

Analysis of Low-Frequency Drone-Borne GPR for Root-Zone Soil Electrical Conductivity Characterization

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Abstract—In this study, we analyzed low-frequency drone-borne ground-penetrating radar (GPR) and full-wave inversion for soil electrical conductivity mapping. Indeed, in the lowest GPR frequency ranges, the soil surface reflexion coefficient depends more on the soil electrical conductivity than on its permittivity. Numerical experiments were conducted within the frequency range 15–45 MHz to analyze parameter sensitivities, the well-posedness of the inverse problem as well as the depth of sensitivity. The results show that the soil surface reflexion is significantly more sensitive to the soil electrical conductivity than the soil permittivity. Therefore, the conductivity can be retrieved using full-wave inversion within this frequency range, with a characterization depth varying from 0.5 to 1 m, depending on the soil properties. Yet, the permittivity also affects the results and should be accounted for in the inversion strategy. Field measurements were performed using low-frequency drone-borne radar with a 5-m half-wave dipole antenna, and electromagnetic induction (EMI) measurements with different depth sensitivities were conducted for comparison. Kriging interpolation was used to get maps from measurement points. The soil conductivity maps obtained by the proposed GPR and EMI are compliant in terms of absolute values and spatial patterns. This study demonstrated the capacity of low-frequency drone-borne GPR for fast, field-scale soil electrical conductivity mapping.

Index Terms—Dielectric permittivity, digital soil mapping, drone, electrical conductivity, ground-penetrating radar (GPR).

I. INTRODUCTION

GROUND-PENETRATING radar (GPR) has been proven to be a promising tool for agriculture, civil engineering, geological exploration, etc. [1], [2], [3]. In recent years, an increasing amount of researchers have focused on using GPR on drones for higher efficiency or conducting measurements in tough environments. Drone-borne GPR was used for glacier or snow cover areas investigation [4], [5], [6], for underground detection and imaging [7], [8], and for soil moisture mapping [9], etc.

The soil electromagnetic (EM) properties can be remotely retrieved using geophysical methods and do contain useful information for agriculture, land-use management, environmental science, etc. Soil moisture can be directly related to the

soil dielectric permittivity through petrophysical relationships such as Topp's and Ledieu's models [10], [11]. Existing techniques for soil moisture measurement are the gravimetric method, time-domain reflectometry (TDR), capacitance probes and impedance sensors for small scales [12], [13], GPR for field scales with high-resolution and high-efficiency [14], [15], [16], and space-borne passive and active radar systems for large scales [17], [18], [19], [20]. The application of GPR for soil moisture measurement is reviewed by Klotzsche *et al.* [21] and Zajíčová and Chuman [22]. Lambot *et al.* [23] and Lambot and André [24] introduced the radar equation accounting for the antenna effects, including antenna-medium interactions in both far-field and near-field conditions, for full-wave modeling and inversion of the radar signal. It has been demonstrated to be an effective approach to map soil moisture [15].

In addition, soil electrical conductivity is also important in soil surveys since it depends on the soil texture, clay content, soil moisture, salinity, etc. It is usually measured by electrical resistivity tomography (ERT) or EM induction (EMI) [25], [26], [27], [28], [29], [30]. Yet, ERT needs electrodes in contact with the soil while EMI, for root-zone characterization, needs the coils to be in the vicinity of the soil surface, i.e., at a few cm or dm distance. Airborne EMI configurations do exist, but they provide sensitivity depths that are then much larger than the root zone and are more dedicated to geological exploration [31], [32], [33]. For agricultural applications, there would be benefits to characterize soil electrical conductivity of the root zone using drone-borne configurations, e.g., at a few meters distance from the soil surface. In that respect, GPR operating in its lower frequency ranges, or so-called intermediate frequencies, appears to be a solution.

Parameter sensitivity analysis is important since it determines if it is possible to measure the parameter of interest by specific techniques. For instance, in the EMI frequencies, e.g., typically 1–100 kHz, the measurements are sensitive to the soil electrical conductivity and magnetic permeability, but the effect of permittivity is negligible. For the lightning response of grounding electrodes, Visacro and Alipio [34] presented the variation of soil resistivity and relative permittivity in relation to a frequency ranging from 100 Hz to 4 MHz, so that the impulsive response of electrodes would not be affected by the relative permittivity of soil when the frequency is below 10 kHz. Likewise, Salvador *et al.* [35] showed that the sensitivity of soil conductivity starts to decrease at around 10 MHz. The difference in sensitivity

Manuscript received 12 May 2022; revised 8 July 2022; accepted 7 August 2022. Date of publication 11 August 2022; date of current version 31 August 2022. This work was supported in part by the Politique Scientifique Fédérale (BELSPO), Belgium in the frame of the Research Program for Earth Observation STEREO III, RAPAS project under Grant SR/00/238 and in part by the Fonds de la Recherche Scientifique (FNRS), Belgium. (Corresponding author: Kaijun Wu.)

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ties is also found in GPR applications. Meles *et al.* [36] analyzed a single crosshole transmitter–receiver pair using around 200-MHz Ricker wavelet and showed the sensitivity of permittivity is much larger than of conductivity. Di Matteo *et al.* [37] and Algeo *et al.* [38] observed that the early-time GPR signal was more affected by soil permittivity variations than by conductivity, considering a Gaussian pulse with a center frequency of 250 MHz. When focusing full-wave inversion on the surface reflexion only, it was proven that the apparent electrical conductivity can be neglected when it is less than 100 mS/m with the operating frequency higher than 100 MHz [39], making it possible to measure the soil dielectric permittivity with high frequencies without having to take into account electrical conductivity effects. Similarly, focusing on the surface reflexion of a two-layered medium, 800–2600-MHz GPR and inversion were applied by Moghadas *et al.* [40], and they found a better sensitivity to the relative permittivity than to the conductivity from the response surface of the objective functions. On the contrary, the sensitivities of these two parameters were the opposite for EMI data, whose operating frequency range was 1–50 kHz.

In this article, we analyzed the low-frequency drone-borne GPR and full-wave inversion for soil EM properties mapping, namely, the soil relative dielectric permittivity and electrical conductivity. First, we discussed the parameter sensitivity by presenting the transverse electric (TE) mode reflexion coefficient as a function of the permittivity and conductivity for different frequencies. Second, focusing on the frequency range 15–45 MHz, we conducted numerical experiments to further investigate the sensitivity of the surface reflexion to permittivity and conductivity. Based on the full-wave inversion method and objective function plots, we analyzed: 1) the main hypotheses for full-wave inversion; 2) the effect of the permittivity and flying height; and 3) the effect of the multilayered medium, hereby to investigate the characterization depth. Finally, field measurements were conducted in a bare agricultural field. A 5-m half-wave dipole was mounted on a drone to provide the low operating frequency range 15–45 MHz. For data processing, the radar equation of Lambot *et al.* [23] and Lambot and André [24] was used to get rid of the antenna effects, and the full-wave inversion was applied according to the discussions from the numerical experiments. For comparison, EMI maps with different depth sensitivities were provided as well for the same site.

