Modeling of Multilayered Media Green's Functions With Rough Interfaces

François Jonard, Frédéric André, Nicolas Pinel, Craig Warren, Harry Vereecken, and Sébastien Lambot

***Abstract*— Horizontally stratified media are commonly used to represent naturally occurring and man-made structures, such as soils, roads, and pavements, when probed by ground-penetrating radar (GPR). Electromagnetic (EM) wave scattering from such multilayered media is dependent on the roughness of the interfaces. In this paper, we developed a closed-form asymptotic EM model considering random rough layers based on the scalar Kirchhoff-tangent plane approximation (SKA) model that we combined with planar multilayered media Green's functions. In order to validate our extended SKA model, we conducted simulations using a numerical EM solver based on the finite-difference time-domain (FDTD) method. We modeled a medium with three layers—a base layer of perfect electric conductor (PEC) overlaid by two layers of different materials with rough interfaces. The reflections at the first and at the second interface were both well reproduced by the SKA model for each roughness condition. For the reflection at the PEC surface, the extended SKA model slightly overestimated the reflection, and this overestimation increased with the roughness amplitude. Good agreement was also obtained between the FDTD simulation input values and the inverted root mean square (rms) height estimates of the top interface, while the inverted rms heights of the second interface were slightly overestimated. The accuracy and the performances of our asymptotic forward model demonstrate the promising perspectives for simulating rough multilayered media and, hence, for the full waveform inversion of GPR data to noninvasively characterize soils and materials.**

***Index Terms*— Finite-difference time-domain (FDTD), gprMax, Green's function, ground-penetrating radar (GPR), Kirchhoff-tangent plane approximation (KA), model inversion, multilayered media, radar, rough interfaces, scattering.**

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I. Introduction

GROUND-PENETRATING radar (GPR) is a widely used geophysical method for nondestructive probing of media in many different fields, such as agricultural and environmental engineering, civil engineering, hydrology, and archeology [1], [2]. It allows rapid data collection and has been successfully used to characterize a range of different media (e.g., soils, pavements, and trees) [3]–[6] or to detect embedded objects [7], [8].

Scattering by random rough interfaces of stratified media, such as soils and roadways, has to be accounted for to accurately retrieve the electromagnetic (EM) properties of the different layers by GPR. When the roughness amplitude becomes nonnegligible compared to the radar wavelength, specular reflections are decreased and diffuse reflections occur at the rough interfaces, leading to smaller echoes in the recorded GPR data.

A wide range of asymptotic EM models have been proposed to describe scattering from random rough interfaces. These models have mainly been developed for one-layer media with a rough interface (see [9] and references therein, [10]–[12]). Some of these models have been extended in order to account for the roughness of both interfaces of this single-layer configuration. Among others, the small perturbation method (SPM) has been extended to account for two interfaces [13]–[16] and is valid for small height variations compared to the EM wavelength. Soubret *et al.* [17] extended the reduced Rayleigh equations to the case of two slightly rough interfaces. Fuks [18], Blumberg *et al.* [19], and Gu *et al.* [20] developed a model for scattering from a slightly rough surface overlying a strongly rough surface compared to the incident EM wavelength. Pinel *et al.* [21], [22] extended the Kirchhoff-tangent plane approximation (KA) reduced to the geometric optics approximation to two random rough interfaces. Also, reductions of the KA to the scalar KA (SKA) have been proposed for dealing with the coherent scattering from random rough layers [23]–[25]. Concerning the so-called unified models for random rough layers, we can cite the full-wave model [26], [27], the small-slope approximation (SSA) method [28], as well as the radiative transfer model [29].

In contrast to single rough layer EM models, the literature on EM models for multilayered media with multiple rough interfaces remains sparse [30], and only a few models dealing with more than two rough interfaces have been developed. To the best of our knowledge, only classical asymptotic models exist and are only valid for slightly rough interfaces [31]–[40]. The proposed solutions are generally based on the SPM. One exception is the recent paper by Afifi *et al.* [38], where both the SPM and the SSA have been applied and investigated. The advantage of using the SSA is the extension of the validity domain to rougher surfaces. Considering the backscattering from rough interfaces at normal incidence, i.e., incidence angle classically used for an off-ground GPR configuration, this implies that the coherent component is the main contributor to the total scattering process. However, if only the first order of the SPM is used, the coherently scattered intensity reduces to that of flat surfaces. Therefore, it is necessary to use at least the second-order SPM [40] or the SSA [38]. For the SSA, the solution proposed in [38] is restricted to Gaussian height distributions and correlation functions. Regarding the SPM, an expression of the second-order coherent normalized radar cross section (NRCS) has been derived recently [40], but only for 2-D problems.

In this paper, we present a new closed-form asymptotic EM model considering random rough layers based on the SKA model that we combined with planar multilayered media Green's functions and a full-wave, closed-form radar-antenna model. This generalizes the model of Jonard *et al.* [41], in which only scattering in reflection from the rough surface, i.e., the upper air/soil medium interface, was considered. The newly developed model applies to multilayered media with random rough layers, and it takes into account the scattering in transmission through the rough interfaces. The objective is also to propose an easily implementable and computationally efficient model suitable for inversion using a 3-D analytical formulation. This new model was validated through comparisons with a 3-D reference GPR simulation software, namely, gprMax [42], and the performance of the model for retrieving medium properties from GPR full-wave inversion [43] was investigated.

This paper begins with a description of the modeling of the planar multilayered media Green's functions in Section II. Section III provides a description of the proposed EM model accounting for the scattering from multilayered media with random rough interfaces. Section IV then presents the finite-difference time-domain (FDTD) simulations carried out using gprMax, and Section V introduces the inversion of the proposed model. In Section VI, we present and discuss the main results, and finally, we give a summary and concluding remarks in Section VII.

