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The objective of this paper is to evaluate on bare soils the surface backscattering models IEM, Oh, and Dubois in X-band. This analysis uses a large database of TerraSAR-X images and in situ measurements (soil moisture and surface roughness). Oh's model correctly simulates the radar signal for HH and VV polarizations whereas the simulations performed with the Dubois model show a poor correlation between TerraSAR data and model. The backscattering Integral Equation Model (IEM) model simulates correctly the backscattering coefficient only for *rms*<1.5 cm in using an exponential correlation function, and for *rms*>1.5 cm in using Gaussian function. However, the results are not satisfactory for a use of IEM in the inversion of TerraSAR data. A semi-empirical calibration of IEM was done in X-band. Good agreement was found between the TerraSAR data and the simulations using the calibrated version of the IEM.

***Index Terms*— Integral Equation Model (IEM), Oh Model, Dubois Model, TerraSAR images**

I. INTRODUCTION

Numerous radar backscattering models have been reported in the literature. The most frequently used are those developed by Oh et al. ([1], [2], [3], [4]), Dubois et al. ([5]), and Fung et al. ([6]). These models are supposed to reproduce the radar backscattering coefficient ($\sigma°$), and to allow the estimation of soil surface parameters (moisture content and roughness) from SAR images. For bare soils, the models link the radar backscattering coefficient to soil parameters (dielectric constant, roughness) and to SAR sensor parameters (radar wavelength, incidence angle, polarization). However, discrepancies are observed in several studies between SAR backscattering coefficients and those predicted by the models (e.g. [7], [8], [9], [10]), rendering the inversion results inaccurate).

The description of surface roughness on bare soils is currently based on three parameters: the correlation function, the correlation length, and the standard deviation of heights (*rms*). The backscattering coefficient varies considerably with the shape of the correlation function. Moreover, the measurements of correlation length are often inaccurate because of inappropriate measurement protocols (short length, reduced number, and low horizontal resolution of roughness profiles).

Baghdadi *et al*. ([10], [11], [12]) proposed an empirical calibration of the IEM in C-band (HH, VV and HV polarizations), based on experimental data of SAR images and ground measurements (soil moisture and surface roughness). The approach consisted of replacing the correlation length measurements by a fitting parameter; so that the IEM model reproduces exactly the radar backscattering coefficient. Calibration results showed that the fitting parameter was found dependent on *rms* surface height, radar polarization, and incidence angle. Moreover, preliminary results using SAR data in X- and L-bands showed a dependence of the fitting parameter on radar wavelength.

The objective of the present study is to evaluate the three most popular models used in inversion procedures (Oh, Dubois, and IEM) using databases acquired during over numerous study sites in France and Tunisia. The databases consist of TerraSAR-X SAR data (X-band) and measurements of soil moisture and surface roughness over bare soils. Moreover, we propose an extension of the calibration of IEM model to SAR data in X-band.

II. EXPERIMENTAL DATA

A. Study areas

A database composed of TerraSAR-X acquisitions and ground measurements over numerous agricultural study sites in France and Tunisia has been used (Figure 1, Table 1). Ground measurements of soil moisture and surface roughness were conducted simultaneously to SAR acquisition campaigns on several bare soil reference fields (with low local topography).

- Orgeval site: located to the East of Paris (long. 3°07'E, lat. 48°51'N, France). Soil composition is about 78% silt, 17% clay, and 5% sand.
- Villamblain site: located to the South of Paris (long. 1°34'E, lat. 48°00'N, France). Soil composition is about 60% silt, 30% clay, and 10% sand.
- Mauzac site: located near Toulouse in the South of France (long. 01°17'E, lat. 43°23'N). The soil at this site has a texture loamy sand, composed of 48% silt, 16% clay, and 36% sand.
- Garons site: located near Nîmes in the South of France (long. 04°23'E, lat. 43°45'N). Soil composition is 54%

silt, 40% clay, and 6% sand.

- Kairouan site: located to the South of Tunis, Tunisia (long. 09°54'E, lat. 35°35'N). Soil composition is about 11% silt, 32% clay, and 57% sand.
- Versailles site: located to the West of Paris, France (long. 02°05'E, lat. 48°47'N). Soil composition is about 58% silt, 24% clay, and 18% sand.
- Thau site: located near Montpellier in the South of France (long. 03°40'E, lat. 43°30'N). Soil composition is about 52% silt, 35% clay, and 12% sand.
- Seysses site: located near Toulouse in the South of France (long. 01°17'E, lat. 43°29'N). Soil composition is about 50% silt, 16% clay, and 34% sand.