II. METHODOLOGY

A. Plane Wave Reflexion Coefficient

In order to provide fundamental insights into the sensitivity of the surface reflexion to the medium permittivity and conductivity in the low GPR frequency range, the parameter sensitivity in the frequency range of interest, we plotted the reflexion coefficient at the air-medium interface as a function of the relative permittivity and electrical conductivity. For air-launched GPR, the reflexion coefficient at the soil surface describes how much energy is reflected when an EM wave reaches the air–soil interface. The reflected wave, especially

its amplitude, is affected by the EM properties of the medium. In addition, wave frequency is also a factor to be taken into account. In the first fundamental analysis, we consider that: 1) the EM wave is seen as a plane wave; 2) the magnetic permeability is equal to the magnetic permeability of free space μ_0 ($\mu_0 = 4\pi \cdot 10^{-7}$ H/m); and 3) dielectric permittivity and electrical conductivity are frequency-independent [41], [42]. The local-plane wave TE mode reflexion coefficient at the soil interface is therefore expressed as [43]

$$R = \frac{\gamma_0 - \gamma_1}{\gamma_0 + \gamma_1} \quad (1)$$

where γ is the propagation constant, with subscript 0 and 1 representing the air and the soil, respectively. The propagation constant γ is defined as [43]

$$\gamma = \sqrt{-\omega^2 \mu \left(\varepsilon - j \frac{\sigma}{\omega} \right)} \quad (2)$$

with $j = \sqrt{-1}$. ω is the angular frequency. In the propagation constant γ_1 of the soil (or the medium), μ is the soil magnetic permeability, and $\mu = \mu_0$ is assumed. ε is the permittivity (F/m), and $\varepsilon = \varepsilon_0 \varepsilon_r$, where ε_0 is the free space permittivity ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m). ε_r is the soil relative permittivity. σ is the soil electrical conductivity (S/m).

B. Radar Equation and Full-Wave Modeling

The radar equation describes the radar measurements, and particularly accounts for the antennas, and inherently, interactions between the antennas and the medium as well as 3-D wave propagation in multilayered media. The radar equation in the far-field condition is expressed in the frequency domain as [23], [24]

$$S_{11}(\omega) = H_i(\omega) + \frac{H(\omega)G_{xx}(\omega)}{1 - G_{xx}(\omega)H_f(\omega)} \quad (3)$$

where $S_{11}(\omega)$ is measured by a vector network analyzer (VNA) $H_i(\omega)$ is the global reflexion coefficient of the antenna for fields incident from the radar reference plane onto the source point. $H_i(\omega) = S_{11}(\omega)$ in free space conditions where $G_{xx}(\omega) = 0$. $H_f(\omega)$ is the global reflexion coefficient of the antenna for fields incident from the antenna phase center (backscattered field) onto the radar reference plane. $H(\omega)$ is the antenna transmitting-receiving response function.

The Green's function $G_{xx}(\omega)$ we use in this study is the solution of Maxwell's equations for EM waves propagating in planar multilayered media [23], [44], [45]. It is defined as the x -directed electric field at a field point for a unit-strength x -directed electric source at a source point at the same location. The spatial domain Green's function is defined as [23], [45]

$$G_{xx} = \frac{1}{4\pi} \int_0^{+\infty} \tilde{G}_{xx} dk_\rho \quad (4)$$

where k_ρ is the spectral domain variable. The spectral-domain Green's function $\tilde{G}_{xx}$ is computed as

$$\tilde{G}_{xx} = \left(\frac{\Gamma_n R_n^{\text{TM}}}{\sigma_n + j\omega\varepsilon_n} - \frac{j\omega\mu_n R_n^{\text{TE}}}{\Gamma_n} \right) e^{-2\Gamma_n h_n} \quad (5)$$

where $j = \sqrt{-1}$. The subscript n denotes the n th interface or layer ($n = 0, \dots, N - 1$). Dielectric permittivity $\varepsilon_n = \varepsilon_{r,n}\varepsilon_0$, where $\varepsilon_{r,n}$ is the relative dielectric permittivity of the n th layer. μ_n is the magnetic permeability and σ_n is the electrical conductivity. h_n is the layer thickness, or the distance between the first interface and the source/receiver point (antenna phase center) when $n = 0$. Γ_n is the vertical wavenumber defined as

$$\Gamma_n = \sqrt{k_\rho^2 - \omega^2 \mu_n \left(\varepsilon_n - j \frac{\sigma_n}{\omega} \right)} \quad (6)$$

where R_n^{TM} and R_n^{TE} are the global transverse magnetic (TM)-mode and TE-mode reflexion coefficients at interface n , which are defined as, respectively,

$$R_n^{\text{TM}} = \frac{r_n^{\text{TM}} + R_{n+1}^{\text{TM}} e^{-2\Gamma_{n+1}h_{n+1}}}{1 + r_n^{\text{TM}} R_{n+1}^{\text{TM}} e^{-2\Gamma_{n+1}h_{n+1}}} \quad (7)$$

$$R_n^{\text{TE}} = \frac{r_n^{\text{TE}} + R_{n+1}^{\text{TE}} e^{-2\Gamma_{n+1}h_{n+1}}}{1 + r_n^{\text{TE}} R_{n+1}^{\text{TE}} e^{-2\Gamma_{n+1}h_{n+1}}} \quad (8)$$

$$r_n^{\text{TM}} = \frac{(\sigma_{n+1} + j\omega\varepsilon_{n+1})\Gamma_n - (\sigma_n + j\omega\varepsilon_n)\Gamma_{n+1}}{(\sigma_{n+1} + j\omega\varepsilon_{n+1})\Gamma_n + (\sigma_n + j\omega\varepsilon_n)\Gamma_{n+1}} \quad (9)$$

$$r_n^{\text{TE}} = \frac{\mu_{n+1}\Gamma_n - \mu_n\Gamma_{n+1}}{\mu_{n+1}\Gamma_n + \mu_n\Gamma_{n+1}} \quad (10)$$

where r_n^{TM} and r_n^{TE} denote the local plane wave TM- and TE-mode reflexion coefficients. These expressions are in a recursive form, and the recursion is initiated by the observation that there are no up-going waves from the lower half-space. Therefore when $n = 0$, R_0^{TM} and R_0^{TE} are the TM and TE global reflexion coefficients including all reflexions and multiples from all multilayered interfaces, $R_{N-1}^{\text{TM}} = r_{N-1}^{\text{TM}}$ and $R_{N-1}^{\text{TE}} = r_{N-1}^{\text{TE}}$.

Antenna characteristic functions are obtained by antenna calibration through several measurements over a known reference plane, e.g., a copper plane, and solving a matrix equation from the radar equation expressed in (3) [23]. In this study, given the relatively low-frequency range, a lake is used as a relatively large surface, which is needed as the calibrating reflector, assumed as infinite in the Green's function model (4). The lake is chosen deep enough to assume a half-space medium and the water EM properties are calculated using the model of Debye [46] with the parameterizations of Lane and Saxton [47] and Klein and Swift [48] for temperature effects, e.g., as by Tran *et al.* [49].

C. Full-Wave Inversion

The medium EM properties are retrieved from the measured radar signal S_{11} using full-wave inversion. First, the measured Green's function is calculated from the radar signal using the radar equation (3) as

$$G_{xx}^*(\omega) = \frac{S_{11}(\omega) - H_i(\omega)}{H(\omega) + S_{11}(\omega)H_f(\omega) - H_i(\omega)H_f(\omega)}. \quad (11)$$

Then the Green's function is transformed into the time domain as $\mathbf{g}_{xx}^*(t)$ (where t denotes the time) in order to select the part of the signal that does correspond to the surface reflexion only. Hence, later reflexions from deeper interfaces are ignored,

thereby reducing the model configuration to a half-space medium.

