MODELLING THE BACKSCATTERING COEFFICIENT OF SALT-AFFECTED SOILS: APPLICATION TO WADI EL-NATRUN BOTTOM, EGYPT

Ziad Aly, Ferdinand Bonn and Ramata Magagi

Université de Sherbrooke, CARTEL, Sherbrooke, Québec, Canada J1K 2R1
ziad.aly(at)usherbrooke.ca

ABSTRACT

One of the most crucial environmental problems affecting developing countries in arid and semi-arid regions is soil salinity. Its detection using radar imaging systems is one of promising domains of remote sensing research. Detection is based essentially on the relationship between the quantity of existing salts in the soil, the soil moisture content, and the dielectric properties of this mixture. Due to the components of the mixture and their corresponding dielectric properties, backscattering of these types of soils can be modelled and monitored. Parameters influencing the radar detection of salt-affected soils are grouped into two main groups: those related to the sensor and those related to the target. Some of these parameters cause information attenuation during monitoring of the salt-affected soils; however, others give us information that help to better understand the phenomena. Some of the latter parameters can be controlled and others are imposed. Most previous studies neglected the effect of the presence of salts combined with the other parameters on the backscattering coefficient. In this paper, we present the salinity effect on the calculation of the backscattering coefficient using several backscattering models. The results show that the high dielectric constant, due to the extensive presence of salts, has a significant effect on the backscattering value. To validate the modelling approach with actual data, four RADARSAT-1 satellite images in standard modes were selected for the area of Wadi El-Natrun, Egypt, where fieldwork was conducted simultaneously with some of the RADARSAT-1 image acquisitions.

Keywords: Radar backscattering of soil, soil salinity, RADARSAT-1.

INTRODUCTION

In many areas of the world, salinity is one of the principal environmental causes of soil degradation, and consequently, a source of reduction in the biomass. According to certain estimates, approximately 7% of soils all over the word suffer from this phenomenon (1). These types of soils appear mainly in arid and semi-arid areas where precipitations are insufficient to drain the soluble salts contained in the soil profile. Most of the developing countries are located in these two areas. The separation of such types of soils can be easy using the visible and the infrared wavelengths, but in the coastal, black clay soils and desert areas delineation is not evident. This is due to the confusion between the reflectance of soils in these areas (2). Faced with this problem, radar can demonstrate its capability to delineate these affected soils using their dielectric properties.

The theory of soil moisture measurements using radar is based on the large difference between the dielectric constant, ε', for dry soil (ε'=2) and water (ε'=80). As the water content of a dry soil increases the dielectric constant rises consequently, which directly affects the backscattering coefficient, $\sigma°$ (3). The presence of soluble salt in the soil solution also has a direct effect on the value of the dielectric constant. The imaginary part of the dielectric constant of water is sensitive to salinity when microwave frequencies are below 10 GHz, whereas the real part of the dielectric constant of water is sensitive to salinity with frequencies >5 GHz (4). Typically, a raise in salinity increases the dielectric constant, as the salinity moves up conductivity. This effect is higher at frequencies <3 GHz (5). Due to this effect, salt affected soils can be detected with radar, but in this case, surface roughness and vegetation effects must be eliminated to accurately measure soil moisture (6). Compared to studies that evaluate the relationship between permittivity and soil water content, those studying the relationship between the dielectric constant, soil salinity, and the backscattered coefficient $\sigma°$ are rare. Considering the complexity of the relationship between these three parameters, we simulate this relation using theoretical and semi-empirical backscattering models. This simulation takes into account the properties of the studied soil using the Dobson mixing model (4), and their related changes in the outputs of the models. It also enables us to imagine the behaviour of the backscattered coefficient based on the theoretical input parameters. It offers a completely theoretical field, added to the empirical data, for studying our phenomenon thoroughly. In this paper, we examine the effect of salt presence on the backscattering coefficient for the C-band frequency and the RADARSAT-1 configuration in combination with the two parameters mentioned above.

To support and validate our results a field campaign was carried out in a zone suffering from soil salinity in an Egyptian desert depression named: Wadi El-Natrun. This area was among one of the marginal areas that the Egyptian government decided to restore to increase the agricultural surface, necessary to feed the population in strong growth.

METHODOLOGY

Mixing model adaptation

In this model, soil is a mixture of four components: soil, free water, bound water, and air. The two portions of the free water dielectric constant component are calculated using the following equations:

$$
\begin{aligned}
\varepsilon_{fw} &= \varepsilon'_{fw} - \varepsilon''_{fw}\, i \\
\varepsilon'_{fw} &= \varepsilon_{w\infty} + \frac{\varepsilon_{wo} - \varepsilon_{w\infty}}{1 + (2\pi f \tau_w)^2} \\
\varepsilon''_{fw} &= \frac{2\pi f \tau_w (\varepsilon_{wo} - \varepsilon_{w\alpha})}{1 + (2\pi f \tau_w)^2} + \frac{\sigma_{mv}}{2\pi \varepsilon_o f} \\
\sigma_{mv} &= (\sigma_G + \sigma_{bulk}).\frac{1 - \rho_b \rho_s - \rho_b A_s d_\delta \cdot 10^4}{m_v} \\
S_{mv} &\approx 0.64 \sigma_{mv} \%
\end{aligned}
\tag{1}
$$

