurements may also bias the results, as the surface roughness is measured initially by the chain method (SRF) [18] in this study, and then the measured SRF is transformed to Root Mean Square height s. As described in section II-C1, the datasets of simultaneous chain and laser measurements are not large, which may cause less representativeness of the calibration relationship. In addition, a conversion model is used in this study to calibrate the TDR measurements. This conversion model may also cause errors in deriving the corresponding soil moisture.

Furthermore, the application of Δ_{HH} requires a constant soil moisture during multi-angular SAR measurement. However, it is rather difficult over the out-door agricultural fields, compared with the surface roughness which is stable during large period. Considering the complex and rapid soil moisture dynamic, the γ_{HH} parameter is more appropriate to characterize surface roughness than Δ_{HH}. Furthermore, at relative wet soil condition ($> 20\%$), the soil moisture influence on γ_{HH} is negligible and it is the optimal condition to retrieve the surface roughness. Thus, the multi-angular descriptor γ_{HH} derived from RADARSAT-2 data is proposed to retrieve the surface roughness.

Moreover, this study also verifies that the RADARSAT-2 signature is more dominated by soil moisture than surface roughness at low incidence angle ($\leq 31°$), in accordance with [12]. Thus, after the surface roughness is retrieved from the multi-angular SAR descriptor γ_{HH}, the corresponding soil moisture is then estimated with RMSE of 6.1-8.5 m^3/m^3 from the low incidence angle RADARSAT-2 data.

The limitation of this study is also clear, as it only uses the backscattering coefficient in horizontal polarization to demonstrate the advantage of multi-angular SAR acquisitions, as this parameter is found to be more sensitive to bare soils than other polarization channels [7], [24]. However, the incidence angle diversity should be also exploited in a polarimetric mode, and such integration of multi-angular and multi-polarization is expected to furthermore improve the bare soil characterization.

As the demonstrations in this study, the multi-angular RADARSAT-2 acquisitions have great potentials to separate the surface roughness effects from backscattering signature in order to retrieve soil moisture accurately. Further works are still important to verify this potential by using large multi-angular SAR databases acquired from RADARSAT-2 (and/or other platform) over various study conditions.

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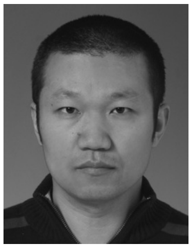

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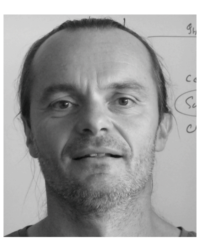

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He has published 10 chapters in books, more than 80 papers in refereed journals and presented more than 380 papers during International Conferences, Symposiums and Workshops. He has presented advances courses and seminars on Radar Polarimetry to a wide range of organizations and events. He received the Award for a Very Significant Contribution in the Field of Synthetic Aperture Radar (EUSAR2000) and the 2007 IEEE GRSS Letters Prize Paper Award. He has published a book co-authored with Dr. Jong-Sen Lee: Polarimetric Radar Imaging: From basics to applications, CRC Press, Taylor & Francis editor, 397 pages, January. 2009, ISBN: 978-1-4200-5497-2. He is a recipient of the 2007 IEEE GRSS Education Award In recognition of his significant educational contributions to Geoscience and Remote Sensing. He has been elevated to IEEE Fellow (January 2011) with the accompanying citation: for contributions to polarimetric Synthetic Aperture Radar. He is a recipient of the 2012 Einstein Professorship from the Chinese Academy of Science. He was recognized as an IEEE GRSS Distinguished Lecturer in 2014. He is a recipient of the CNFRS-URSI Medal under the auspices of the French Academy of Sciences (2015).