The inverse problem is formulated in the least-squares sense and the objective function to minimize is expressed as [15], [39]

$$\phi(\mathbf{b}) = (\mathbf{g}_{xx}^*(t) - \mathbf{g}_{xx}(\mathbf{b}, t))^T (\mathbf{g}_{xx}^*(t) - \mathbf{g}_{xx}(\mathbf{b}, t)) \quad (12)$$

in which $\mathbf{g}_{xx}^*(t)$ is also the synthetic Green's function vector in the numerical experiment. $\mathbf{g}_{xx}(\mathbf{b}, t)$ is the modeled Green's function with $\mathbf{b}$ being the parameter vector defined for the inverse model $\mathbf{b} = [h, \varepsilon_r, \sigma]$. The definition of the parameter vector $\mathbf{b}$ for the lookup table (LUT) is explained in Sections IV and V for specific analysis or experiment. An LUT, containing all the modeled Green's functions for all model parameter combinations, is used for robust and fast inversion. Indeed, in that case, the objective function is calculated in the full parameter space and the global minimum is directly obtained, without having to resort to an optimization algorithm. The LUT is a collection of calculated Green's functions, as defined $G_{xx}(\omega)$ in (4) [23], for a given model parameter space. It represents the modeled signals that are compared to the radar measurements during inversion. The retrieved parameters are then those which provide the best agreement, in the least-squares sense, between the corresponding signal in the LUT and the measured Green's functions.

The measured and modeled Green's functions are originally obtained in the frequency domain as $G_{xx}^*(\omega)$ and $G_{xx}(\mathbf{b}, \omega)$, respectively. The inverse Fourier transform is used to transform data into the time domain as $\mathbf{g}_{xx}^*(t)$ and $\mathbf{g}_{xx}(\mathbf{b}, t)$, respectively.

III. SENSITIVITY ANALYSIS

We plotted the reflexion coefficient (1) as a function of the relative dielectric permittivity ε_r and electrical conductivity σ for the three different frequencies, namely, 5, 30, and 500 MHz, to represent the parameter sensitivity. Note that the local-plane wave in the TM mode presents the same results, so we only consider it in the TE mode in this article.

Fig. 1 shows the amplitude of the reflexion coefficient at 5, 30, and 500 MHz as a function of ε_r and σ . We observe that the sensitivity of the reflexion coefficient depends on the frequency as well as on the medium properties. Specifically, the maximum amplitude of the reflexion coefficient is the highest at 5 MHz (around 0.92) and the lowest is at 500 MHz (around 0.67). At 5 MHz, the coefficient does not change significantly with respect to ε_r . On the contrary, at 500 MHz, it does not change with respect to σ . However, at 30 MHz, the coefficient varies as a function of both ε_r and σ , and it changes with a higher sensitivity with respect to σ . When $\sigma = 0$, the curves of the reflexion coefficient amplitude with respect to ε_r are the same for the three frequencies.

Following (1) and (2), the sensitivity of the reflexion coefficient with respect to electrical conductivity increases with decreasing frequency while the sensitivity of the reflexion coefficient with respect to the relative dielectric permittivity increases with increasing frequency. Besides, when $\sigma = 0$, the reflexion coefficient is a function of the relative permittivity

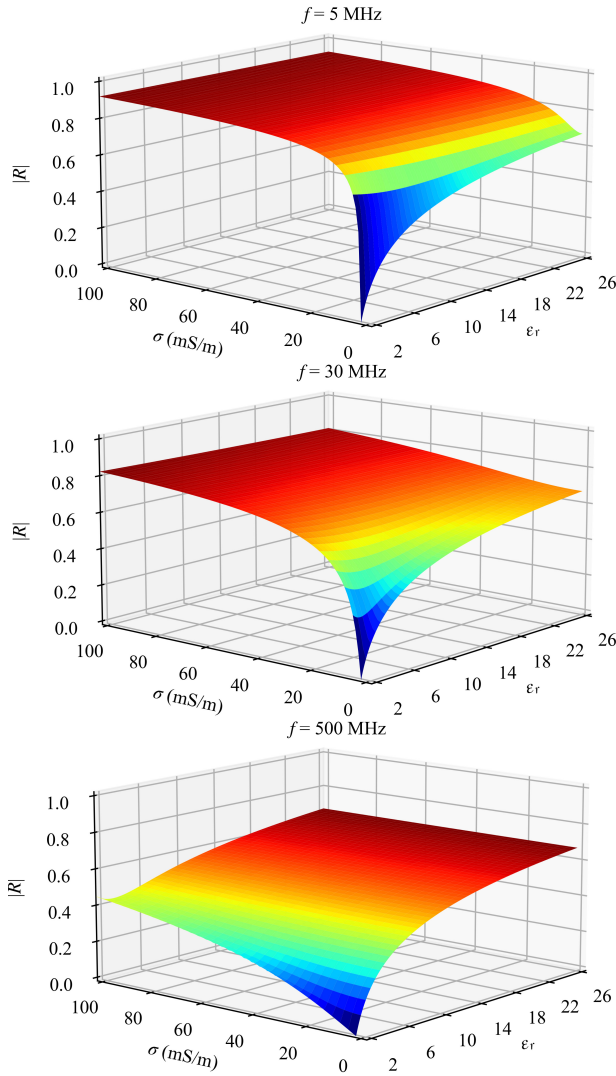


Fig. 1. Plane wave reflexion coefficient at the air-medium interface as a function of the relative permittivity and electrical conductivity for three different frequencies.

only, and it does not change with the frequency (assuming that the permittivity does not depend on frequency in that range), e.g., for most of the GPRs, $R = (\sqrt{\epsilon_0} - \sqrt{\epsilon_1})/(\sqrt{\epsilon_0} + \sqrt{\epsilon_1})$, where subscripts 0 and 1 denote air and the soil, respectively. However, when $\sigma \neq 0$, the reflexion coefficient is a complex number.

In conclusion, the reflexion coefficient at the air-medium interface fundamentally depends on the dielectric permittivity, electrical conductivity, and magnetic permeability of the medium. The lower the frequency, the larger the sensitivity to the electrical conductivity. The higher the frequency, the larger the sensitivity to the permittivity. It originates from the frequency term in the propagation constant γ as in (2). In the kHz ranges, where the so-called EMI instruments operate, the sensitivity of the reflexion coefficient to the electrical conductivity is high and the sensitivity to the dielectric permittivity is negligible. In the frequencies larger than about 300 MHz (where most GPRs and radar remote sensing instruments operate), that is the contrary, the sensitivity of the reflexion coefficient to permittivity is dominating while

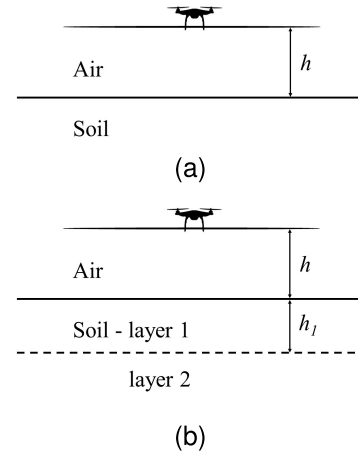


Fig. 2. Model configurations for the numerical experiments. h is the distance between the source/receiver and the soil surface. (a) Source and receiver above a lossless dielectric half-space, i.e., the soil, with the distance h , for configurations i and ii. (b) Source and receiver above a two-layered medium with varying layer thicknesses h_1 , for configuration iii.

the sensitivity to electrical conductivity is negligible. In the intermediate frequencies (e.g., 1–300 MHz), both parameters affect the reflexion coefficient, with a continuously increasing effect of permittivity with increasing frequency and vice-versa for electrical conductivity. Therefore, we conducted numerical analyses to further investigate the parameter sensitivity and the effects on full-wave inversion.