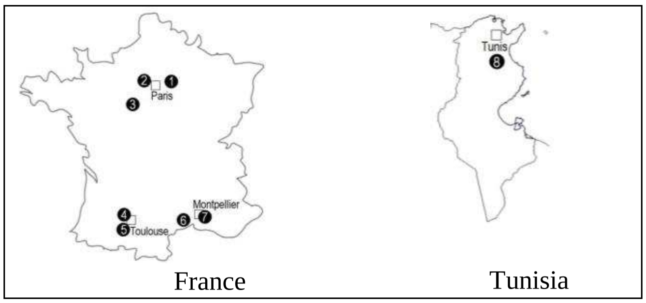

Fig. 1. Location of various study sites in France and Tunisia. ″1″: Orgeval, ″2″: Versailles, ″3″: Villamblain, ″4″: Seysses, ″5″: Mauzac, ″6″: Thau, ″7″: Garon, ″8″: Kairouan.

B. Satellite data

Fourty-five TerraSAR-X images (X-band ~ 9.65 GHz) were acquired between the 15th of January 2008 and the 18th of November 2010 with different incidence angles between 25° and 52°, and in mono-polarization mode (HH, VV). The imaging mode used was Spotlight with a pixel spacing of 1 m. Characteristics of TerraSAR images used in this study are summarized in Table 1. Images were first calibrated to enable the derivation of backscattering coefficients (σ°). The average backscattering coefficient was then calculated for each reference field.

C. Field data

Field measurements of soil moisture and surface roughness have been achieved. The soil moisture measurements were carried out from the top 5 cm of soil because the low penetration of radar signal at X-band. The soil moisture (*mv*) of each bare soil reference field was assumed to be equal to the mean value measured from several samples collected in that field in using a calibrated TDR (Time Domain Reflectometry) probe. The soil moistures range from 5 to 41cm^3/cm^3 with a standard deviation of about 5cm^3/cm^3.

Roughness measurements were made using laser and needle profilometers (1 and 2 m long and with 0.5, 1, and 2 cm sampling intervals). Ten roughness profiles along and across the direction of tillage (five parallel and five perpendicular) were established in each reference field. From these measurements, the two roughness parameters, root mean square (*rms*) surface height and correlation length (*L*), were calculated using the mean of all correlation functions. The *rms* surface heights range from 0.42 cm to 4.55 cm. The lower values of *rms* (<1.5 cm) corresponded to sown plots, whereas the higher values (above 2.5 cm) corresponded to recently ploughed plots. The correlation length (*L*) varies from 2.32 cm in sown fields to 10.41 cm in ploughed fields.

TABLE I
MAIN CHARACTERISTICS OF THE DATABASE USED IN THIS STUDY (226 DATA IN HH AND 130 IN VV). σ°: BACKSCATTERING COEFFICIENT, *MV*: SOIL MOISTURE, *RMS*: STANDARD DEVIATION OF HEIGHTS, L: CORRELATION LENGTH.

Site	Number of data (σ° , mv , rms , L)	Year	Radar configurations (polarization-incidence)
Orgeval	12 27	2008	HH-50° For calibration HH-26° For calibration
Orgeval	30 28 4 7	2009	HH-50° For calibration HH-26° For calibration VV-26° For calibration VV-50° For calibration
Orgeval	15 19	2010	HH-50° For validation HH-26° For validation
Villamblain	30	2009	HH-52° For validation
Mauzac	15 5 5	2009	HH-43° For calibration HH-28° For calibration HH-49° For calibration
Garons	5	2009	HH-25° For validation
Kairouan	14 21	2010	HH-30° For calibration HH-35° For validation
Versailles	18 12	2010	VV-33° For calibration VV-54° For calibration
Thau	11 25 14 14	2010	VV-26° For calibration VV-35° For calibration VV-41° For validation VV-52° For validation
Seysses	9 16	2010	VV-33° For validation VV-46° For calibration

In general, the precision on the roughness measurements is influenced mainly by the roughness profiles length, the number of profiles, and the horizontal resolution (sampling interval) of profiles ([13], [14]). It was demonstrated that significant errors are observed when short profiles with a low horizontal resolution are used.

