Evaluation of Electromagnetic Scattering from Heterogeneous Soils for Ground-Penetrating Radar Measurements through a Simple Modeling

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***Abstract*—Higher frequency ground-penetrating radar (GPR) is becoming more common for various applications. It can achieve higher resolution, but, at the same time, it becomes sensitive to heterogeneous soil, resulting in unwanted scattering appeared in data, which makes analysis and interpretation of the data difficult. In this paper, a simple model is proposed as a tool to evaluate the influence of heterogeneity of soil on scattering. The modeling demonstrates the scattering caused by soil heterogeneity is characterized as the Mie scattering. The influence of soil heterogeneity on GPR measurements is investigated through the modeling. The results exhibit that the amount of permittivity variation of soil is mostly dominates the scattering power; however, when correlation length of soil permittivity distribution is at multiples of wavelength, the influence of correlation length becomes greater.**

I. INTRODUCTION

Ground-penetrating radar (GPR) has been used to survey geological structures and is becoming a more common tool for near-surface applications, which include landmine detection, environmental studies, and agriculture. In these applications, measurements are usually in smaller scale, and higher resolution and higher sensitivity compared to conventional surveys are required. Therefore, relatively high frequencies (higher than 500 MHz) are often preferred. With high frequencies, GPR becomes more sensitive to the heterogeneity of soils surrounding targets, resulting in unwanted scattering of electromagnetic waves from heterogeneous soil, which appears in the data. The unwanted scattered waves in the data are commonly referred to as clutter, and clutter makes the analysis and interpretation of data difficult and confusing. Fig. 1 shows an example of clutter caused by heterogeneous soils. Both radar profiles were acquired with the same five targets buried at the same locations and depths, but in different types of soil. These targets can easily be recognized with their hyperbolic signatures in Fig. 1a, which was measured in homogeneous soil. However, in heterogeneous soil (Fig. 1b), their signatures were disturbed by clutter and reflections were weak because of scattering loss, which makes these targets difficult to be detected. It is very important to study the influence of heterogeneous soils on GPR in order to assess its effectiveness and limitations.

Authors developed a modeling method of clutter caused by heterogeneous soils, which provides the typical power of clutter with a simplified heterogeneous soil model. The modeling does not require the exact pattern of soil heterogeneity, but it uses statistical properties of the permittivity distribution. The validity of the technique was demonstrated with various soil heterogeneity caused by an infiltration [1] and seasonal change [2]. In this paper, the influence of various soil heterogeneities is discussed through the modeling method.

II. GPR CLUTTER MODELING

A. Characterizing Soil Heterogeneity

The modeling technique aims to provide the amount of clutter to be observed by a GPR taking into account soil heterogeneity. Therefore, the soil heterogeneity must be

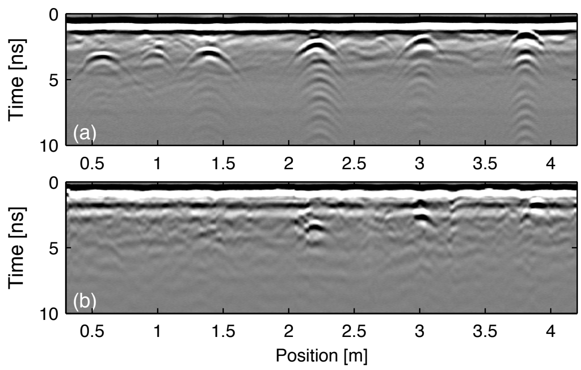

Fig. 1. GPR vertical profiles in (a) homogeneous and (b) heterogeneous soil. Targets and their burial locations and depths were same in both soils.

determined first. The heterogeneity for GPR may be determined from the spatial distribution of dielectric permittivity because permittivity is the most influencing parameter on reflectivity of electromagnetic waves [3], [4]. It can be measured by time domain reflectometory (TDR) at various locations and a semivariogram, which is a geostatistical analysis, can quantify the heterogeneity from the spatial distribution of permittivity. For a 1D permittivity distribution $\epsilon(x)$ measured by TDR, the semivariogram $\gamma(h)$ is computed as [5]:

$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{N_h}\left[\varepsilon(x_i+h)-\varepsilon(x_i)\right]^2 \tag{1}$$

where h is the lag distance between two data points, $\varepsilon(x_i+h)$ and $\varepsilon(x_i)$, and N_h is the number of data pairs with a constant lag distance h from all data points. Often, the semivariance $\gamma(h)$ increases with the lag distance h up to a certain value and then it becomes constant. The lag distance h and semivariance $\gamma(h)$ where $\gamma(h)$ becomes constant are called range a and sill C, respectively. The range indicates the mean distance at which a data pair does not correlate anymore and thus it is equivalent to correlation length and characteristic length [6]. The sill corresponds to the maximum variance within a data set and thus it is the indication of the variability. The exponential semivariogram model with no nugget effect given as [5]:

$$\hat{\gamma}(h) = C\left[1-\exp\left(\frac{-3h}{a}\right)\right] \tag{2}$$

is fitted to the obtained experimental semivariograms in order to determine range a and sill C. Since the exponential model asymptotically reaches its sill, the practical range a is defined as the distance where the modeled semivariance reaches 95% of the sill [7], [8].

B. Dielectric Sphere Model for GPR Clutter Calculation

A simple model is constructed with the model parameters obtained by the semivariogram, i.e., correlation length a and variability C, as well as with the mean of the measured soil permittivity ε_m. The model considered in this study is conceptually illustrated in Fig. 2. It consists of a dielectric sphere embedded in a dielectric homogeneous space. The homogeneous background is defined having a dielectric permittivity equal to the mean permittivity, i.e., $\varepsilon_1 = \varepsilon_m$. The circumference of the dielectric sphere is chosen to be equal to the correlation length and thus the diameter of the sphere d is defined as $d = a/\pi$, where a is the correlation length of the soil

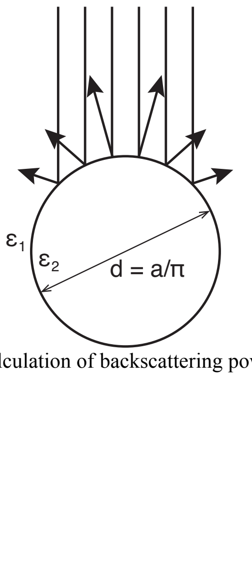

Fig. 2. Model for the calculation of backscattering power.

permittivity distribution determined by the geostatistical analysis as described in the previous section. The permittivity of the sphere ε_2 is set so that the contrast to the ambient medium is equal to the square root of variability as follows:

$$\Delta\varepsilon = \varepsilon_2 - \varepsilon_1 = \sqrt{C} \tag{3}$$

With this model, the radar cross-section (RCS) that is proportional to the backscattering power of the dielectric sphere is theoretically calculated, assuming a monostatic configuration and plane wave incidence. There are two ways to calculate RCS for the model: the Mie solution and Rayleigh approximation.

By the Mie solution, the RCS σ_s of a dielectric sphere is given as follows [9]:

$$\sigma_s = \frac{1}{x^2}\left|\sum_n (2n+1)(-1)^n(a_n-b_n)\right|^2 \tag{4}$$

where $x = kr$, k is the wavenumber in the ambient medium, and r is the radius of the sphere. In case there is no change in the magnetic permeability between the dielectric sphere and ambient medium which is assumed in this study, the coefficients a_n and b_n are given by

$$a_n = \frac{m^2 j_n(mx)\left[xj_n(x)\right]' - j_n(x)\left[mxj_n(mx)\right]'}{m^2 j_n(mx)\left[xh_n^{(1)}(x)\right]' - h_n^{(1)}(x)\left[mxj_n(mx)\right]'} \tag{5}$$

$$b_n = \frac{j_n(mx)\left[xj_n(x)\right]' - j_n(x)\left[mxj_n(mx)\right]'}{j_n(mx)\left[xh_n^{(1)}(x)\right]' - h_n^{(1)}(x)\left[mxj_n(mx)\right]'} \tag{6}$$

where m denotes the refractive index. The functions $j_n(x)$ and $h_n^{(1)}(x)$ are the spherical Bessel function of first kind of order n and spherical Hankel function of order n, respectively. Primes mean derivatives with respect to the argument.