IV. NUMERICAL EXPERIMENTS

The aim of the numerical experiments is to further investigate the parameter sensitivity based on the full-wave inversion and its objective function within the frequency range 15–45 MHz, hereby to find out the critical hypotheses, on which the full-wave inversion relies. The parameters to be analyzed are the relative dielectric permittivity ϵ_r , electrical conductivity σ and distance h between the antenna phase center and the medium surface. We also analyzed how medium layering affects the retrieval of the soil properties in order to find out the depth of sensitivity.

Specifically, for inversion, the soil is seen as a semi-infinite homogeneous medium. Three simulation model configurations were considered in this study, referring to one- and two-layered media, respectively (see Fig. 2). Configuration i consists of a lossless half-space, corresponding to the basic model used for the inversion (no modeling errors). This configuration is to investigate the uniqueness and stability of the full-wave inverse solution in the 15–45-MHz frequency range. We analyzed two parameters each time, resulting in objective functions in the 2-D parameter planes $\epsilon_r - h$, $\sigma - h$ and $\sigma - \epsilon_r$, respectively. The third parameter stays the same for each parameter plane in the simulation and the inverse model. In configuration ii we analyzed how the differences in h , thereby representing a modeling error, affect the estimation of σ and ϵ_r , respectively. The differences in h here mean the differences between h defined in the simulation and in the inverse model, hereby to investigate the resolution needed for the LUT h vector. Configuration iii is a source over a two-layered medium

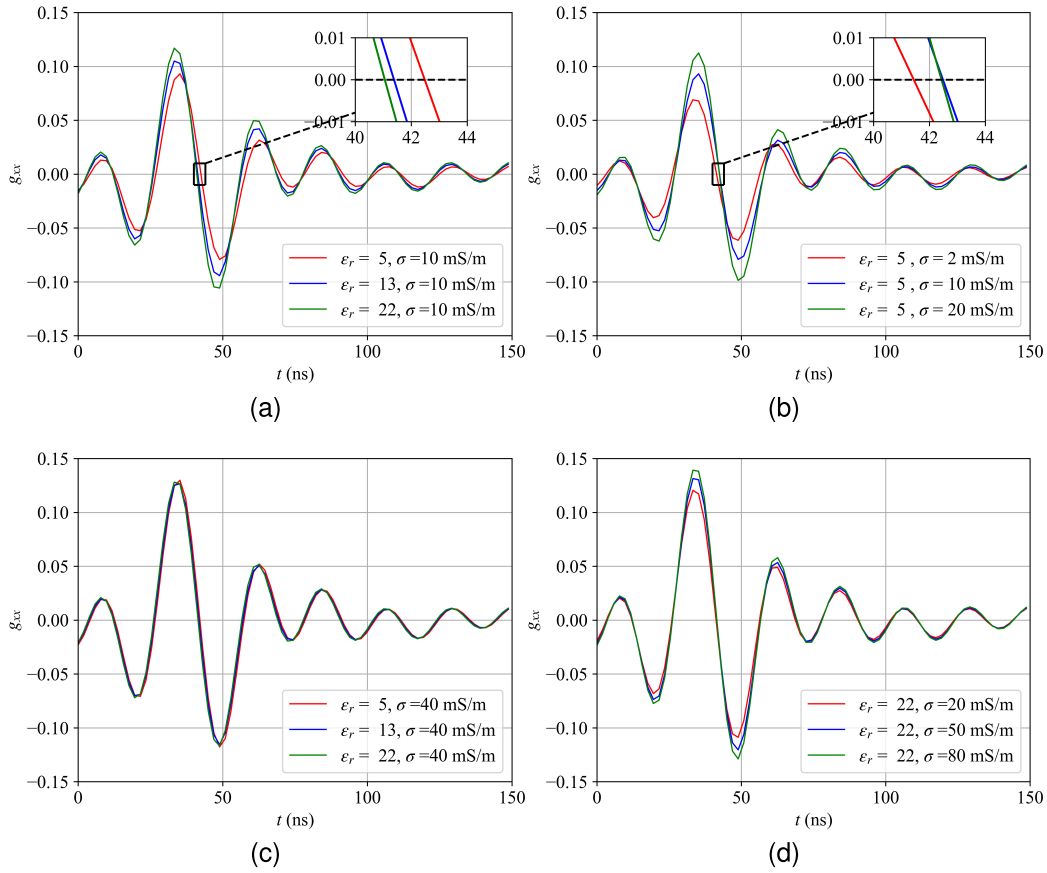


Fig. 3. Synthetic Green's functions in the time domain, generated for the source over a half-space medium (configuration i). The legend in each figure denotes the property of the medium. The antenna height $h = 6$ m.

with varying layer thickness, in order to estimate the depth of sensitivity of the surface reflexion (see Fig. 2). In this configuration, only one parameter (ϵ_r or σ) is considered each time, namely, there is only one unknown in the inverse model, hereby to find out the characterization depth for a specific EM property. Different LUTs were used for the different model configurations.

A. Configuration i: Source Over a Homogeneous Dielectric Half-Space

In this configuration, there is a transmitting source and receiver over a dielectric half-space. First, we present the synthetic Green's functions in the time domain with $h = 6$ m in Fig. 3. Normally, when h remains the same, the amplitude of g_{xx} increases with the increase of σ and ϵ_r . From Fig. 3(d), we observe that even when ϵ_r is extremely high (i.e., $\epsilon_r = 22$), the amplitude of g_{xx} still increases with σ increasing. However, the amplitude of g_{xx} does not change with ϵ_r when σ is 40 mS/m [see Fig. 3(c)]. In addition, we observe the reflexion delays in both Fig. 3(a) and (b). The delay is more significant when ϵ_r is low (e.g., $\epsilon_r = 5$). This is because when σ is not equal to 0, the reflexion coefficient is a complex number according to (1) and (6) in this frequency range. For instance, when $\epsilon_r = 5$, and $\sigma = 2, 10$, and 20 mS/m, respectively, the phase of reflexion coefficients are 0° , 161° , and 166° at the frequency 30 MHz. This results in a slight delay in the reflexion. Therefore, within this frequency range,

the sensitivity of the reflexion to the electrical conductivity σ is higher than to the relative permittivity ϵ_r .

Figs. 4 and 5 presents the 15–45-MHz response surfaces of the objective function in the $\sigma - h$ and $\epsilon_r - h$ parameter planes. The parameter vector $\mathbf{b}$ in (12) is defined as $[\sigma, \mathbf{h}]$ and $[\epsilon_r, \mathbf{h}]$, respectively. Each subcaption presents the values defined in the simulation model, and the third parameter stays the same in the simulation and the inverse model. For instance, in parameter planes of $\sigma - h$ as shown in Fig. 4(a), (c), and (e), ϵ_r is defined as 13 in both simulation and inverse models. Parameters being analyzed are divided into 101 discrete values resulting in 10201 objective function calculations, as well as 101×101 LUTs for each plane.