where ε'_{fw} is the real part of the dielectric constant of the free water,
ε''_{fw} is the imaginary part of the dielectric constant of the free water,
$\varepsilon_{w\alpha}$ is the high frequency limit of ε_w,
ε_{wo} is the static dielectric constant of the water,
f is the frequency in Hertz,
τ_w is the relaxation time of water,
σ_{mv} is the effective conductivity in $S\cdot m^{-1}$,
ε_o is the permittivity of free space equal to $8.854\cdot10^{-12}$ $F\cdot m^{-1}$,
S_{mv} is the approximate salinity percentage.

Changes were brought to the parameters of the mixing model suggested by (4) to describe exactly the soil physical characteristics of the Wadi El Natrun area as a representative area of salt affected soils in the arid zone. To introduce the effect of salinity and temperature into the value of the dielectric constant of the free water, (7) suggests the following equations:

$$
\begin{aligned}
&\varepsilon_{sw0}(T, S_{sw}) = \varepsilon_{sw0} \cdot a(T, S_{sw}) \\
&\varepsilon_{sw0}(T,0) = 87.134 - 1.949 \cdot 10^{-1} T - 1.276 \cdot 10^{-2} T^2 + 2.491 \cdot 10^{-4} T^3 \\
&a(T, S_{sw}) = 1.0 + 1.613 \cdot 10^{-5} T S_{sw} - 3.656 \cdot 10^{-3} S_{sw} \\
&\tau_{sw}(T, S_{sw}) = \tau_{sw}(T,0) \cdot b(T, S_{sw}) \\
&\tau_{sw}(T,0) = 1.1109 \cdot 10^{-10} - 3.824 \cdot 10^{-12} T + 6.938 \cdot 10^{-14} T^2 - 5.096 \cdot 10^{-16} T^3 \\
&b(T, S_{sw}) = 1.0 + 2.282 \cdot 10^{-5} T S_{sw} - 7.638 \cdot 10^{-4} S_{sw} - 7.760 \cdot 10^{-6} S_{sw}^2 + 1.105 \cdot 10^{-8} S
\end{aligned}
\tag{2}
$$

Soil physical properties used to compute Eqs. (1) and (2) are given in Table 1.

Table 1: Physical parameters of soil, where SL, L, ZL, SC, ZC are sandy loam, loam, silty loam, sandy clay and silty clay soils, respectively. A_s *is the soil specific surface area,* σ_2 *is the Gouy-Layer charge density and* ρ_b *is the bulk density.*

Texture	SL	L	ZL	SC	ZC
% sand	65	40	20	50	5
% clay	15	20	15	45	45
A_s / m^2/g	70	150	77	250	300
σ_2 / esu/cm^2	5928	5933	5960	5955	5872
ions·10^{18} / cm^{-3}	3.22	2.385	3.252	3.472	2.821
ρb / g/cm^3	1.75	1.70	1.55	1.60	1.45
coeff. σ_G	15.516	46.877	12.016	51.756	58.534
coeff. σ_{mv}	0.3028	0.282	0.379	0.276	0.322

It is assumed that the temperature is constant at 25°C; this is acceptable as an average for the soil temperature collected during the field trip. The real density ρ_s is fixed at 2.65 g/cm^3. The valence has also been changed to 1, taking into account the predominance of sodium in the soil. Other constants used in this model are the same as cited in the initial publication (4). Five different humidity M_v levels are tested: 10, 20, 30, 40, and 50%. Only the sandy loam and loam soil results will be presented in this paper.

This temperature assumption will affect the relaxation time of water, ion concentration and the static dielectric constant of the water. (8) mentioned that the real part of the dielectric constant of non-frozen soils is approximately independent of temperature for all soil types, while the imaginary part of the same types of soil is dependent on the temperature, showing a rise at low frequencies and a drop with temperature at higher ones.

Backscattering model simulation

RADARSAT-1 data were simulated according to two theoretical models: the Small Perturbation Model (SPM) and the Physical Optic Model (POM) (9) as well as the Dubois Semi-empirical Model (DM) (10). In order to better understand the behavior of radar signal backscattering in our study area, simulation variables were subdivided into two groups:

- Variables related to the system, RADARSAT-1 in this case, such as frequency, incidence angle, resolution, and polarization.
- Variables related to the phenomenon and the soil: topography, permittivity affected by volumetric water content, soil temperature, soil texture, soil structure, soil salinity, as well as the roughness (micro topography) of the surface.
- Variables related to the vegetation cover if present.

Due to these parameters, the intensity of σ^o changes and produces variations on pixel grey level in the image.