II. Planar Multilayered Media Green's Functions

EM wave propagation in 3-D planar layered media can be described using closed-form Green's functions in the frequency domain, which are exact solutions of Maxwell's equations [43], [44]. For the particular case of radar applications, the Green's functions usually represent the backscattered electric field for a unit strength electric source. The Green's function is first calculated in the spectral domain and, subsequently, transformed into the 3-D spatial domain through Sommerfeld's integral [45]. The spectral domain Green's function is calculated using the global reflection coefficients of the multilayered medium obtained using a recursive scheme [44].

III. Interface Roughness Model

In general, random rough surfaces are assumed to be stationary with a Gaussian height distribution. A rough surface can, therefore, be described by the following statistical quantities: the root mean square (rms) of the surface heights and the spatial autocorrelation function, with its associated spatial autocorrelation length [46]. The shape of the autocorrelation function is usually taken as either Gaussian or exponential depending on the considered rough surfaces.

A. Single Interface

To account for the impact of the roughness of a single surface on radar EM wave propagation and scattering in the specular direction, the Ament model [47], [48] is usually used. This model, which is derived from the Kirchhoff-tangent plane scattering theory, describes the scattering losses in the specular direction due to the reflection onto a random rough interface. This model has been applied in several studies investigating the roughness effect on EM wave scattering over sea or soil surfaces [41], [49] and for rough building materials [50]. In this model, the global surface reflection coefficient is multiplied by a scattering loss factor ($\mathcal{A}$), which is based on the Rayleigh parameter as a function of frequency, given in the following equation:

$$\mathcal{A} = e^{-g/2} \tag{1}$$

where

$$g = \left(\frac{4\pi s_{\mathrm{r}} \cos\theta_{\mathrm{i}}}{\lambda}\right)^2 \tag{2}$$

with θ_{i} the incidence angle, s_{r} the rms of the surface heights, and λ the wavelength in free space. The modified reflection coefficient r^{m} that models the reduction of the reflection amplitude in the specular direction is then defined by

$$r_{\mathrm{TE}}^{\mathrm{m}} = \mathcal{A}\ r_{\mathrm{TE}} \tag{3}$$

$$r_{\mathrm{TM}}^{\mathrm{m}} = \mathcal{A}\ r_{\mathrm{TM}} \tag{4}$$

where r_{TE} and r_{TM} are the transverse electric (TE) and transverse magnetic (TM) mode Fresnel reflection coefficients for a perfectly flat surface, respectively. Equations (3) and (4) assume that the surface heights have a Gaussian distribution with large surface curvatures compared to the EM wavelength, as well as negligible shadowing and multiple scattering effects [48]. In this paper, normal incidence is considered ($\theta_{\mathrm{i}} = 0$), so the shadowing and multiple scattering effects can be neglected.

B. Extension to a Multilayered System

For the case of a multilayered system, as shown in Fig. 1 (N layers, $N - 1$ interfaces), the problem becomes more complex, as multiple transmissions and reflections occur inside the multilayered medium.

Recently, the SKA has been extended to the case of a single-layer problem with two interfaces [21]. We present here

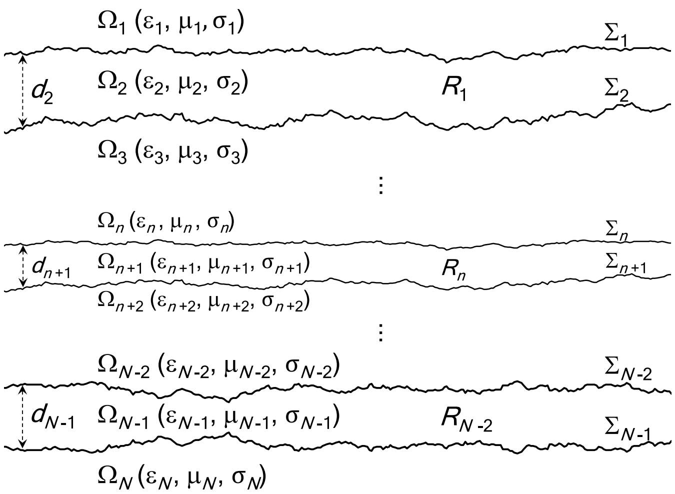

Fig. 1. 3-D planar multilayered medium with rough interfaces (Σ_n is the interface n, Ω_n is the layer n characterized by a dielectric permittivity ϵ_n, a magnetic permeability μ_n, an electric conductivity σ_n, and a thickness d_n, and R_n is the equivalent Fresnel reflection coefficient).

the equations for a reflection inside a layer Ω_n onto a layer Ω_{n+1} with thickness d_{n+1}. In this case, the classical expression of the so-called equivalent Fresnel reflection coefficient R_n for the flat case is given in the following equation:

$$R_n = r_n + \frac{\left(1 - r_n^2\right) r_{n+1} e^{-2\Gamma_{n+1} d_{n+1}}}{1 + r_n r_{n+1} e^{-2\Gamma_{n+1} d_{n+1}}} \tag{5}$$

where r_n and r_{n+1} are the Fresnel reflection coefficients onto the upper and lower interfaces of the considered layer, respectively, and Γ_{n+1} is the vertical component of the propagation wavenumber of the wave inside the layer Ω_{n+1} multiplied by j.