In the $\sigma - h$ plane, we observe that the minimum of the objective function is unique. The minimum region of the objective function with respect to σ extends when σ and h increase. However, in the $\epsilon_r - h$ plane, the minimum of the objective function is also unique except for Fig. 4(b), where ϵ_r is relatively small, for which two minima are observed (one local and one global). Besides, for both $\sigma - h$ and $\epsilon_r - h$ planes, the minimum regions are relatively perpendicular to the h -axis when σ or ϵ_r is high. The minimum region bends to a larger h direction in the $\sigma - h$ plane in Fig. 4(a). On the contrary, it bends to a smaller h direction in the $\epsilon_r - h$ plane in Fig. 4(b). There is no bending when the third parameter, namely, ϵ_r for $\sigma - h$ and σ for $\epsilon_r - h$, are high (see Fig. 5). This phenomenon is more obvious in the $\epsilon_r - h$ plane than

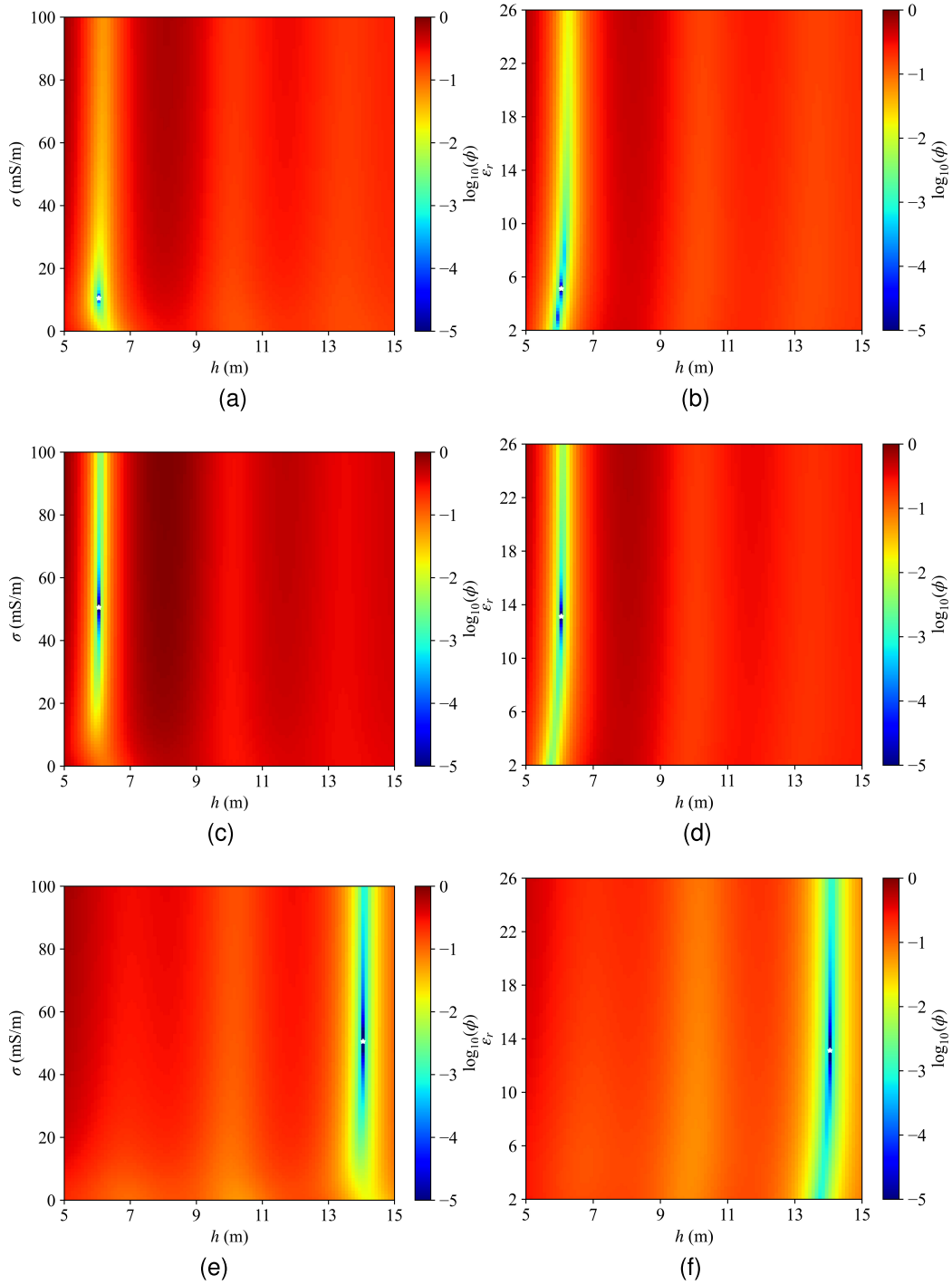


Fig. 4. 15–45-MHz response surface of the objective function logarithm $\log_{10}(\phi)$ in parameter planes of $\sigma - h$ (a), (c), and (e) with $\epsilon_r = 5$ in both simulation and inverse models, and of $\epsilon_r - h$ (b), (d), and (f) with $\sigma = 10$ mS/m in both simulation and inverse models. White stars represent the true parameter values defined in simulation models. The subcaptions present the simulation models setting (true value). (a) $\sigma = 10$ mS/m, $h = 6$ m. (b) $\epsilon_r = 5$, $h = 6$ m. (c) $\sigma = 50$ mS/m, $h = 6$ m. (d) $\epsilon_r = 13$, $h = 6$ m. (e) $\sigma = 50$ mS/m, $h = 14$ m. (f) $\epsilon_r = 13$, $h = 14$ m.

in the $\sigma - h$ plane, which also leads to the two minima in Fig. 4(b). It is explained by the reflexion delay observed in Fig. 3(a) and (b). The delays are relatively small for varying σ , so there is only bending of the minimum region in Fig. 4(a). But when ϵ_r is small, the uniqueness of the solution in the $\epsilon_r - h$ plane is affected. In conclusion, the distance between the antenna phase center and the medium interface h is always

the most sensitive parameter. The lower the flying height, the stronger the surface reflexion.