Theoretical models are usually based on assumptions. These assumptions are not always simple; this is why we often use them with approximations, which make them more practical and usable. Table 2 illustrates the fields of validity of the applied models. Note that for the theoretical models, the fields of validity are often defined by the values of roughness: the standard deviation of the heights (rms) and the correlation length ℓ often expressed per unit of wavelength λ, because they are attached to the wave number $k = 2\pi/\lambda$.

On the other hand, the empirical models have been effectively applied over definite sites, and due to their dependence on local observations, they are commonly valid only for these conditions, and cannot be directly transferred to other sites. In addition, these models suppose that the effect of correlation length on the backscatter coefficient is low which further restricts their applicability.

Table 2: Validity domain of backscattering models.

Models	**SPM**	**POM**	**DM**
Surface	smooth	Intermediary	All
rms (s) /cm	$ks < 0.3$	$(2ks\cos\theta)^2 \sim 3$	0.3-3, $ks < 2.5$
Correlation length ℓ /cm	$k\ell < 3$	$k\ell > 6$, $\ell^2 > 2.76s\lambda$	-
Volumetric water content M_v /%	-	-	< 35
Incidence angle θ /degree	-	-	30 - 65

In order to estimate the best RADARSAT-1 mode for the simulated salt affected soil, four different standard modes are considered. These modes are *S1* with an incidence angle θ = 23°, *S3* with θ = 34°, *S5* with θ = 39° and *S7* with θ = 47°.

Based on the fact that the topography of the area is almost flat and smooth, we assume that the soil roughness s , expressed as rms, is 0.27 cm and that the correlation length ℓ is 2.67 cm. SPM and POM backscattering models are used based on their consideration of the imaginary part of the dielectric constant, Eq. (3), and on their fitting to the soil simulation. Dielectric constant data were taken from the mixing model simulation results. We also use the exponential autocorrelation function, that more closely approximates natural and smooth surfaces and we neglect the Gaussian function adapted to rough soils. SPM model Eqs. (3) are presented here followed by POM Eqs. (4):

$$\begin{aligned} \sigma^o_{pp}(\theta) &= \sigma^o_{coh}(\theta) + \sigma^o_{inc}(\theta) \\ \sigma^o_{pp}(\theta) &= 8k^4h^2\cos^4\theta\,\left|\alpha_{pp}\right|^2 W(2k\sin\theta) \\ \alpha_{hh} &= (\varepsilon-1)\Big/\left(\cos\theta+\sqrt{\varepsilon-\sin^2\theta}\right)^2 \\ W(2k\sin\theta) &= \left(1+2(k/\sin\theta)^2\right)^{-3/2} \end{aligned} \qquad (3)$$

where σ^o_{inc} is the incoherent component of backscattering coefficient, σ^o_{coh} is the coherent component, k is the wave number, and $W(2k\sin\theta)$ is the exponential autocorrelation function.

$$\begin{aligned} \sigma^o_{ppn}(\theta) &= 2k^2\cos^2\theta\ \Gamma_{p(\theta)}\ \exp\left((2ks\cos\theta)^2\right).\sum_{n=1}^{\infty}(2ks\cos\theta)^{2n}/n!.\ell \\ \ell &= n\ell^2\Big/\left(n^2+2(k\ell\sin\theta)^2\right)^{3/2} \end{aligned} \qquad (4)$$

where $\Gamma_{p(\theta)}$ is the reflectivity at polarization p (v or h). Due to the value of the incidence angle over 10° and the characteristics of the satellite, only the incoherent part σ^o_{inc} of the model is used to calculate the backscattering coefficient σ_{pp} for horizontal transmit-receive polarization *hh*. Dubois model Eq. (5) is used to show the effect of the salinity on the backscattering coefficient when the real part of the dielectric constant is considered and the imaginary part is neglected.

$$\sigma^o_{hh} = 10^{-2.75}\,\frac{\cos^{1.5}\theta}{\sin^5\theta}\,10^{0.028\,\varepsilon\tan\theta}\,(kh\sin\theta)^{1.4}\,\lambda^{0.7} \qquad (5)$$

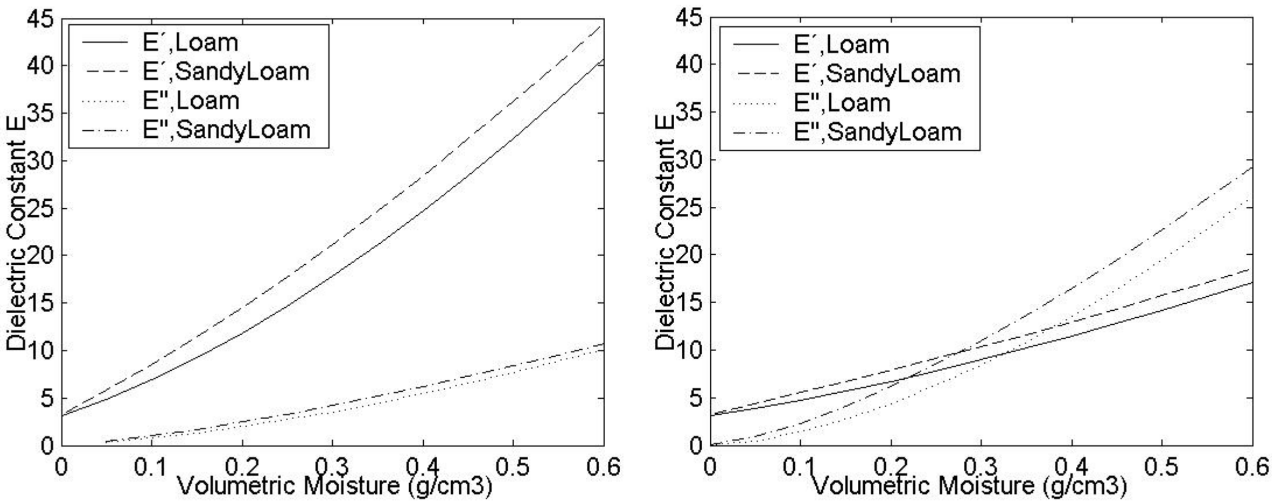
Study area and field measurement description