The Rayleigh approximation simplifies the Mie solution (4)-(6) as follows [9]:

$$\sigma_s = 4x^4\left|\frac{m^2-1}{m^2+2}\right|^2 \tag{7}$$

The equation exhibits that the scattering power due to the particle is inversely proportional to the fourth power of the wavelength (or proportional to the fourth power of the sphere size) in Rayleigh scattering region.

III. Demonstration of the Clutter Modeling

The modeling method was applied to GPR measurements during an infiltration experiment in an outdoor test site [1]. The soil in this site was medium sand covered by a variety of grasses and in natural condition. A GPR with Vivaldi antennas and the center frequency of 1.5 GHz was repeatedly scanned on a line after irrigation of water, which was much more than the maximum capacity of soil. The heterogeneity of soil and accordingly in the power of GPR clutter were expected to change during infiltration process.

Fig. 3 compares clutter power extracted from GPR data and modeled. In this comparison, clutter was extracted from GPR data by picking highest amplitude below surface reflections at

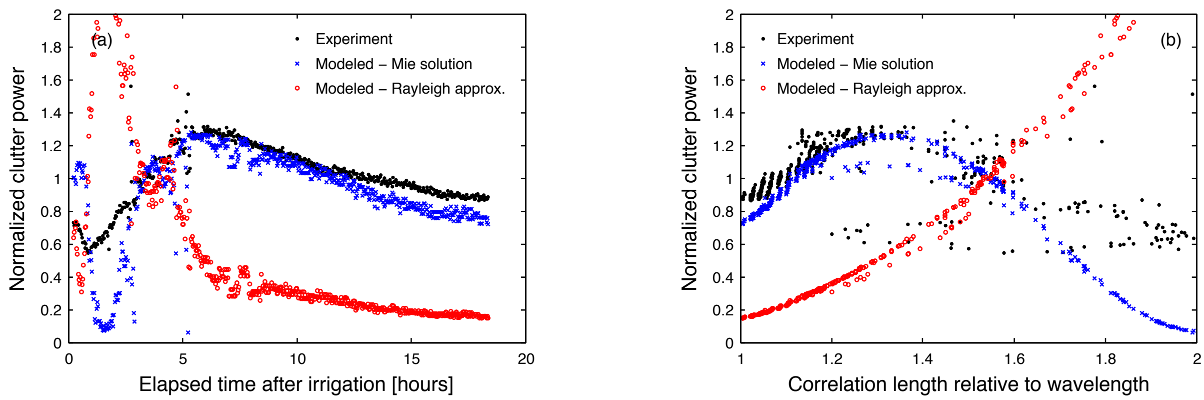

Fig. 3. Clutter power extracted from experiments (black dots), modeled by the Mie solution (blue crosses), and by the Rayleigh approximation (red circles) plotted as a function of (a) elapsed time after irrigation and (b) correlation length of soil permittivity distribution relative to wavelength. The clutter power was normalized by the value at three hours after irrigation for the comparison.