Fig. 6 shows objective functions in the $\sigma - \epsilon_r$ plane. Overall, only one minimum is observed in each plot, and all the global minima are shaped ellipse with its minor axis being parallel with the σ -axis. The black curves are flatter than the white, indicating a poor sensitivity of the objective function with

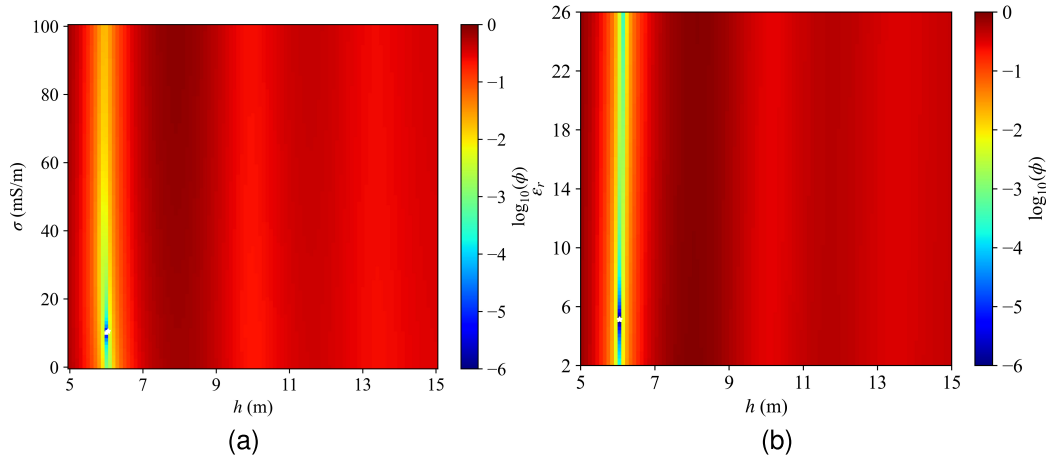


Fig. 5. 15–45-MHz response surface of the objective function $\log_{10}(\phi)$ in parameter planes (a) of $\sigma - h$ with $\epsilon_r = 20$ and (b) of $\epsilon_r - h$ with $\sigma = 50$ mS/m. White stars represent the true parameter values defined in simulation models. The subcaptions present the simulation models setting (true value). (a) $\sigma = 10$ mS/m, $h = 6$ m. (b) $\epsilon_r = 5$, $h = 6$ m.

TABLE I
ERROR ON THE ESTIMATED ELECTRICAL CONDUCTIVITY σ AND RELATIVE PERMITTIVITY ϵ_r
FOR DIFFERENT NUMERICAL EXPERIMENTS (CONFIGURATION II)

		Simulation model parameter (actual values)									
Index		1	2	3	4	5	6	7	8	9	
σ (mS/m)		10	10	10	50	50	50	80	80	80	
ε_r		5	13	22	5	13	22	5	13	22	
Error E^a (-) on the estimated electrical conductivity σ and relative permittivity ε_r											
$\Delta h^b = 0.05$ m	$E\sigma$	0.00	0.30	0.90	0.22	0.14	0.04	0.28	0.24	0.17	E_{mean} 0.25
	$E\varepsilon_r$	0.22	0.18	0.19	0.60	0.62	0.53	0.60	0.85	0.75	0.50
$\Delta h = 0.01$ m	$E\sigma$	0.00	0.10	0.20	0.04	0.02	0.00	0.06	0.05	0.03	0.05
	$E\varepsilon_r$	0.07	0.03	0.04	0.26	0.16	0.12	0.50	0.26	0.19	0.18

^aThe relative error is used and expressed $E = |(V_{true} - V_{estimated})/V_{true}|$, where V denotes the value of σ or ϵ_r .

^b Δh is the height difference (error) between the simulation and the inverse models.

respect to ϵ_r . According to this low sensitivity, ϵ_r could be ideally reduced to two possible values (e.g., $\epsilon_r = 10, 20$), which permits an assumption of a very low sensitivity for ϵ_r while conducting the full-wave inversion. However, these conditions might not be satisfying for very dry or wet soils.

As expected, within this low-frequency range of 15–45 MHz, the sensitivity of the objective function with respect to ϵ_r is the lowest among the three parameters, but it cannot be totally neglected in the inversion. To inverse with more stability, the flying height should be close to the soil in order to ensure a high signal-to-noise ratio. But at the same time, it should be far-field conditions (otherwise the more complicated near-field model should be used). Therefore, following the analysis of [50] relating the far-field assumption to the size of the antenna, i.e., the minimum distance $h = 1.2 \times \text{size antenna aperture}$, and according to the length of the dipole antenna to be used for the field measurement (5 m) and the stability of the full-wave inversion method, the best flying height is considered as 5–6 m above the soil.

B. Configuration ii: Source Over a Homogeneous Half-Space With Errors on the Third Parameter

In this configuration, error Δh was added to parameter h in the inverse model. Specifically, in the simulation, the true

value of h is 6 m. The actual values of σ and ϵ_r are presented in Table I, resulting in 9 (index 1–9) models in total. But in the two inverse models, h is considered as 6.05 and 6.01 m (i.e., $\Delta h = 0.05$ and 0.01 m), respectively. ϵ_r ranges from 2 to 26 and σ ranges from 0 to 100 mS/m (i.e., $\mathbf{b} = [\epsilon_r, \sigma]$). Both ϵ_r and σ are divided into 101 with values evenly spaced. For each model, the estimated error on σ and ϵ_r is quantified as the relative error E (–) (defined as note ^a in Table I). The mean error E_{mean} was calculated to compare the estimation of σ and ϵ_r for both Δh conditions.

The results are presented in Table I. From the mean errors E_{mean} , smaller Δh produces less error in the estimation for both σ and ϵ_r as expected, and the overall estimated electrical conductivity σ is more accurate than the permittivity ϵ_r . Moreover, the estimated error on ϵ_r increases when the actual σ increases. However, when the actual conductivity is low (e.g., 10 mS/m), a high permittivity, which is related to the wet soil conditions, would affect the retrieval of conductivity σ , e.g., when $\epsilon_r = 22$, $E_\sigma = 0.90$ for $\Delta h = 0.05$ m, and $E_\sigma = 0.20$ for $\Delta h = 0.01$ m, while the latter is acceptable. These are because: 1) the sensitivity of conductivity is higher than the permittivity within this frequency range as discussed before and 2) error in the flight height h causes a delay in the surface reflexion, resulting in a phase shift between the simulated and modeled wave which generates more error in