Our study site is at Wadi El-Natrun, a sandy depression located west of the Nile delta, latitude 30°17' and 30°38'N and longitude 30°02' and 30°30'E. It is directed NW-SE; its northern end is 108 km from Alexandria and its southern end is 70 km from Cairo. It is down to 24 m under the sea level and 38 m under the water level at the Rosette branch of the Nile (11). At the bottom of this depression, there are eight principal and two secondary salted lakes. The arid climate of this area is the driver of a continuous evaporation of the lakes water, which generates the formation of vast crusts of salt, named "Natrun" or Natron, from where comes the name of this depression (12). It is also the origin of the chemical symbol for sodium, Na, Natrium in German.

The selected representative areas are characterized by a homogeneous flat smooth surface devoid of any human activities. Soil sampling was synchronized with RADARSAT-1 images acquisitions in May 2002, to minimize the error rate between the backscattered signals and the ground truth of the target. Due to the RADARSAT-1 configuration, samples were taken from the upper 5 cm (9). Furthermore, the period of the field trip was characterized by dry climatic conditions with no precipitation. These conditions determine a homogeneous and stable soil moisture and salinity profile in the soil, such that the dielectric constant can be assumed representative for the area.

RESULTS

First, to estimate the effect of the salt presence in soil, we simulate its presence for the following types of soil: Sandy Loam and Loam that do exist in the study area. We can see in Figure 1 that the existence of such soil components has a critical effect on the behaviour of the dielectric constant in its real and imaginary parts as well.



(A) (B)

Figure 1: Salinity effect on the dielectric constant, (A) without salinity and (B) with 50% salinity, for loam and sandy loam soils, E' *and* E" *are the real and imaginary parts of dielectric constant, respectively.*

This effect is very significant on the imaginary part, especially when the soil moisture rises over 30% depending on the soil texture, which determines the quantity of free water, Figure 2. At such a percentage of moisture, the effect of salts dominates the dielectric constant value rather than the moisture content; this effect did not appear more clearly in the finer soil textures due to salt retention by fine particles such as silt and clay. The high cation exchange capacity (CEC) of these soils does not allow a wide interaction between the solid components of the soil: salt, silt and clay, and the liquid component. Therefore, the presence of sand particles lets the salt react in the soil mixture, and consequently increases the imaginary part of the dielectric constant of the soil.

Under dry conditions below 20% of relative humidity, however, such a variation cannot be distinguished and the effect is limited to the real part of the dielectric constant. This is due to the lower conductivity of the soil, thus a weak variation on the imaginary part. The real part is then only influenced by the soil texture and soil humidity, and inversely correlated to the salinity presence. This decreases the value of the real part of the dielectric constant and increases the imaginary part at the same time, which widens the gap between the two parts and lets the complex value of the dielectric be mainly influenced by the imaginary parts.