Equation (5) can be further simplified as

$$R_n = \frac{r_n + r_{n+1} e^{-2\Gamma_{n+1} d_{n+1}}}{1 + r_n r_{n+1} e^{-2\Gamma_{n+1} d_{n+1}}}. \tag{6}$$

By contrast, for the general case of independent random rough interfaces, the expression can be written as in [24], [25]

$$R_{n,\text{rough}} = r_n \mathcal{A}_n + \frac{\left(1 - r_n^2\right) r_{n+1} e^{-2\Gamma_{n+1} d_{n+1}} \mathcal{A}_{n+1}}{1 + r_n r_{n+1} e^{-2\Gamma_{n+1} d_{n+1}} \mathcal{A}_{\text{r}(n+1,n)} \mathcal{A}_{\text{r}(n+1,n+2)}}. \tag{7}$$

The attenuation terms related to the roughness can be formulated as follows for Gaussian statistics (i.e., Gaussian height probability density function):

$$\mathcal{A}_n = e^{-2[-j\,\Gamma(n)\, s_\text{r}(n)]^2} \tag{8}$$

$$\mathcal{A}_{n+1} = e^{-2[-j\,\Gamma(n+1)\, s_\text{r}(n+1)]^2 - s_\text{r}(n)^2[-j\,\Gamma(n) + j\,\Gamma(n+1)]^2} \tag{9}$$

$$\mathcal{A}_{\text{r}(n+1,n)} = e^{-2[-j\,\Gamma(n+1)\, s_\text{r}(n)]^2} \tag{10}$$

$$\mathcal{A}_{\text{r}(n+1,n+2)} = e^{-2[-j\,\Gamma(n+1)\, s_\text{r}(n+1)]^2} \tag{11}$$

in which $s_\text{r}(n)$ is the rms of the surface heights of the interface Σ_n separating layers Ω_n and Ω_{n+1}.

With a view to extending the formulation by iterations to multilayers, expression (7) should be rewritten by introducing $r_{n+1,\text{rough}}$. It corresponds to the Fresnel reflection coefficient in the TE or TM polarization modified by the roughness of the considered interface, as expressed in (3) or (4), respectively. For interface $n+1$, it mathematically corresponds to

$$r_{n+1,\text{rough}} = r_{n+1}\, e^{-2[-j\,\Gamma(n+1)\, s_\text{r}(n+1)]^2}, \tag{12}$$

so that (7) can be rewritten as

$$R_{n,\text{rough}} = r_n \mathcal{A}_n + \frac{(1 - r_n^2) r_{n+1,\text{rough}} e^{-2\Gamma_{n+1} d_{n+1}} \mathcal{A}_{\text{t}(n,n+1)}}{1 + r_n r_{n+1,\text{rough}} e^{-2\Gamma_{n+1} d_{n+1}} \mathcal{A}_{\text{r}(n+1,n)}}, \tag{13}$$

with

$$\mathcal{A}_{\text{t}(n,n+1)} = e^{-s_\text{r}(n)^2[-j\,\Gamma(n) + j\,\Gamma(n+1)]^2} \tag{14}$$

the last term $A_{\text{t}(n,n+1)}$ corresponding physically to the decrease of the amplitude of the wave during its transmission between layers Ω_n and Ω_{n+1} due to the roughness of interface Σ_n.

The extension of the approach for a single layer with two interfaces to a multilayered system can be performed as explained in the following. First, for the flat case, it can be shown that the equivalent Fresnel reflection coefficient R_n has the same formal expression as for a single layer (two interfaces) in (5), except that the Fresnel reflection coefficient r_{n+1} must be replaced by the equivalent Fresnel reflection coefficient R_{n+1}. Then, the resolution of this system can be made in several ways. Here, following [43], it is resolved within the calculation of the Green's function by using a recursive scheme and by starting with the lower interface (Σ_{N-1}). For the rough case, the same method is used, and the modification from $r_{n+1,\text{rough}}$ to $R_{n+1,\text{rough}}$ must also be made

$$R_{n,\text{rough}} = r_n \mathcal{A}_n + \frac{\left(1 - r_n^2\right) R_{n+1,\text{rough}} e^{-2\Gamma_{n+1} d_{n+1}} \mathcal{A}_{\text{t}(n,n+1)}}{1 + r_n R_{n+1,\text{rough}} e^{-2\Gamma_{n+1} d_{n+1}} \mathcal{A}_{\text{r}(n+1,n)}} \tag{15}$$

for all $n \leq N-2$; at the initialization $n = N-1$ (corresponding to the lower interface Σ_{N-1}), we have

$$\begin{aligned} R_{N-1,\text{rough}} &= r_{N-1,\text{rough}} \\ &= r_{N-1}\, e^{-2[-j\,\Gamma(N-1)\, s_\text{r}(N-1)]^2} \end{aligned} \tag{16}$$

IV. Numerical Simulation Using an FDTD Model

In order to validate the extended SKA model, we conducted a series of numerical simulations. We used gprMax [42], which is an open source software that simulates EM wave propagation in the time domain. gprMax uses Yee's algorithm [51] to solve Maxwell's equations in 3-D using the FDTD method. In this paper, comparisons between our frequency domain model and gprMax were performed using fast Fourier transforms.

We used a spatial resolution of $\Delta x = \Delta y = \Delta z = 0.0025$ m and a temporal resolution of $\Delta t = 4.81 \times 10^{-12}$ s (to satisfy the Courant–Friedrichs–Lewy condition). The domain size was $2.5 \times 2.5 \times 1.05$ m, which was enabled through the use of efficiently performing perfectly matched layer (PML) absorbing boundary conditions [52]. A higher order split-field PML was introduced by Correia and Jin [53], and since

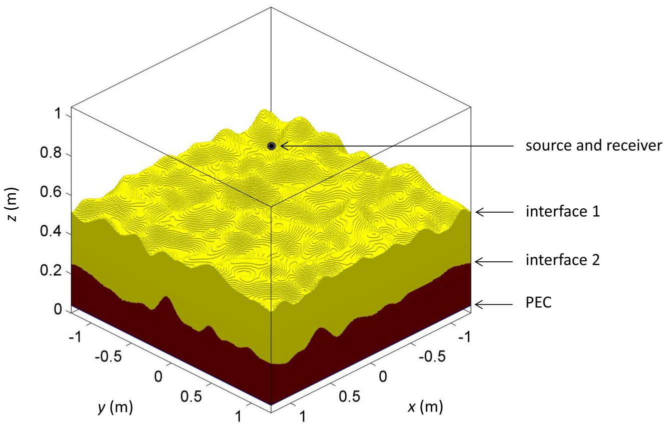

Fig. 2. Geometrical model used for the FDTD simulations with a spatial domain of 2.5 × 2.5 × 1.05 m and a spatial resolution of 0.0025 m. The position of the source and receiver is at $z = 0.85$ m and in the center of the xy plane.