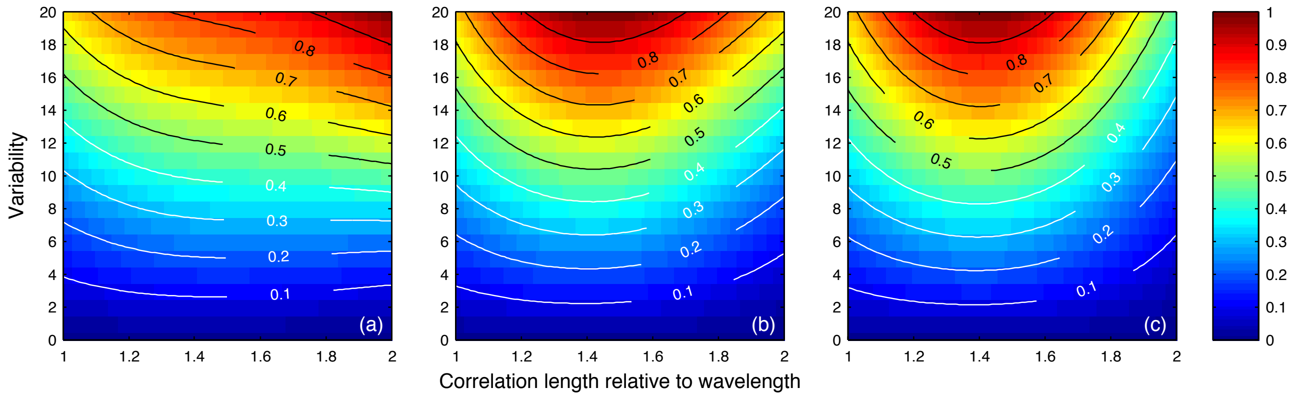

Fig. 4. Clutter power calculated by the dielectric sphere model for various variability and correlation length at the mean relative permittivity of (a) 5, (b) 15, and (c) 25. Clutter power was normalized within the calculated range in each case.

each elapsed time after irrigation. As depicted in Fig. 3a, the modeling up to three hours after irrigation does not fit the experiments. This may be because the simple model cannot represent the very dynamic change of soil state due to infiltration process. After this period, clutter power modeled by the Mie solution fits well to extracted clutter power. On the other hand, clutter power modeled by the Rayleigh approximation shows different behavior from that of the experiment and modeled by the Mie solution. This result indicates that scattering by heterogeneous soil is Mie scattering in the case of relatively high frequency GPR, which is different to the conventional low frequency GPR measurements for large-scale surveys that is said to exhibit Rayleigh scattering. This makes sense considering the fact that the correlation length ranged from 1 to 2 relative to wavelength in this experiment as shown in Fig. 3b. In this range of correlation length, soil heterogeneity and wavelength are in the similar scale, which violates the assumption of the Rayleigh approximation, i.e., target dimension must be much smaller than wavelength. That is why the Rayleigh approximation does not fit to the experiments, whereas the Mie solution provides reasonably well-fitted modeling results.

IV. Influence of Soil Heterogeneity on GPR Clutter

In the previous section, it was demonstrated that the simple dielectric sphere model was able to calculate the power of clutter that was caused by soil heterogeneity. The modeling technique allows us to investigate the influence of heterogeneous soil on GPR clutter. Fig. 4 shows normalized clutter power calculated by the model with various correlation lengths and variability at the mean relative permittivity of 5, 15, and 25, which may correspond to dry, wet, and very wet soil conditions. The ranges of correlation length and variability were chosen to cover a wide variety of soil [10], [11]. From the figures, a tendency that can be found at all the mean permittivity in common is that clutter power is higher in the top part of figures, meaning that the higher variability soils exhibit the higher clutter power observed. This is understandable, because scattering is caused by the variation of permittivity in space. On the other hand, the correlation length also influences on the power of clutter, although the degree of influence seems different at different mean permittivity. In order to compare the influence of correlation length and variability, the gradients of Fig. 4 with respect to correlation length and variability are calculated and the ratio given as:

$$R(a,C)=\frac{\partial\sigma_s(a,C)}{\partial C}\Big/\frac{\partial\sigma_s(a,C)}{\partial a} \qquad (8)$$

is shown in Fig. 5. The ratio exhibits which factor is more influential to observed clutter power – correlation length or variability. In these figures, red means that correlation length

