Modelling the backscattering coefficient of salt-affected soils using

AIEM model

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ABSTRACT

Soil salinity principally affects soil properties, environment and productivity of agricultural areas for developing countries. Currently, no inversion algorithms exist for directly determining soil salinity from microwave remote sensing data, but we hope to draw on the soil moisture retrieval algorithms to obtain soil salinity amount. So the effect of moisture and salinity on dielectric constant and the backscattering coefficient (VV and HH polarization mode) are simulated using the advanced integral equation model (AIEM) combined with the modified Dobson dielectric mixing model. The results indicate that real part of dielectric constant decreases with soil salinity content, however, the imaginary part increases with it especially for the high moisture regions. Both soil moisture and salinity affect the VV and HH polarization backscattering coefficient, with moisture the backscattering coefficient increases evidently, but with soil salinity backscattering coefficient increase at the small moisture region and it remains unchanged for the HH polarization or expresses the weakly downward tendency for VV polarization respectively at the high moisture region. Moreover, the simulation results also suggest that VV or HH polarization can be used to retrieve soil salinity for the soil with low moisture (<0.3 cm³·cm⁻³).

Key Word: Soil salinity, dielectric constant, dielectric mixing model, backscattering coefficient, AIEM (advanced integral equation model)

1 INTRODUCTION

One of the most principal environmental problem affecting developing countries is soil salinization, especially in arid and semi-arid regions, where precipitations are insufficient to drain the soluble salts contained in the soil profile. Soil salinity also influences soil properties and cause land degradation and the reduction of productivity of agricultural areas. Its detection can use radar imaging system to distinguish from non-affected saline soils based on their dielectric properties [1].

Currently, no inversion algorithms exist for directly determining soil salinity from microwave remote sensing data. However, a number of soil moisture inversion algorithms have been developed and applied over the last two decades [2-4].

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The theory of soil moisture measurement is based on large difference in dielectric constant between dry soil and water\cite{5}. As the water content of a dry soil increase, the dielectric constant rises consequently, which directly affects the backscattering coefficient. The dielectric constant is comprised of the permittivity or real part and the loss factor or imaginary part. The presence of soluble salt in the soil solution also has a direct effect on the value of the dielectric constant. When comparing the complex dielectric constant of pure water with saline (sea) water ($\approx 49.69$)\cite{6}, minimal difference in the real part, but significant difference in the imaginary part is observed less than 7GHz\cite{7,8}. In contrast to the non-affected soils, the imaginary part of the dielectric constant of affected wet soils is higher than or comparable to the real part\cite{1}. Studies that evaluate the relationship between dielectric constant, soil salinity and the backscattering coefficient are rare, but soil moisture retrieval algorithms can be drawn to retrieve soil salinity, which emphasize the imaginary part of dielectric constant.

Considering the complexity of the relationship among soil moisture, soil salinity, backscattering coefficient and dielectric constant, we plan to simulate salinity effect on the backscattering coefficient of soils using theoretical model: AIEM. So, we can offer some scientific basin for retrieving soil salinity content using microwave remote sensing data. During the simulation, the parameter used in Dobson mixing model should be taken account for the salt-affected soil and made some changes.

## 2 METHODOLOGY

### 2.1 Dobson model

Salinity is an important element of the electrical conductivity for a given material. Therefore, the dielectric constant related to electric conductivity is affected by any changes in the salinity. Since the propagation of the radar signal is mainly governed by the dielectric constant, it is essential to understand the behavior of both the real part and imaginary part of dielectric constant with soil salinity increase.

Different dielectric mixing models (theoretical, semi-empirical and empirical) were developed for soil materials\cite{5-6,9}. In these models, soil is a mixture of four components system: soil particle, air, free water and bound water volume fractions. The commonly used of them is model proposed by Dobson et al\cite{1985}. Assuming soil with the known bulk density $\rho_b$ and specific density $\rho_s$, the final expression for the dielectric mixing constant as function of soil moisture ($m_v$) is\cite{5}:

$$\varepsilon_m^a = 1 + \frac{\rho_a}{\rho_s}(\varepsilon_r^a - 1) + m_v^\beta \varepsilon_{fw}^a - m_v$$

(1)

where $\alpha=0.65$, $\varepsilon_r$ is permittivity of solid soil, $\beta$ is a coefficient expressed as a function of sand and clay percentage.