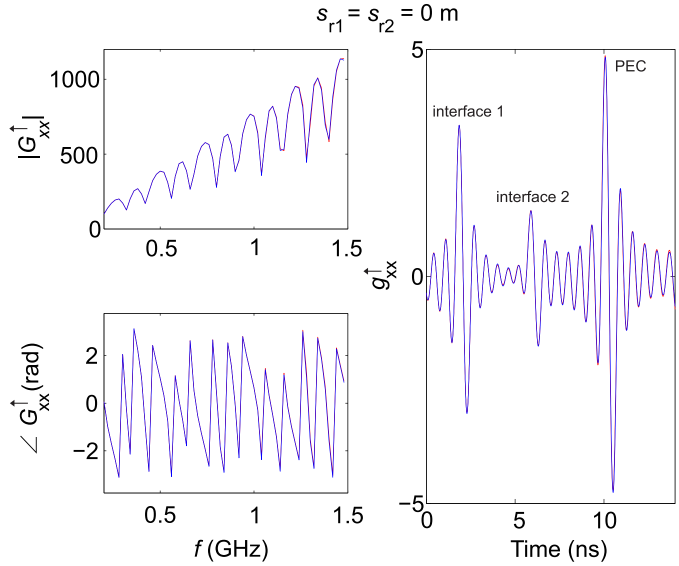

Fig. 3. Green's functions computed by our asymptotic extended SKA model (red curves) and the FDTD simulations (blue curves) in the frequency (the frequency range of 0.2–1.5 GHz) and time (the time window of 0–14 ns) domains for perfectly flat interfaces ($s_{r1} = s_{r2} = 0$).

then, a series of different unsplit implementations have been reported [54]–[56], including a multipole PML method [57]. A Hertzian dipole was used as a point source, polarized in the x-direction, and excited with a waveform having the shape of the first derivative of Gaussian. The center frequency of this waveform was 900 MHz, and the main range was 200–2000 MHz. The source and the receiver (which stored the time histories of the electric and magnetic field components) were collocated in the center of the xy plane and at a height of $z = 0.85$ m from the base of the model. The geometrical model used for these FDTD simulations, shown in Fig. 2, consisted of two material layers: the upper material layer had a relative permittivity of 4 ($\epsilon_r = 4$) and an average thickness of 30 cm, and the lower layer had a relative permittivity of 10 ($\epsilon_r = 10$) and an average thickness of 20 cm. We used an electric conductivity of zero for the two layers in order to maximize scattering from the interfaces and, hence, to better compare both modeling approaches. Our medium is therefore nondispersive. A perfect electric conductor (PEC) layer was located at the base of the model in order to receive echoes that were transmitted through the second interface. Two interfaces were considered as potentially rough: the upper interface of the top material layer and the interface between the two material layers. Six different rms values of the surface heights were considered for both of them (i.e., $s_r = \{0; 0.005; 0.01; 0.015; 0.02; 0.025\}$ m), leading to 36 combinations of roughness conditions. A Gaussian spatial autocorrelation function with a spatial autocorrelation length of 0.15 m was used. This value was selected as a compromise between having a large enough autocorrelation length so that the surface has gentle slopes to remain in the validity domain of the extended SKA model (typically, rms slopes less than about 0.3), as the multiple reflections from the same interface and shadowing are not accounted for, and by keeping a problem of limited size to be efficiently computable. For each roughness condition, 50 Monte Carlo realizations were performed in order to emulate infinitely large surfaces.

A. Green's Functions From the FDTD Models

The electric field calculated in gprMax ($b(t)$) includes the direct transmission between the transmitter and receiver (R_i), as well as the convolution with the source signal ($a(t)$), t being the propagation time. In order to calculate the layered media Green's functions, which consider a unit source for each frequency, from gprMax and compare them to those provided by the proposed model, these two contributions need to be filtered out. As for real radar systems, the radar equation of Lambot *et al.* [43], [58] can be applied to FDTD simulated data. In the frequency domain, this equation is formulated as:

$$S_{11}(\omega) = \frac{B(\omega)}{A(\omega)} = R_i(\omega) + \frac{T(\omega)\, G_{xx}^{\uparrow}(\omega)}{1 - R_s(\omega)\, G_{xx}^{\uparrow}(\omega)} \tag{17}$$

where $S_{11}(\omega)$ is the ratio between the received electric field $B(\omega)$ and the electric source $A(\omega)$, ω being the angular frequency; $R_i(\omega)$ is the direct transmission between the transmitter and receiver (free-space response); $T(\omega) = T_i(\omega)T_s(\omega)$ where $T_i(\omega)$ is the antenna global transmission coefficient for incident fields and $T_s(\omega)$ is the antenna global transmission coefficient for scattered fields; $R_s(\omega)$ is the antenna global reflection coefficient for scattered fields; and $G_{xx}^{\uparrow}(\omega)$ is the planar layered medium Green's function.