III. EVALUATION OF RADAR BACKSCATTERING MODELS

In this section, the three most used radar backscattering models Oh, Dubois and IEM will be evaluated in using the large database of TerraSAR-X data and soil measurements (bare soils). The errors of the models were studied as function of the radar angle of incidence, the polarization, and the *rms* surface height.

A. Oh model

The semi-empirical Oh model relates the co-polarized ratio p ($=\sigma°_{HH}/\sigma°_{VV}$), the cross-polarized ratio q ($=\sigma°_{HV}/\sigma°_{VV}$) and the cross-polarized backscatter coefficient ($\sigma°_{HV}$) to incident angle (θ), wave number ($k\sim 2\ cm^{-1}$ in X-band), *rms* surface height, correlation length, and volumetric soil moisture (*mv*) or the soil dielectric constant ([1-4]). Oh et al. proposed analytical expressions for p and q in 1992. The expression of q was modified in 1994 and a new expression that incorporates the effect of the incident angle was proposed. In 2002, an expression was given for $\sigma°_{HV}$ and new expressions for p and q. Finally, Oh proposed a new formulation in 2004 for q that ignores the correlation length. The validity of Oh model was tested for $0.4<mv<0.29\ m^3/m^3$, $0.13<krms<6.98$ (in X-band, $0.06<rms<3.5$ cm), $10°<\theta<70°$.

Our database contains data with only HH and VV polarizations. Because of this we have calculated $\sigma°_{VV}$ and $\sigma°_{HH}$ in using the expressions of p, q and $\sigma°_{HV}$ as follows: $\sigma°_{VV}=\sigma°_{HV}/q_{yyyy}$ and $\sigma°_{HH}=(p_{yyyy}/q_{yyyy})\sigma°_{HV}$ where *yyyy* corresponds to 1992 or 2002 for p and 1992, 1994, 2002 or 2004 for q.

Oh's model was compared to the experimental database by using $\sigma°_{HV}$, p and q. Results shows that the backscatter coefficients $\sigma°_{HH}$ measured from TerraSAR images and those simulated by the Oh model are of the same order of magnitude for all Oh model versions. The mean difference between TerraSAR in HH polarization and model (bias) varies between -0.66 and +0.87 dB. As for the RMSE (root mean square error), it is between 2.64 and 2.82 dB. The 2002 model is slightly better than the other versions (Bias=-0.01dB and RMSE=2.64dB) (Fig. 2). The error of the model does not seem to depend on the incidence (θ). The behaviour of the error as a function of soil moisture shows two trends. The first trend corresponds to values of *mv* lower than about 25-30%, where we find that Oh's model considerably over-estimates $\sigma°_{HH}$ (by 7 dB maximum). For values of *mv* above 25-30%, Oh's model under-estimates $\sigma°_{HH}$ by 3 dB maximum. This results was observed by Baghdadi et al. ([9]) in using C-band data. Moreover, results show higher error for *rms* lower than 1.5 cm.

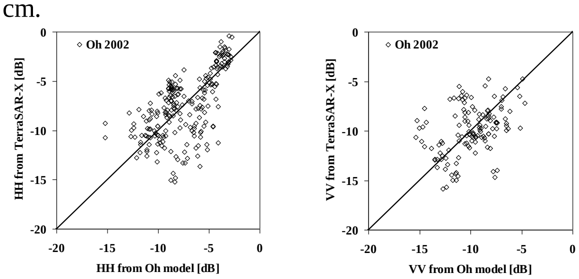

Fig. 2. $\sigma°_{HH}$ and $\sigma°_{VV}$ measured from TerraSAR-X images versus those simulated from 2002 Oh model.

For VV polarization, the difference between SAR data and simulated data ranges from –1.88 dB (1994 model) to -0.01 dB (2002 model). The RMSE varies between 2.66 (2002 model) and 3.13 dB (1994 model). The analysis of the error as a function of θ, *rms* and *mv* shows the same behaviour with the soil moisture but not a clear tendency with θ and *rms*. The database in VV polarization is not big enough for a detailed study of the behaviour of the error as a function of *rms* and θ.

B. *Dubois Model*

The semi-empirical expressions of radar backscatter coefficients $\sigma°_{HH}$ and $\sigma°_{VV}$ suggested by Dubois *et al*. ([5]) for bare soils depend of the incident angle, the dielectric constant, the *rms* surface height, and the radar wavelength. The algorithm is optimized for bare soils with *krms*≤2.5 (in X-band, *rms*≤1.25 cm), *mv*≤35%, and θ≥30°.