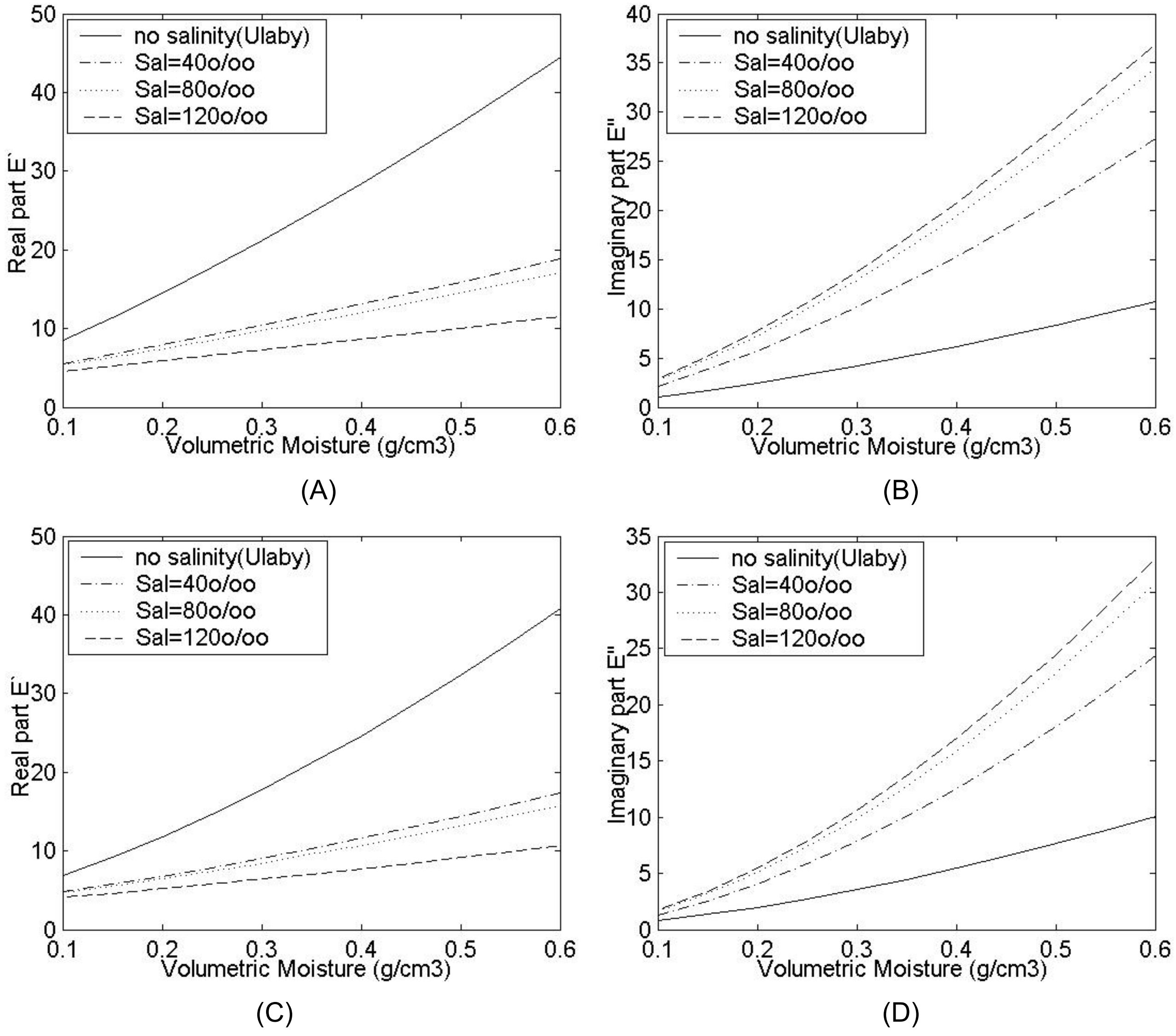


Figure 2: Real and imaginary parts of the dielectric constant for sandy loam (A,B) and loam (C,D) soils at different salinity levels.

When simulating the SPM and POM, it can be seen that the backscattering coefficient shown in Figures 3a,b and 3c,d, respectively, increases with respect to the partial dependence of the two models on the imaginary part of the dielectric constant ε". However, we can observe the effect of neglecting the presence of this part in the Dubois model in Figure 3e,f. In the latter model, the value of the backscattering coefficient decreases dramatically with the increase of the salinity level.

Figure 4 shows the effect of the incidence angle on the value of the backscattering coefficient. We realize that *S1* is the most adequate mode of RADARSAT-1 to predict the presence of salt in simulated salt affected soils, using the same level of M_v, however, the backscattering coefficient σ^o magnitude is higher for the coarser texture, sandy loam, using the same incidence angle. The magnitude of the backscattering coefficient is inversely proportional to the incidence angle. For a higher incidence angle, *S7*, $\theta = 47°$ the sensor is incapable of distinguishing the effect of salinity percentage variation. This is normal, based on the relationship between the salt and the moisture content, and the capability of the radar at low incidence angles to measure the moisture effect. In this case the soil texture has a narrow effect on the backscattering coefficient value.