For the FDTD simulations, Equation (17) can be rewritten as:

$$B(\omega) = A(\omega)R_i(\omega) + A(\omega)\frac{T(\omega)\, G_{xx}^{\uparrow}(\omega)}{1 - R_s(\omega)\, G_{xx}^{\uparrow}(\omega)} \tag{18}$$

Defining $H_i = A(\omega)R_i(\omega)$ and $H = A(\omega)T(\omega)$, then Equation (18) becomes:

$$B(\omega) = H_i(\omega) + \frac{H(\omega)\, G_{xx}^{\uparrow}(\omega)}{1 - R_s(\omega)\, G_{xx}^{\uparrow}(\omega)} \tag{19}$$

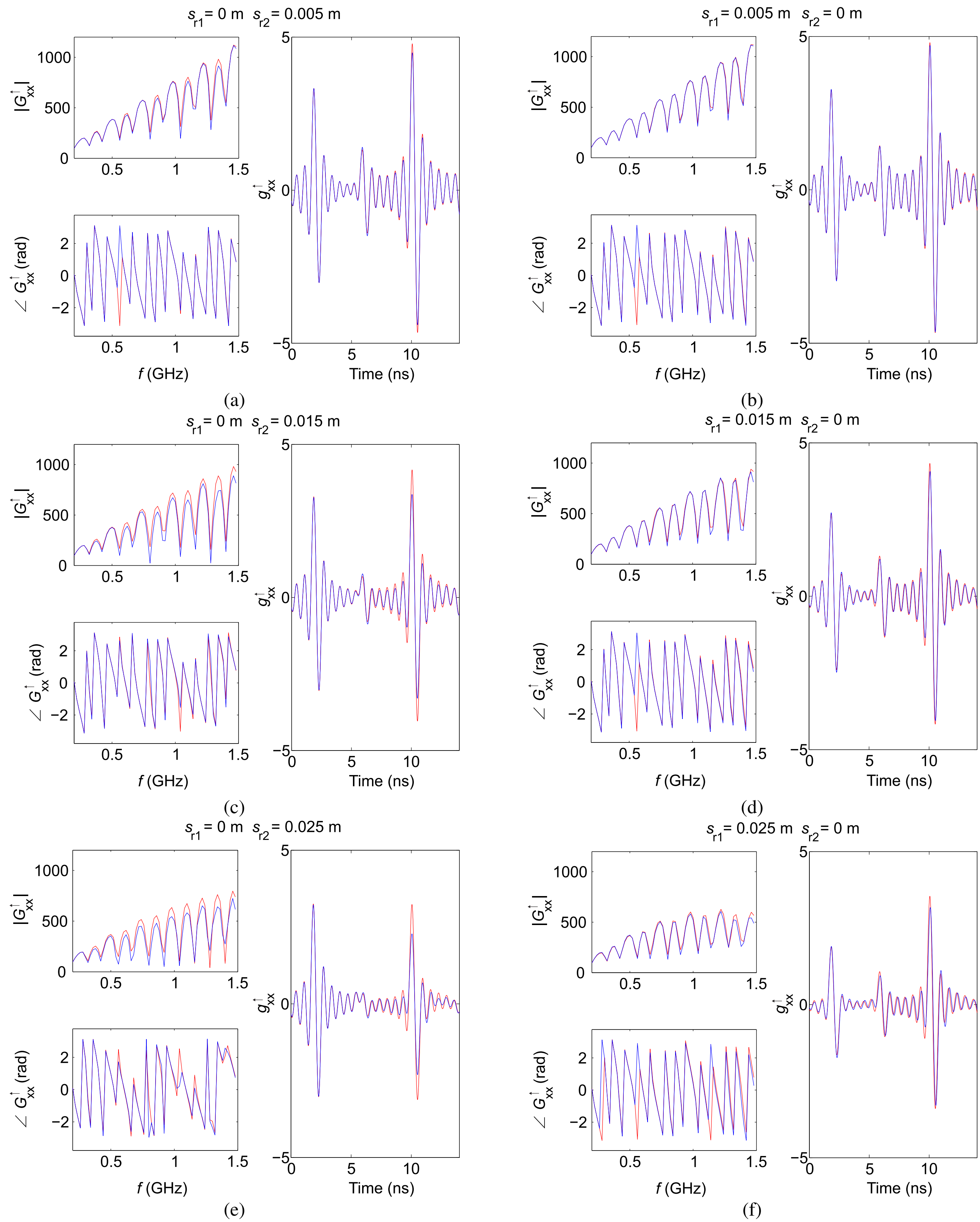

Fig. 4. Green's functions computed by our asymptotic extended SKA model (red curves) and the FDTD simulations (blue curves) in the frequency and time domains for rough interfaces with different rms values of the surface heights (s_{r1} and s_{r2}). (Left) Smooth top interface $s_{r1} = 0$. (Right) Smooth intermediate interface $s_{r2} = 0$. The relative dielectric permittivity of the top layer is 4, while the relative permittivity of the bottom layer is 10. The top layer has an average thickness of 30 cm, while the bottom layer has an average thickness of 20 cm.

As the receiver reduces to a field point in the FDTD simulations (i.e., there is no physical antenna in the models), $R_s(\omega) = 0$ and Equation (19) becomes:

$$B(\omega) = H_i(\omega) + H(\omega)\, G_{xx}^{\uparrow}(\omega) \tag{20}$$

which links the electric field calculated in the FDTD simulations to the Green's function defined above.

The virtual gprMax antenna functions H_i and H may be determined by solving a system of two equations for the two unknowns H_i and H. H_i is directly obtained from an FDTD simulation with free-space conditions in which $G_{xx}^{\uparrow}(\omega) = 0$. Once H_i is known, H can be calculated by solving Equation (19) for a known configuration (e.g., the source and receiver at some distance over an infinite PEC) for which $B(\omega)$ can be obtained from the FDTD simulation, and $G_{xx}^{\uparrow}(\omega)$ can be analytically calculated.

V. Inversion

The inverse problem consisted of finding the minimum of the following objective function (OF):

$$\phi(\mathbf{p}) = |\mathbf{G}_{xx}^{\uparrow *}(\omega) - \mathbf{G}_{xx}^{\uparrow}(\mathbf{p}, \omega)|^{T}\, |\mathbf{G}_{xx}^{\uparrow *}(\omega) - \mathbf{G}_{xx}^{\uparrow}(\mathbf{p}, \omega)| \tag{21}$$

where $\mathbf{G}_{xx}^{\uparrow *}$ is the Green's function obtained from the FDTD simulations, $\mathbf{G}_{xx}^{\uparrow}$ is the Green's function simulated with the extended SKA model, and $\mathbf{p}$ is the parameter vector to be estimated and is defined as $\mathbf{p} = [s_{r1}, s_{r2}]$. Optimization was performed using the multilevel coordinate search (MCS) algorithm [59].