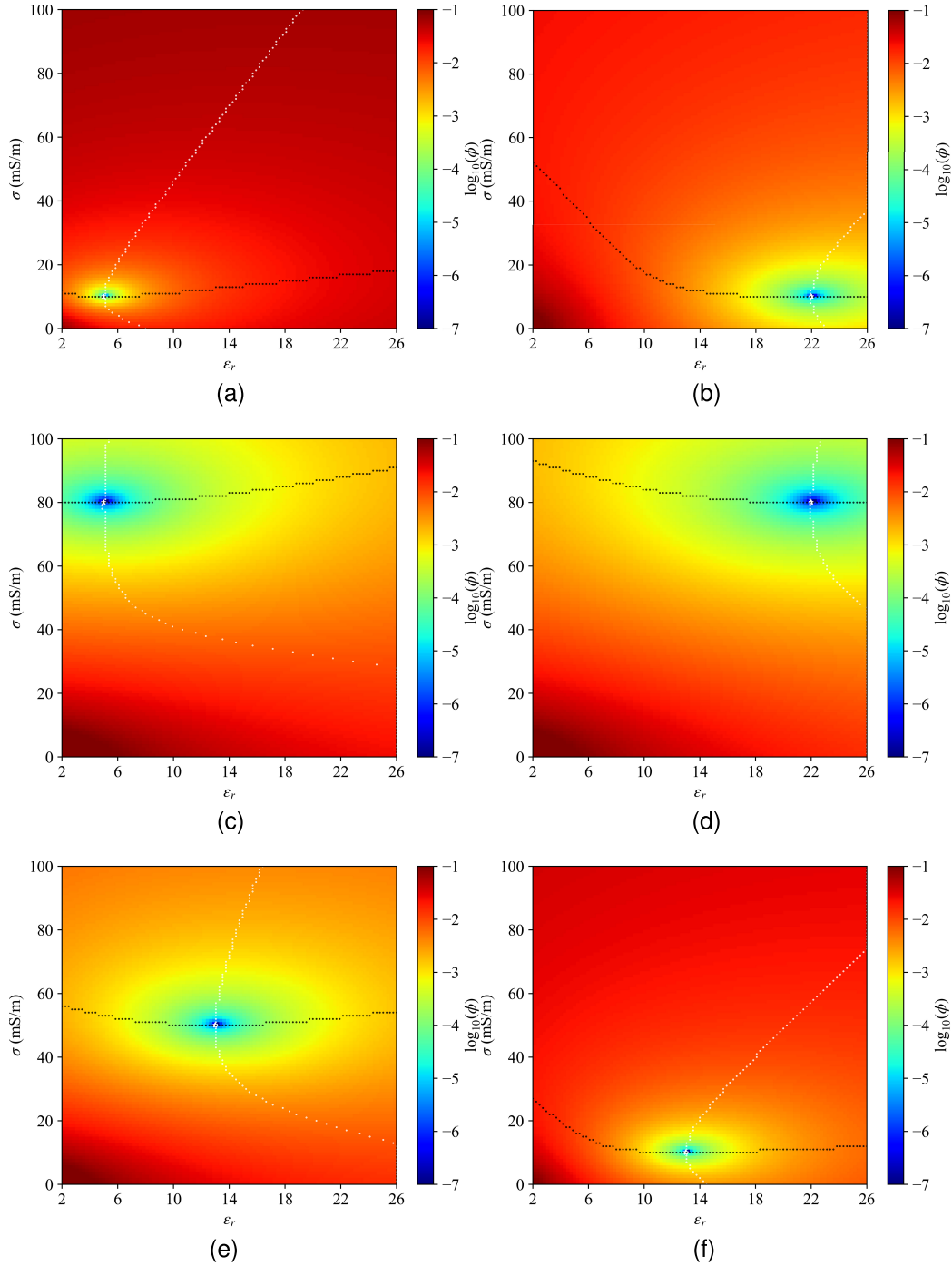


Fig. 6. 15–45-MHz response surface of the objective function logarithm $\log_{10}(\phi)$ in parameter planes of $\sigma - \epsilon_r$ with $h = 6$ m. White stars represent the true parameter values. Black curves represent the minimum region of the objective function with respect to the dielectric permittivity ϵ_r . White curves represent the minimum region of the objective function with respect to the conductivity σ . Subcaptions present the simulation models setting (true value). (a) $\sigma = 10$ mS/m, $\epsilon_r = 5$. (b) $\sigma = 10$ mS/m, $\epsilon_r = 22$. (c) $\sigma = 80$ mS/m, $\epsilon_r = 5$. (d) $\sigma = 80$ mS/m, $\epsilon_r = 22$. (e) $\sigma = 50$ mS/m, $\epsilon_r = 13$. (f) $\sigma = 10$ mS/m, $\epsilon_r = 13$.

the estimation of ϵ_r . The delay caused by the high σ does not affect too much since the delay is not significant unless ϵ_r is very low [e.g., $\epsilon_r = 5$, see Fig. 3(b)]. But still, it does not affect the uniqueness of the objective function minimum as seen in Fig. 4(a).

To conclude, with a resolution of 0.01 m for the LUT h vector in the inverse model, the soil electrical conductivity σ can be well estimated using the full-wave inversion method.

The retrieval of the relative permittivity ϵ_r is more affected by the resolution of the h parameter in the inverse models. In addition, although differential GPS could be used for cm accuracy radar positioning, it does not provide the distance between the soil surface and the radar. In principle, laser altimeters or ultrasonic sensors could be used to estimate heights, which would reduce the number of unknowns in the inverse problem and thereby limit nonuniqueness issues.

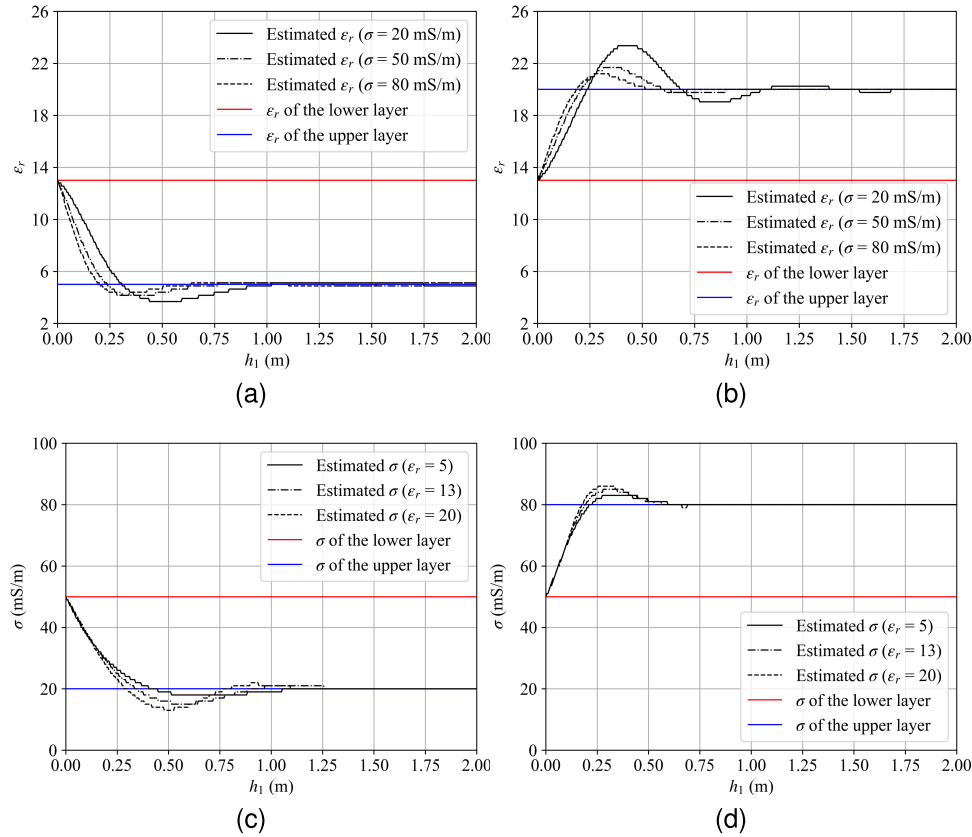


Fig. 7. Estimated relative dielectric permittivity ϵ_r and electrical conductivity σ as a function of thickness h_1 of the top layer for configuration iii. For (a) and (b), σ stays the same for both layers, and three values were considered (i.e., $\sigma = 20, 50$, and 80 mS/m). For (c) and (d), ϵ_r stays the same for both layers with three values considered (i.e., $\epsilon_r = 5, 13$, and 20).

Nevertheless, given that the soil surface is inherently rough and is usually covered by vegetation, significant errors (e.g., >1 cm) are expected. Moreover, the characterization scale of these sensors (several cm^2) is generally much lower than the characterization scale of the radar (several m^2). The benefit of estimating height with low-frequency GPR is that the retrieved height is not affected by vegetation or roughness (if not too large) and the determination scale is inherently consistent.