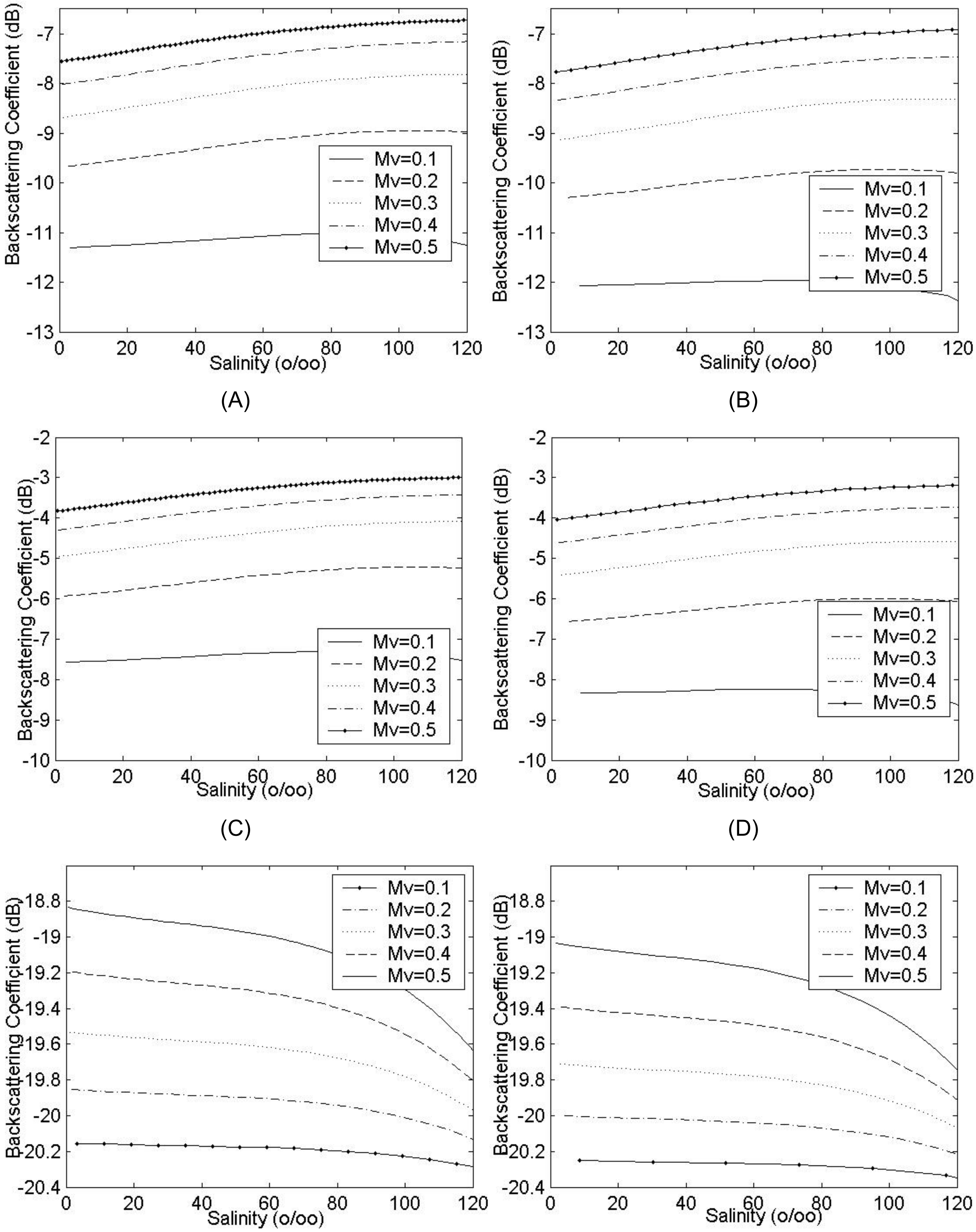
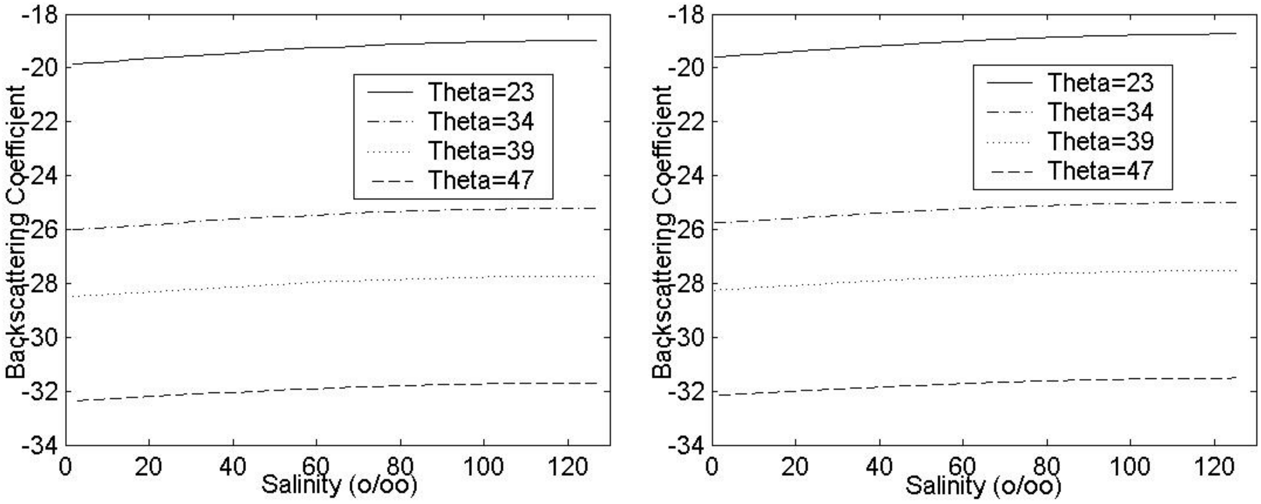


Figure 3: Salinity effect on the backscattering coefficient in sandy loam and loam with different moisture contents (Mv) for SPM (A)(B), POM (C)(D) and Dubois model (E)(F).