VI. Results and Discussion

A. Green's Functions' Comparisons

Fig. 3 shows the Green's functions computed using the asymptotic extended SKA model and FDTD simulations (mean of 50 Monte Carlo simulations) in the frequency ($\mathbf{G}_{xx}^{\uparrow}(\omega)$) and time ($\mathbf{g}_{xx}^{\uparrow}(t)$) domains for the configuration with perfectly flat interfaces. Both the models naturally agree perfectly. Figs. 4 and 5 show the Green's functions computed using the asymptotic extended SKA model and FDTD simulations (mean of 50 Monte Carlo simulations) in the frequency ($\mathbf{G}_{xx}^{\uparrow}(\omega)$) and time ($\mathbf{g}_{xx}^{\uparrow}(t)$) domains for different interface roughness conditions. In the time domain, the reflection at the first interface is always very well reproduced by the extended SKA model for each roughness condition. The reflection at the second interface is also well reproduced. For the reflection at the PEC surface, the extended SKA model slightly overestimates the reflection, and this overestimation increases with the roughness amplitude. The overestimation also increases more significantly with an increase of the roughness amplitude at the second interface compared with an equivalent increase of the roughness amplitude at the first interface. In the frequency domain, the amplitude of the Green's function is also well reproduced by the extended SKA model for different roughness conditions on the first interface when the second interface is considered as flat. When applying roughness to the second interface, the extended SKA

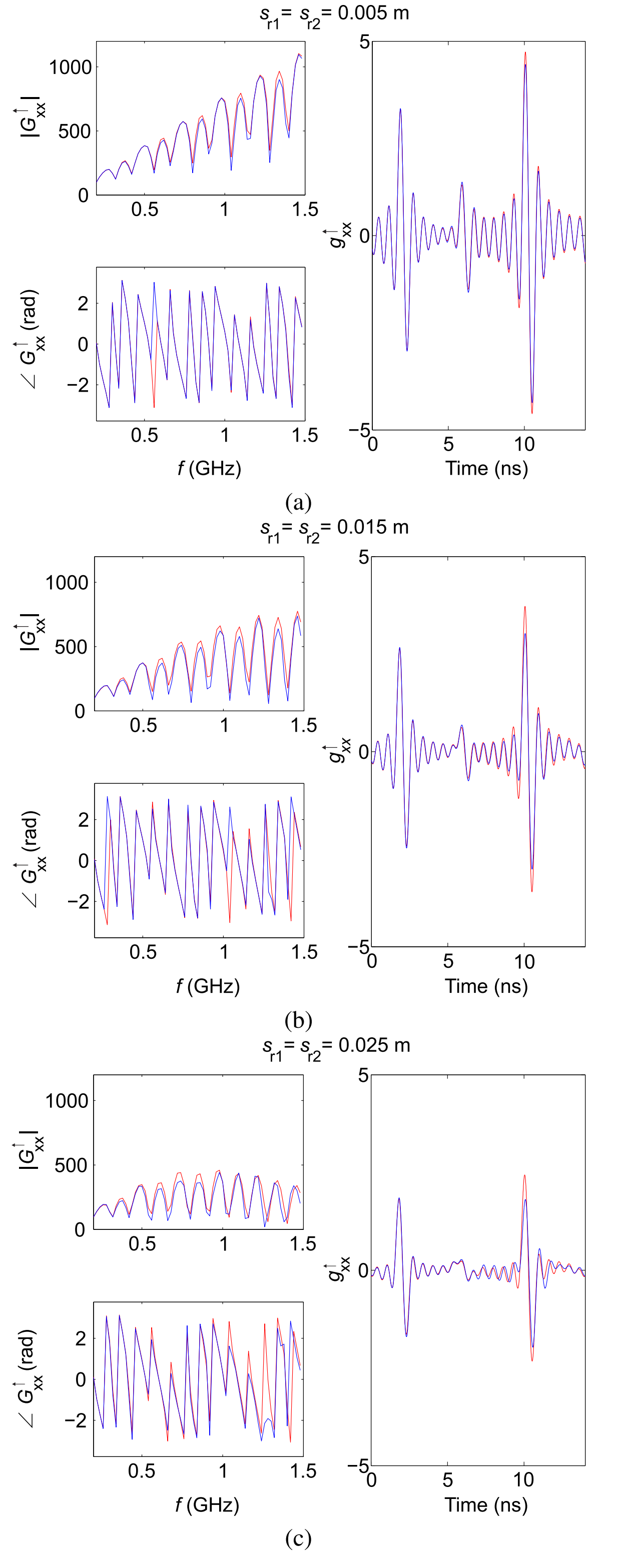

Fig. 5. Green's functions computed by our asymptotic extended SKA model (red curves) and the FDTD simulations (blue curves) in the frequency and time domains for rough interfaces with rms values of the surface heights (s_{r1} and s_{r2}) between 0.005 and 0.025 m. The relative dielectric permittivity of the top layer is 4, while the relative permittivity of the bottom layer is 10. The top layer has an average thickness of 30 cm, while the bottom layer has an average thickness of 20 cm.

model slightly overestimates the amplitude of the Green's function. This overestimation increases both with increasing