However, the Dobson model was established under the electric conductivity of saturated soil sample extract being about 1 dS/m, which is less than the criterion (4 dS/m) between the salt-affected and non-affected soils\cite{10}, thus the model is not applicable for the salt-affected soils. For the salt-affected soils, some modifications should be taken account. In order to account for the ionic-conductivity losses due to soil salinity, the dielectric constant of free water for the saline soil is calculated according Debye relaxation form modified by Lane and Saxton\cite{11}. In terms of Stogryn’s formulation\cite{6}, real and imaginary parts of saline water are given by:
where the subscript $sw$ refer to saline water properties, $f$ is the frequency in herz, $\varepsilon_0$ is the permittivity of free space equal to $8.854\cdot10^{-12}$ F·m$^{-1}$, $\varepsilon_{sw0}$ is the high frequency limit, the value is 4.9 and $\varepsilon_{sw0}$ is the static dielectric constant of saline water, $\tau_{sw}$ and $\sigma_{eff}$ are the relaxation time and the effective ionic conductivity in Siemens per meter (S/m), which is soil texture dependent parameter. $\varepsilon_{sw0}$ and $\tau_{sw}$ are expressed as a function of salinity ($S$) and temperature ($T$) in following equations$^{[6,12]}$:

$$
\varepsilon_{sw0}(T, S) = \varepsilon_{sw0}(T, 0) \cdot a(T, S)
$$

(4)

$$
\varepsilon_{sw0}(T, 0) = 87.134 - 1.949 \cdot 10^{-1} T - 1.276 \cdot 10^{-2} T^2 + 2.491 \cdot 10^{-4} T^3
$$

(5)

$$
a(T, S) = 1.0 + 1.613 \cdot 10^{-5} TS - 3.656 \cdot 10^{-3} S
$$

(6)

$$
\tau_{sw}(T, S) = \tau_{sw}(T, 0) \cdot b(T, S)
$$

(7)

$$
\tau_{sw}(T, 0) = 1.1109 \cdot 10^{-10} - 3.824 \cdot 10^{-12} T + 6.938 \cdot 10^{-14} T^2 - 5.096 \cdot 10^{-16} T^3
$$

(8)

$$
b(T, S) = 1.0 + 2.282 \cdot 10^{-5} TS - 7.638 \cdot 10^{-4} S - 7.76 \cdot 10^{-6} S^2 + 1.105 \cdot 10^{-8} S^3
$$

(9)

In Dobson model, $\sigma_i$ is modified into the following form:

$$
\sigma_i = \sigma_{eff} \cdot \frac{\rho_s - \rho_b}{\rho_m}\n$$

(10)

where $\sigma_{eff}$ is an empirical parameter used to calculate the imaginary part of the free water and obtained by measuring the percent content of sand and clay, but it is not relevant to soil salinity, thus the effective electrical conductivity of $NaCl$ solution $\sigma_{NaCl}$ is used to instead of $\sigma_{eff}$ . Weyl had given equations for the conductivity of dilute aqueous $NaCl$ solutions. However, unsatisfactory results were achieved when his equations were applied to solutions as concentrated as those discussed in $^{[11]}$. Thus, Stogryn derived the new expressions for the ionic conductivity of concentrated $NaCl$ solutions. These are $^{[6]}

$$
\sigma_{NaCl}(T, N) = \sigma_{NaCl}(25, N) \{1.0 - 1.46192 \cdot 10^{-2} \Delta + 8.08 \cdot 10^{-5} \Delta^2 - 6.584 \cdot 10^{-8} \Delta^3 - 3.922 \cdot 10^{-9} \Delta^4 - N(1.721 \cdot 10^{-5} - 0.13538 N + 0.0086 \cdot 10^{-2} N^2 - 0.002 \cdot 10^{-2} N^3)\}
$$

(11)

$$
\sigma_{NaCl}(25, N) = N(10.394 - 2.3776 N + 0.68258 N^2 - 0.13538 N^3 + 1.0086 \cdot 10^{-2} N^4)
$$