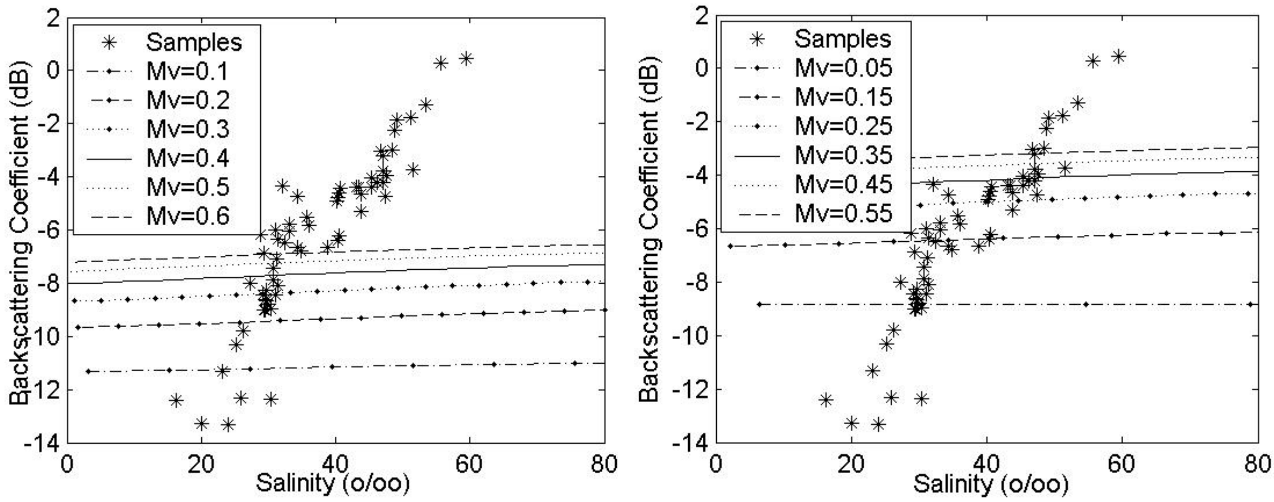
For the same incidence angle and same texture, the SPM and POM models are compared with the soil sample values. Figure 5 shows that almost half of the samples of the sandy loam soil are located outside the validity range of the SPM model, which is valid for volumetric moisture content below 30%. However, then the POM model covers almost all the samples, which corresponds to the field result.

These results can be explained by the domain of validity of these models, which are examined under normal conditions, and the absence of salt effect. In addition, the assumptions and constraints of the simulations cannot be constant all the time and can fluctuate in the field.



(A) (B)

Figure 4: The effect of incidence angle on σ^o using 45% moisture content for sandy loam (A) and loam (B) soils.



(A) (B)

Figure 5: Relationship between σ^o of S1 mode simulation for sandy loam soil and the soil samples salinity, (A) for SPM and (B) for POM.

Contrary to the simulation results, results obtained from the images and soil samples are highly correlated. The imaginary dielectric constant ε''_{S1} calculated from the S1 mode image was compared to the imaginary dielectric constant measured in soil samples ε''_{SS}. This comparison gave the following linear regression, Figure 6a:

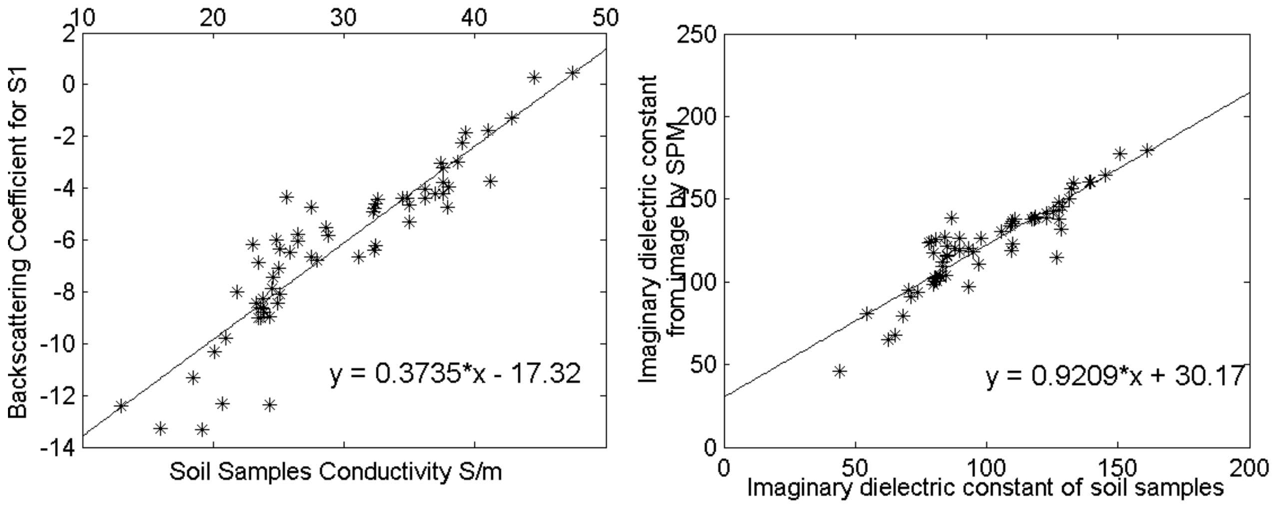
$$\varepsilon''_{S1} = 0.9209\ \varepsilon''_{SS} + 30.17$$