The Dubois model seems to under-estimate the radar signal by about 1.78 dB in VV polarization (between 0.28 dB for 26° and 3.38 dB for 50-54°). For HH polarization, the difference between SAR data and simulated data varies from -2.97 dB for 30-35° to 3.19 dB for 49-52°. The RMS error is about 3.06 dB in VV polarization and about 3.85 dB in VV polarization (Fig. 3). The bias and RMSE values are higher with Dubois model than with Oh model. Simulations performed with the Dubois model show an under-estimation of backscatter coefficients for surfaces with low levels of roughness (for *rms*<1.5 cm) and an over-estimation for surfaces with a roughness greater than 1.5 cm. Moreover, the Dubois model over-estimates the measured backscatter coefficients for values of *mv* less than 15% and under-estimates $\sigma°_{HH}$ and $\sigma°_{VV}$ for *mv* above 15%. This behaviour of the error with *mv* and *rms* were also observed by Baghdadi et al. ([9]) in using C-band data.

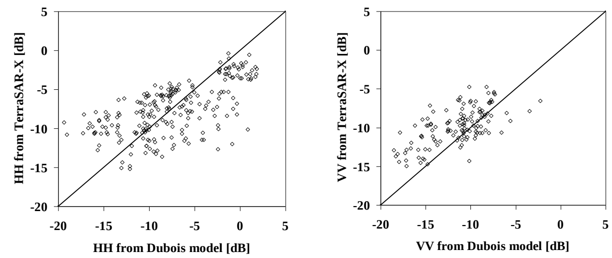

Fig. 3. $\sigma°_{HH}$ and $\sigma°_{VV}$ measured from TerraSAR-X images versus those simulated from Dubois model.

C. *IEM model*

In X-band, the Integral Equation Model [6] has a validity domain that covers only a part of the range of roughness values that are commonly encountered for agricultural surfaces (*krms*≤3 corresponds to *rms*≤1.5 cm in X-band,). Over bare soils in agricultural areas, IEM simulates the backscattering coefficients ($\sigma°_{HH}$, $\sigma°_{HV}$, $\sigma°_{VV}$) using the characteristics of the sensor (incidence angle, polarization, and radar wavelength) and the soil (dielectric constant, *rms* surface height, correlation length, and correlation function). The surface correlation function is exponential for low surface roughness values and Gaussian for high surface roughness values.

In HH and VV polarizations, the IEM model simulates correctly the backscattering coefficient only for two cases: *rms*<1.5 cm and exponential correlation function, and *rms*>1.5 cm and Gaussian function (Fig. 4). For these two cases in VV polarization, the mean difference between IEM and TerraSAR (bias) is better than -1 dB (-0.75 for *rms*<1.5 cm and -0.55 dB for *rms*>1.5 cm) with a RMSE about 4 dB (4.21 for *rms*<1.5 cm and 3.94 dB for *rms*>1.5 cm). In HH polarization, the biases are of -1.88 dB and -0.01 dB for surfaces with *rms*<1.5 cm and *rms*>1.5 cm, respectively. The RMSE for HH database is of the same order of magnitude than for VV polarization (3.51 for *rms*<1.5 cm and 4.89 dB for *rms*>1.5 cm). When an exponential correlation function is used for *rms*>1.5 cm and a Gaussian function for *rms*<1.5 cm, the RMSEs are higher (between 6.2 and 11.9 dB).

In practice, during the inversion of SAR images for estimating soil moisture, the *rms* values could not be known. Thus, it is difficult to choose the adapted correlation function, what would lead to an inaccurate estimation of the soil moisture due to the inadequacy between IEM simulations and SAR data. To improve the performance of IEM model and to make possible its use in the inversion process of SAR images in X-band, we propose to replace the correlation length by a fitting parameter in considering the same correlation function whatever the range of *rms* height. The choose to replace the correlation length is related to the uncertainty of the correlation length measurements when conventional profilometers of 1 or 2 m long are used ([13], [14]). In the following paragraph, we propose a semi-empirical calibration of the IEM by redefining the measured correlation length so as to ensure better agreement between the model and the data.