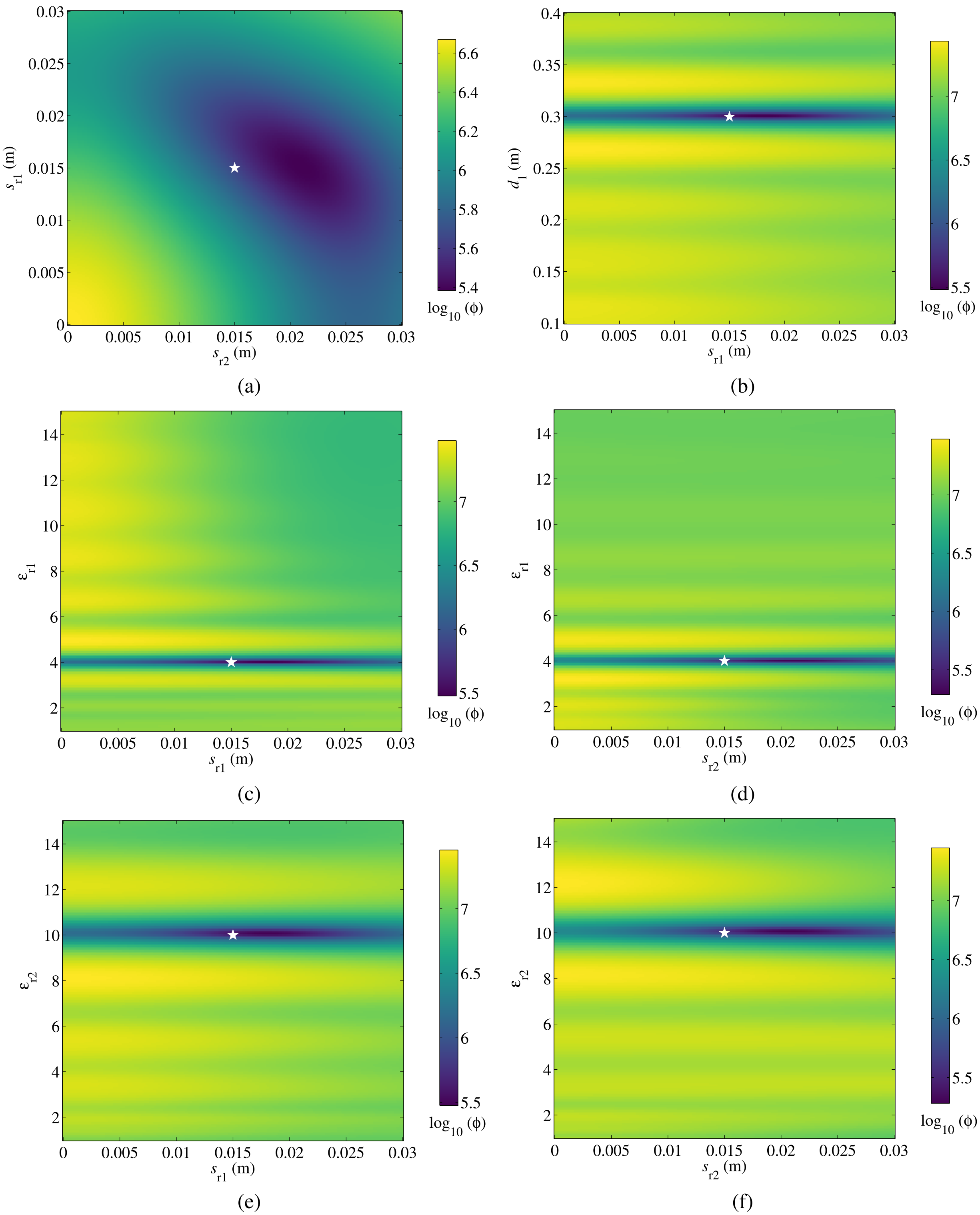

Fig. 6. Sections of the OF logarithm $\log_{10}(\phi(\mathbf{p}))$ for inversion of the roughness model in (a) $s_{r1} - s_{r2}$, (b) $d_1 - s_{r1}$, (c) $\epsilon_{r1} - s_{r1}$, (d) $\epsilon_{r1} - s_{r2}$, (e) $\epsilon_{r2} - s_{r1}$, and (f) $\epsilon_{r2} - s_{r2}$ parameter planes. The asterisk represents the true parameter values. Note that the color scale differs for each plot.

frequency and with increasing roughness amplitude. Finally, the Green's function phase in the frequency domain, and thereby the propagation time in the time domain, is systematically well described by the model, though some discrepancies with the FDTD simulation data appear as roughness increases.

B. Analysis of the Objective Function

Fig. 6 shows the sections of the logarithm of the OF (21) for five parameters, i.e., the rms of the surface heights of the first (s_{r1}) and second (s_{r2}) interfaces, the thickness of the first layer (d_1), and the relative dielectric permittivity of the first (ϵ_{r1}) and second (ϵ_{r2}) layers in six parameter planes $s_{r1} - s_{r2}$,

$d_1 - s_{r1}$, $\epsilon_{r1} - s_{r1}$, $\epsilon_{r1} - s_{r2}$, $\epsilon_{r2} - s_{r1}$, and $\epsilon_{r2} - s_{r2}$. The OF values were calculated using the FDTD simulation data (mean of 50 Monte Carlo simulations) obtained for rms height values of 0.015 m at both interfaces and by considering a relatively large parameter space ($0 < s_{ri} < 0.03$ m, $1 < \epsilon_{r1/2} < 15$, and $0.1 < d_1 < 0.4$ m), which contained the exact solutions. The range of each parameter was divided into 200 discrete values, resulting in 40 000 OF values for each section. In Fig. 6(a), the minimum of the OF is unique. The two roughness parameters do not appear to be significantly correlated, which is expected as the two layers are well separated in the time domain. In Fig. 6(b)–(f), local minima can be observed, while the global minimum always remains unique. The sensitivity of the roughness parameters is significantly smaller than that of the layer thickness and relative dielectric permittivity parameters. The reduced sensitivity with respect to the roughness parameters may lead to significant errors in their reconstruction, especially for real data which are inherently subject to errors that are expected to flatten the topography of the OF. The minimum of the OF corresponds well to the true values for the layer thickness and relative dielectric permittivity parameters, while it does not correspond exactly to the true parameter values for the roughness parameters, especially for s_{r2}. The errors in the estimation of s_{r2} are due to the differences between the extended SKA model and the FDTD simulation data, as noticed previously in Figs. 4 and 5.