with a coefficient of determination R^2 = 0.8168. This relatively low correlation coefficient value is due to the resolution of the image, and we predict that the fine mode can offer higher values. However, when using the fine mode, we must consider the high speckle content in this mode and the scale of surveying. We consider the value 0.8168 of R^2 to be satisfactory for this resolution.

Figure 6b illustrates the relationship between the σ^o calculated from the S1 mode image and soil sample conductivity ($S \cdot m^{-1}$). This relation can be expressed by the following linear regression:

$$\sigma^o_{hh} = 0.3735S - 17.32$$

with a coefficient of determination R^2 = 0.830. These equations demonstrate that the results derived from soil samples and the radar image are highly correlated. These results are relatively better than those found by (13) with a considered improvement in the correlation coefficient.



(A) (B)

Figure 6: Relationship (A) between σ^o of S1 mode image and the soil sample conductivity, (B) between the ε''_{s1} calculated from S1 image and soil samples ε''_{ss}.

CONCLUSION

The correspondence between the values obtained from the images and those obtained by the analysis of soil samples, and the estimation of the σ^o calculated using the existing backscattering models, either theoretical or semi-empirical, proves the necessity of having a special model designed for the salt affected soils. This new model should adequately account for the presence of salt in the soil mixture.

ACKNOWLEDGMENTS

The authors would like to thank the Programme Canadien des Bourses de la Francophonie (PCBF) for the PhD fellowship to Ziad, the Canadian Space Agency for the RADARSAT-1 data and their timely acquisition, the Canada Research Chair in Earth Observation and Université de Sherbrooke for additional financial support and Paul Gagnon for text editing.

REFERENCES

1 Szabolcs I (1988) Solonetz soils. In: Proceedings of the International Symposium on Solonetz Soils. Problems, Properties, Utilisation, Osijek, Yugoslavia, June 15-20, 1988, edited by M Adam, Agricultural Faculty, University of Osijek, 9-25.

2 Sreenivas K, L Venkataratnam & P V Narasimha-Rao (1995) Dielectric properties of salt affected soils. International Journal of Remote Sensing, 16: 641-649

3 Henderson F M & A J Lewis (1998) Principles and Applications of Imaging Radar. Chapter 8. 3rd edition (John Wiley & Son Inc., New York)

4 Dobson M C, F T Ulaby, M T Hallikainen & M A El-Rayes (1985) Microwave dielectric behavior of wet soil—Part II: dielectric mixing models. IEEE Transactions on Geoscience and Remote Sensing, 23: 35–46

5 Dobson M C & F T Ulaby (1986) Preliminary evaluation of the SIR-B response to soil moisture, surface roughness, and crop canopy cover. IEEE Transactions on Geoscience and Remote Sensing, 24: 517-526

6 Sano I I, A R Huete, D Troufleau, M S Moran & A Vidal (1998) Relation between ERS-1 synthetic aperture radar data and measurements of surface roughness and moisture content of rocky soils in semiarid rangeland. Water Resources Researches, 34: 1491-1498

7 Stogryn A (1971) Equations for calculating the dielectric constant of saline water. IEEE Transactions on Microwave Theory and Techniques, 19: 733-736

8 Curtis J O (1992) Moisture and temperature effects on the microwave dielectric behaviour of soils. Dartmouth College, Hanover, New Hampshire, 220 pp.

9 Ulaby F T, R K Moore & A K Fung (1982) Microwave Remote Sensing: Active and Passive, Vol. II: Radar Remote Sensing and Surface Scattering and Emission Theory (Addison-Wesley, Reading, MA.)

10 Dubois P C, J V Zyl & E T Engman (1995) Measuring soil moisture with imaging radars. IEEE Transactions on Geoscience and Remote Sensing, 33: 915-926

11 Abou-Zied M (1984) Contribution to the geology of Wadi El-Natrun area and its surroundings. M.Sc. Thesis, Faculty of Science, Cairo University

12 Abdel-Razak Z, F Bonn, A Mahmood & L-P Guigni (2001) Application des données Radarsat-1 pour l'identification des zones affectées par la salinité: le Wadi El-Natrun, Égypte. In: 23e Symposium Canadien sur la Télédétection, Québec, Canada, 639

13 Shao Y, Q Hu, H Guo, Y Lu, Q Dong, & Chunming Han (2003) Effect of dielectric properties of moist salinized soils on backscattering coefficients extracted from RADARSAT image. IEEE Transactions on Geoscience and Remote Sensing, 41: 1879-1888