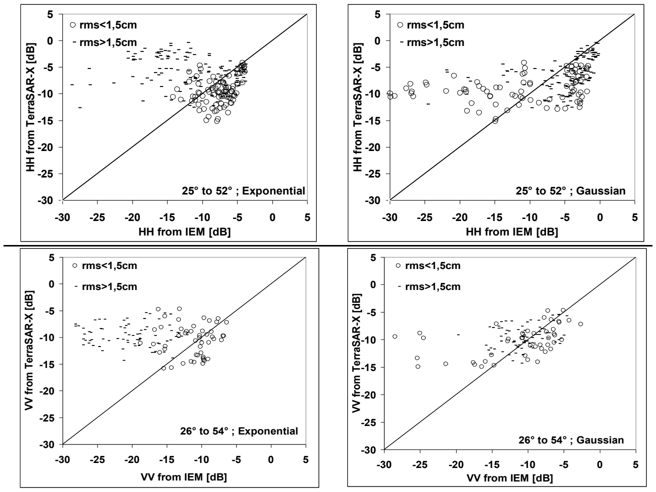

Fig. 4. Comparison between σ°-IEM using correlation length measurements, and σ°-TerraSAR for exponential and Gaussian correlation functions. Mean and standard deviation of the difference were calculated.

IV. Empirical calibration of the IEM

Based on the previous studies carried out by Baghdadi et al. ([10], [11], [12]) in C-band, the objective is to propose a robust calibration of the IEM model in X-band that would allow reproducing correctly the SAR signal. The approach consists of replacing the measured correlation length by a fitting parameter (*Lopt*). As illustrated in Table 1, a part of the database was used in the calibration phase while the remainder of the database was used for the validation of this approach. For each element of the calibration database, *Lopt* ensures a good fit between IEM simulation and SAR data. In the fitting process, all experimental data at inside or outside of the IEM validity domain were used. Results show that the fitting parameter follows the same relationship for *rms* smaller or larger than 1.5 cm.

Like to C-band, *Lopt* has two possible solutions, *Lopt1* and *Lopt2*, which ensure good agreement between the IEM and the SAR backscattering coefficient. When *Lopt1* (the lowest value) was used in the IEM model, it proved difficult for some incidence angles to ensure the correct physical behaviour between σ° and the *rms* (increasing σ° with increasing *rms*, for a given moisture value) for both exponential and Gaussian correlation functions. Only *Lopt2* (the highest value) with Gaussian correlation function ensures a correct physical behaviour of σ°. The fitting parameter *Lopt2* is strongly dependent on *rms* surface height and the incidence angle. It increases as the *rms* increases and decreases with the incidence angle (Fig. 5). Moreover, *Lopt2* in HH were higher than those in VV for the Gaussian function (Fig. 6a).

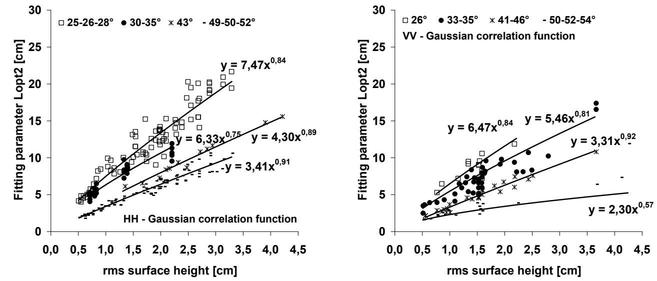

Fig. 5. Fitting parameter *Lopt2* as a function of *rms* (X-band, HH, VV), with Gaussian correlation function.

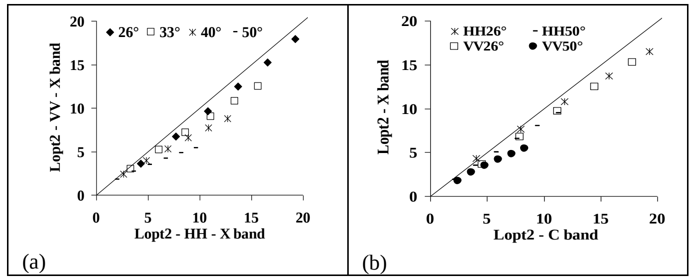

Fig. 6. (a) *Lopt2* in VV as a function of *Lopt2* in HH for X-band, and (b) comparison between *Lopt2* in C-band and those in X-band. The points corresponds to *rms*-values between 0.5 and 3 cm with a step of 0.5 cm.