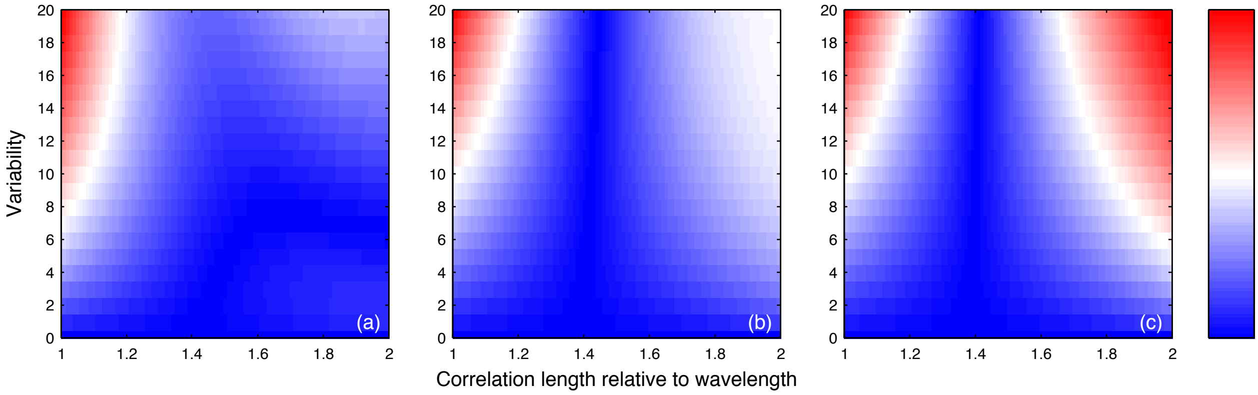

Fig. 5. Map of the influence of correlation length and variability on clutter power at the mean relative permittivity of (a) 5, (b) 15, and (c) 25. Red color represents that correlation length is more influential than variability and blue color represents that variability is more influential than correlation length.

is more influential and blue means variability. All the maps show blue color in the bottom part, meaning clutter power is mainly depend on variability when variability is relatively low. When variability becomes higher, correlation length comes into play. The degree of influence of correlation length differs at different mean permittivity; however it can be seen in all the cases in common that the influence of correlation length becomes higher when the correlation length is at multiples of the wavelength. This might indicate the possibility to reduce clutter in GPR data by filtering certain frequency components at which the correlation length matches multiples of the wavelengths.

V. Conclusion

A simple model that calculates clutter power taking into account statistical properties of permittivity distribution of soil was proposed and demonstrated. The model may need further verifications; however, it was illustrated that the model reasonably calculates clutter power for relatively high frequency GPR and the results agreed with experiments when the Mie solution was employed. On the other hand, the Rayleigh approximation gave results very different to experiments. Therefore, the modeling also demonstrated that the scattering caused by soil heterogeneity in the case of relatively high frequency GPR measurements is in Mie scattering region. This is different to what used to be said in the conventional large-scale GPR measurements – Rayleigh scattering, because lower frequency has been commonly used for large-scale measurements. The study in this paper demonstrated that the region of scattering by soil heterogeneity in small-scale surveys is different to that in large-scale measurements.

Since the model takes soil heterogeneity into account, clutter power can be calculated for various soil heterogeneities, which allows us to investigate which factor is more influential to clutter. As a result, variability is mostly more influential than correlation length; however, the influence of correlation length becomes greater when it is at multiples of wavelength. This might indicate the possibility that, in the case of broadband GPR system, clutter can be reduced by filtering certain frequency components. In addition, the analysis allows us to estimate how much scattering is likely observed and also to evaluate how effectively GPR can work in certain types of soil by measuring and characterizing the spatial distribution of soil permittivity. Such an assessment may help to improve efficiency of GPR, especially in safety and cost critical applications, for example landmine detection.

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