(12)

$$
N = S_{sw}^2(1.707 \cdot 10^{-2} + 1.205 \cdot 10^{-5} S_{sw}^2 + 4.058 \cdot 10^{-9} S_{sw}^4)
$$

(13)

$$
\Delta = 25 - T
$$

(14)
We used the above fourteen formulas to obtain the real and imaginary part of dielectric constant for the type of soil predominated by sodium. For parameters used in modified Dobson dielectric mixing model: the bulk density was set to 1.35 g·cm\(^{-3}\), the specific density was assumed to be 2.65 g·cm\(^{-3}\), the soil temperature was fixed to 27, the percentage volume of clay and sand in Dobson model were respectively set to 50% and 20%.

2.2 Backscattering model: AIEM model

The integral equation model (IEM) was proposed by Fung et al. (1994)\(^{[13]}\), which is the forward physically backscattering model based on radiation transfer theory, considering the surface scattering term only and was verified by laboratory measurements of bistatic scattering from surfaces with small, intermediate and large-scale roughness. The advanced IEM (AIEM) improves the calculation accuracy of scattering coefficient by keeping the absolute phase term in Greens function which was neglected by IEM \(^{[14]}\). Therefore, we applied AIEM to simulate soil single scattering of salt-affected coefficient in our paper. The single backscattering coefficient is expressed by

\[
\sigma_{m}^{p} = \frac{k^2}{2} e^{-2kz} \sum_{n=0}^{\infty} \delta_{n}^{2n} \left| f_{n} \right| W^{n}(-2k_{s}, 0) n!
\]

where \(pp\) indicates the polarization state (\(HH\) or \(VV\)), \(\theta\) is the incident angle, \(k\) is the wave-number, and \(k_{s} = k \cos \theta\) , \(k_{r} = k \sin \theta\) , \(W^{n}\) is the Fourier transform of \(n\)th power of the surface correlation function. For further details on the AIEM model, the reader can refer to Fung et al. (1994)\(^{[13]}\) and Chen et al., (2003)\(^{[14]}\). Fung (1994) showed that, for moderately rough surfaces, an exponential statistical distribution performs better than the Gaussian or the 1.5 power law distributions. Thus, the statistical distribution of saline soil surface which usually are smooth, is assumed to be exponential for the applications described in this paper.

All input parameters of AIEM model used in our paper contain incident angle which assumed to be 40°, surface roughness (the height standard deviation of 0.6cm and the surface correlation length of 2.7cm) and soil dielectric constant derived from the modified Dobson dielectric mixing model.

3 RESULTS

3.1 Analysis of the Simulated Dielectric Constants

To estimate the effect of the salt presence in soil, we first study the effect of moisture (\(m_{v}\)) and salinity (\(S\)) on the dielectric constant of soil predominated by sodium by means of the modified Dobson semi-empirical model. The simulated results are shown in Fig.1, in which the real and imaginary part of soil dielectric constant are plotted as a function of soil volumetric moisture content for salinity ranging from 0 to 120‰ (the upper) and of soil salinity content for volumetric moisture from 0 to 0.5cm\(^{-3}\)·cm\(^{-3}\) (the lower) at 5.3 GHz frequency.

We can see that the effect of soil moisture and salinity on the dielectric constant are different, the real and imaginary part simultaneously increase with soil water content; however, with the increasing of soil salinity, the real part behaves an
evident downward trend, especially for the soil with high moisture. Contrast to that, the imaginary part takes on the increasing fashion with soil salinity. For soils with low moisture, salinity has a little influence on the real part, taking soil volumetric moisture at 0.15 cm³·cm⁻³ as example, when soil salinity decrease from 120‰ to 0‰, the real part increase only from 4.8 to 7.8. However, soil moisture makes the large contribution to real part for soil with small salinity level. As for the imaginary part is concerned, it is affected by both soil salinity and moisture, but the increase rate with salinity is not obvious at the low moisture region than that at the high moisture region. This behavior can be explained by the fact of increase in moisture content lead to a greater quantity of free water and even more amount of dissolved salts. The dissolved salts increase the conductivity, so the imaginary part is relatively high. But for small moisture region, the dielectric constant is dominated by the bound water component and a weak variation on the imaginary when salinity ranging from 0 to 120‰.