For Gaussian correlation function, *Lopt2* follows a power-type relationship ($\alpha\ rms^{\beta}$). α is dependent of incidence angle whereas β is dependent of both polarization and incidence angle:

$$Lopt2\,(rms,\theta,HH) = 18.102\,e^{-0.033\theta}\ rms^{0.7644\,e^{0.0035\theta}} \qquad (1)$$

$$Lopt2\,(rms,\theta,VV) = 18.075\,e^{-0.0379\theta}\ rms^{1.2594\,e^{-0.0145\theta}} \qquad (2)$$

θ is in degree, *Lopt2* and *rms* are in cm. The coefficient of determination R^2 is 0.92.

In order to analyse the effect of radar frequency on the IEM calibration, comparison was done using the expressions of *Lopt2* obtained by Baghdadi et al. in C-band [11] and those obtained in this study in X-band. Figure 6b show C-band and X-band calibration results for radar configurations with HH and VV polarizations and incidence angles of 26° and 50°. With the Gaussian correlation function, the C-band *Lopt2* was higher than the X-band *Lopt2*. Baghdadi et al. [imen] observed a similar behaviour between the L-band *Lopt2* and the C-band *Lopt2*, what leads to the conclusion that *Lopt2* decreases as the radar frequency increases.

V. Validation of the IEM calibration

In order to validate this IEM calibration approach, the validation database (Table 1) was used with *Lopt2* given by the analytical expressions (1) and (2). Results show that the proposed semi-empirical calibration of the IEM provides improved results (Figure 7). For HH polarization, the bias and the standard deviation of the error have decreased from -2.81 dB to +0.36 dB (difference between IEM and TerraSAR-X), and from 8.73 dB to 2.08 dB, respectively. For VV, the standard deviation of the error decrease from 3.78 dB to 1.73

dB. The bias is of the same order before and after calibration (-0.37 dB before and -0.34 dB after calibration).

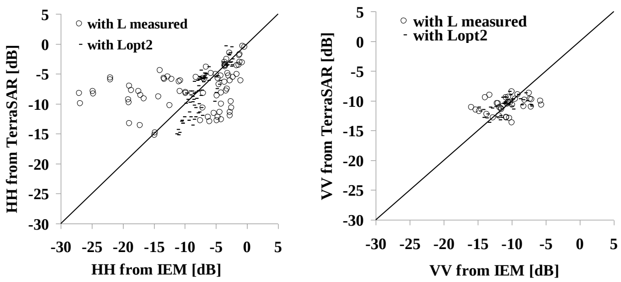

Fig. 7. Validation of the empirical calibration approach in using the fitting parameter *Lopt2* and the validation database (TerraSAR and in situ data).

Moreover, the parameterization of the fitting parameter enables a correct simulation of the backscattering signal. The expressions of *Lopt2* (eq. (1) and (2)) were validated for incidences between 25° and 50°. The use of Gaussian correlation function ensures correct physical behaviour of IEM to approximately *rms*=3.2cm for 25° and *rms*=4.7cm for 50°.

VI. Conclusions

The semi-empirical models of Oh and Dubois as well as the IEM physical backscattering model were evaluated by using TerraSAR-X data and ground measurements on bare soils in agricultural environments. The objective of this article is to evaluate the errors of these models and to propose a semi-empirical calibration of the IEM model in X-band. Oh's model correctly simulates the radar signal for HH and VV polarizations (bias<1dB and RMSE<3dB). Simulations performed with the Dubois model show a poor correlation between TerraSAR data and model simulations (RMSE between 2.2 and 4.4 dB, bias can reach 3.4 dB according to incidence and polarization).

The IEM model simulates correctly the backscattering coefficient only for *rms*<1.5 cm in using an exponential correlation function, and for *rms*>1.5 cm in using Gaussian function. However, the results are not satisfactory for a use of IEM in the inversion of TerraSAR data (bias can reach 1.9 dB and RMSE about 4 dB).

A semi-empirical calibration of the IEM was proposed in this study to ensure better agreement between IEM and the SAR data in X-band. It consisted of finding a fitting parameter which replaces the inaccurate correlation length measurements and corrects the defects of model.The results showed that the fitting parameter was found to be dependent on *rms* surface height, radar wavelength, incidence angle, and polarization. The simulations produced by the calibrated IEM fit correctly SAR measurements (bias and standard deviation of the error were reduced). With this calibration, bare agricultural soils can be characterized by two surface parameters (*rms* height and soil moisture) instead of four (*rms* height, correlation length, correlation function, and soil moisture).

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