C. Roughness Parameters' Inversion

Fig. 7 shows the inverted rms of the surface heights of the two interfaces (s_{r1} and s_{r2}) compared with the rms values used as the input for the 50 FDTD Monte Carlo simulations. Good agreement was obtained between the FDTD simulation input values and the inverted s_{r1} estimates, except for the specific case of a flat top interface ($s_{r1} = 0$) and a rough lower interface ($s_{r2} > 0$). Inverted s_{r2} data slightly overestimate the FDTD simulation input values and the overestimation continuously increases with increasing s_{r2}. These results demonstrate the consistency of the extended SKA model. Nevertheless, we observe the increasing errors for s_{r2} as roughness increases. This is to be attributed to the overestimation by the asymptotic model of the amplitude of the third reflection [see Figs. 4(a), (c), and (e) and 5]. Hence, the asymptotic model underestimates the scattering and, therefore, inverted roughness values of the second interface are overestimated to compensate for this underestimation.

VII. Conclusion

A closed-form asymptotic EM model considering random rough layers was combined with planar multilayered media Green's functions in order to invert radar signals for noninvasive quantification of medium properties. The validation of this extended SKA model was performed using a numerical approach based on the FDTD method. The FDTD simulations were carried out using the gprMax software to model the EM wave propagation in a multilayered medium composed of two layers above a PEC. Two interfaces, i.e., the surface of the top layer and the interface between the two layers,

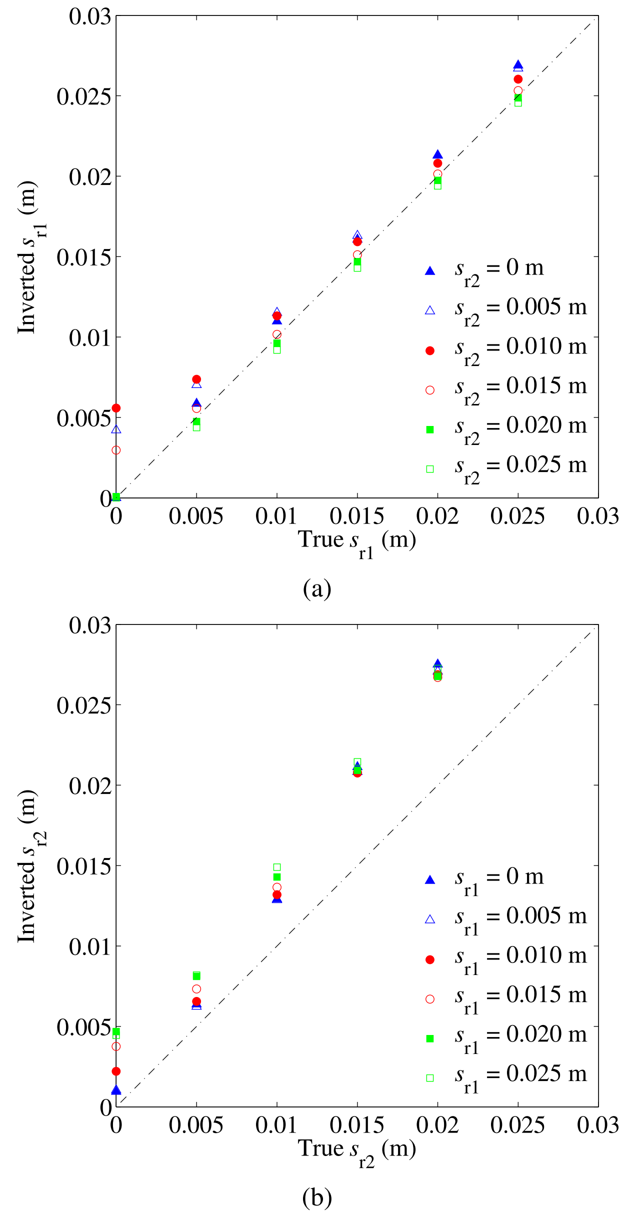

Fig. 7. Comparison of the true (i.e., s_r values used to generate the 50 Monte Carlo FDTD simulations) and inversely estimated rms of the surface heights of (a) first interface and (b) second interface.

were considered as rough with rms of the surface heights ranging from 0 to 0.025 m. The validation was performed by comparing the Green's functions derived from the asymptotic model and the ones derived from the numerical simulations. In order to calculate the layered media Green's functions from the FDTD simulations, the direct transmission between the transmitter and the receiver as well as the source signal were filtered out from the electric field values obtained by gprMax.

The results show that, in the time domain, the reflection at the first interface is always very well reproduced by the extended SKA model for each roughness condition, as well as the reflection at the second interface. In contrast, the extended SKA model slightly overestimates the reflection at the PEC surface and this overestimation increases with the roughness amplitude. In the frequency domain, the amplitude of the Green's function is also well reproduced by the extended SKA model for different roughness conditions on the first interface while considering the second interface as flat. For roughness conditions at the second interface, the extended SKA model slightly overestimates the amplitude of the Green's function, and this overestimation increases with increasing frequency and with increasing roughness amplitude. Good agreement is also obtained between the FDTD simulation input values and the inverted rms height values of the top interface, while the inverted rms height values of the second interface are slightly overestimated. This is to be attributed to the overestimation by the asymptotic model of the amplitude of the reflection on the PEC due to an underestimation of the scattering at the second interface. It has to be noted that the proposed model has been validated for roughness amplitudes (rms heights) up to $\lambda/4$ and surface slopes (rms slopes) up to 0.24, where λ is the smallest wavelength associated with the highest frequency $f =$ 1.5 GHz considered in this paper and the relative dielectric permittivity $\epsilon_r = 4$ of the layer above the second (inner) rough interface. These results demonstrate the consistency of the extended SKA model and the promising perspectives for rough multilayered media reconstruction using full-wave inversion of radar data.

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