Fig. 1 also clearly show that the increase rate with salinity for imaginary part is dependent on the soil moisture level and the real part of dielectric constant is always high than the imaginary part.

Except that, we can see that the simulated results especially for the imaginary part at the certain salinity level are linearly dependent on soil moisture. This conclusion accord with the report of Lasne et al[15], which consider this linear relation caculated by Dobson model lead to an overstimation of the dielectric constant at low moisture contents as well as an underestimation at high moisture contents.

![Fig. 1 Effect of moisture (the upper) and salinity (the lower) on the soil dielectric constant derived from the modified Dobson model at 5.3GHz for volumetric water content ranging from 0.05 to 0.5 cm³·cm⁻³ and salinity content ranging from 0 to 120‰.](image-url)

(left: the real part; right: the imaginary part)
3.2 Analysis of the Simulated Backscattering Coefficients

The simulated results shown in Fig.2 and Fig.3 indicate that backscattering coefficients (VV and HH polarization) derived from AIME model, under the incident of 40° and frequency of 5.3GHz, are affected by both soil moisture and salinity. With increasing of soil water content, the simulated backscattering coefficient increases evidently; with soil salinity, backscattering coefficient increase when soil moisture are less than 0.4cm³·cm⁻³, but when soil moisture is higher than 0.4cm³·cm⁻³, it remain unchanged for the HH polarization mode and expresses the weakly downward tendency for the VV polarization mode. Soil salinity slightly affect the polarization, in particular for high moisture contents. The dependence of the backscattering coefficient on the salinity for low moisture values content constitutes an interesting result for the detection of small amounts moisture. The possible reason for these characteristic is that moisture largely dominates the dielectric constant for soil with high moisture, so when salinity increase from 0‰ to 120‰, the change of backscattering coefficient is not obvious. However, for soil with low moisture content, even the small change in dielectric constant due to the salinity can lead to the backscattering coefficient increase. As stated above, although VV or HH polarization have no potential to discern soil salinity for high moisture region, we can using them to retrieve soil salinity only for the low moisture region (<0.3 cm³·cm⁻³).

Except that, we can see from Fig.2 and Fig.3 that the VV backscattering coefficients is more sensitive to the moisture than the HH coefficients. When the moisture content increase from 0.05 to 0.5 at 0‰ salinity level, VV backscattering coefficients change 7.1 dB from -13.8 to -6.7dB, whereas the HH backscattering coefficients is less than 5.7 dB from -14.0 to -8.3dB.

![Fig. 2 Backscattering coefficients simulated with AIME model at different moisture (0.05-0.5cm³·cm⁻³) for 40°incidence angle at 5.3GHz frequency (left: the VV polarization, right: the HH polarization)](image-url)
4 CONCLUSIONS

The complex dielectric constant and backscattering coefficient for the salt-affected soil were analyzed using the advanced integral equation model (AIEM) combined with the modified Dobson dielectric mixing model. We conclude that the real part decrease with soil salinity content, however, the imaginary part increase with it especially for the high moisture regions, but the increase rate is not obvious for the low moisture region than that for the high moisture region. For soils with low moisture, salinity has a little influence on the real part of dielectric constant; however, soil moisture makes the large contribution to real part for soil with small salinity level.

Both soil moisture and salinity affect the $VV$ and $HH$ polarization backscattering coefficient, with moisture the backscattering coefficient increases evidently, but with soil salinity backscattering coefficient increase at the small moisture region and it remains unchanged for the $HH$ polarization or expresses the weakly downward tendency for $VV$ polarization respectively at the high moisture region. So, the backscattering coefficient dependence on salinity is slight especially for the high moisture region, and we can using $VV$ or $HH$ polarization to retrieve soil salinity only for the soil with low moisture (<0.3 cm$^3$ cm$^{-3}$).

This paper only show the theoretically simulation results using the forward radiation transfer model (AIEM) combined with the modified dielectric mixing model (Dobson), and the results had not been validated by the practical field or laboratory measurement. So, the next work, we should further calibrate the simulation result based on measurements of dielectric constant using Vector Network Analyzer and backscattering coefficient obtained from the microwave remote sensing image, and other real measurement parameters.

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