C. Configuration iii: Source Over a Two-Layered Medium

The simulations carried out above assume that the soil is a semi-infinite homogeneous medium. However, the soil is in general complex and made of different layers, with different textures and properties. The multilayered medium may significantly affect the inversion results if it is not properly accounted for, especially for thin layers with high contrasts. Importantly, it may lead to oscillations of the amplitude of the Green's function with a large period, which is proportional to the electric thickness of the layer [51]. In order to test the simplifying assumption of homogeneity, the radar signal was therefore simulated on the basis of two layers with distinct EM properties. It is also to determine the depth of sensitivity of the surface reflexion in the frequency range 15–45 MHz for a range of medium properties.

For configuration iii, there is a source situated above a two-layered medium. In the simulation models, the distance

between the antenna aperture and the soil surface h is defined as 6 m, and the top layer h_1 varies from 0 to 2 m with a step of 0.005 m. First, in order to investigate the depth sensitivity for the relative dielectric permittivity ϵ_r , ϵ_r is defined differently for the two layers, and σ stays the same with three values considered (20, 50, and 80 mS/m). Equally, for the investigation for the electrical conductivity σ , σ is different for the two layers, and ϵ_r stays the same with three values considered ($\epsilon_r = 5, 13$, and 20). In order to focus on only one parameter each time, the inverse modeling is carried out by considering only one homogeneous layer with h defined as 6 m. For the ϵ_r estimations, σ stays the same as in the simulation model. Therefore, the parameter vector $\mathbf{b} = \epsilon_r$, ranging from 2 to 26, being divided into 101 values. Likewise, ϵ_r stays the same as in the simulation as well for the estimations of σ . $\mathbf{b} = \sigma$ ranging from 0 to 100 mS/m, being divided into 101 values.

Fig. 7 presents the estimated relative dielectric permittivity ϵ_r and electrical conductivity σ as a function of the top layer thickness. The “staircase” effects observed result from the discretization of LUTs. As expected, for both estimated permittivity ϵ_r and conductivity σ , the information of the second layer is estimated when the depth of the upper layer is 0 m. With h_1 increasing, the estimated values gradually approach the value of the top layer and remain afterward. However, ϵ_r is underestimated or overestimated when h_1 is between 0.3 and 0.6 m [see Fig. 7(a) and (b)], and the lower σ ,

the more obvious it is observed. The under- or over-estimation happens for the estimation of σ as well, and more error is produced when relative permittivity ϵ_r is high. The under- or over-estimations result from the destructive or constructive interferences produced by the two reflectors, both contributing to the surface reflexion when dealing with thin layers. The depth sensitivity varies with different values of ϵ_r or σ defined for both layers.

Therefore, it is concluded that σ is more accurately retrieved by full-wave inversion for a multilayered medium, with its characterization depth of 0.5–1 m within this low-frequency range. Its accuracy is somehow affected by a high ϵ_r , e.g., the wet soil.

V. FIELD EXPERIMENT

The field experiment was performed over a bare and flat soil in Gembloux, Walloon Region, Belgium. The area mainly contains loamy soils with natural drainage. The test plot area is about 0.69 ha. To compare, we used the EM38-MK2 in vertical mode (Geonics Ltd., Mississauga, Canada) to measure the soil electrical conductivity. The EM38-MK2 operates at a frequency of 14.9 kHz as is therefore not influenced by the soil dielectric permittivity. The Geonics EM38-MK2 has two receiver coils spaced at 0.5 and 1 m from the transmitter coil, producing two datasets with different depths of characterization (around 0.75 and 1.5 m in vertical mode of operation) and depths of sensitivity (around 0.4 and 0.2 m, respectively) from only one acquisition [52].

A. Drone-Borne Radar Measurements

The proposed drone-borne radar is shown in Fig. 8. The drone is an X8 model, made of eight motors and four arms from RCTakeOff (Overijse, Belgium). The frequency-domain radar system mainly consists of: 1) a handheld VNA (Planar R60, Copper Mountain Technologies, Indianapolis, USA. Size: 130 × 65 × 28 mm); 2) a GPS receiver (GlobalSat BU353S4); 3) an Intel Compute stick; (d) a smartphone-type power bank. Python and Javascript programs were developed to remotely control the microcomputer; (e) a smartphone or tablet; and (f) a 5-m half-wave dipole antenna (VHA 9103, Schwarzbeck Mess-Elektronik, Germany). More detail about the radar system is presented by Wu *et al.* [9].

The operating frequency range was 15–45 MHz with a step of 1 MHz. About 13 measurements were obtained per second. Flights were performed manually with the height around 5–7 m above the soil surface.

B. Data Processing

The data processing includes calibration and inversion. The drone-antenna calibration, i.e., determining its characteristic functions $H_i(\omega)$, $H(\omega)$ and $H_f(\omega)$ in (3), was carried out using seven measurements at different heights over a lake, whose properties (e.g., the temperature and electrical conductivity) were measured by Cond 3210 portable conductivity meter (The Wissenschaftlich-Technische Werkstätten GmbH, Weilheim, Germany). The antenna characteristic functions



Fig. 8. Prototype of the drone-borne 15–45-MHz GPR for soil electrical conductivity mapping.

were calculated by solving a system of equations as (3). Therefore, $\mathbf{g}_{xx}$ of the soil surface can be obtained from S_{11} measured by the VNA. In the inverse model, or the LUT, $\mathbf{b} = [\sigma, \epsilon_r, \mathbf{h}]$. $0 \text{ mS/m} \leq \sigma \leq 100 \text{ mS/m}$ with a step of 1 mS/m, $4 \text{ m} \leq h \leq 8 \text{ m}$ with a step of 0.01 m, and ϵ_r is set to only two values, i.e., 10 and 20 as discussed in configuration i, resulting in a 3-D LUT from 81002 calculations. Normal kriging interpolation was used to obtain maps from measurement points for both drone-borne GPR and EMI.

C. Soil Electrical Conductivity Maps

Fig. 9 shows the results from drone-borne GPR and EMI, including measurement points and their kriged maps as the background. The pixel sizes of the three maps are 1 m. Overall, the conductivity variations are close for the three maps. From the GPR result, we observed the lowest conductivity area is in the northwest of the plot, while the high-conductivity area is in the southeast, with its values ranging from 20 to 50 mS/m. From EMI results [see Fig. 9(b) and (c)], the low conductivity areas are in the northwest, corresponding to the GPR result, but the high conductivity areas are more centered than the conductivity map obtained from the GPR. In addition, from the two EMI maps, the conductivity values measured by the 1-m offset between the receiver and transmitter are generally higher than the values measured by the coil offset of 0.5 m. Quantitatively, we used the root mean square error (RMSE) of the EMI and GPR results using the pixel values of the maps, calculated by

$$\text{RMSE} = \sqrt{\sum_{n=1}^N \frac{(\sigma_{n,\text{EMI}} - \sigma_{n,\text{GPR}})^2}{N-1}} \quad (13)$$

where N is the amount of pixel, and $N = 6810$ for the three maps. $\sigma_{i,\text{EMI}}$ and $\sigma_{i,\text{GPR}}$ are the pixel values in the EMI and GPR maps, respectively. The RMSE between GPR and 0.5-m offset EMI is 5.04 mS/m, and between GPR and 1-m offset EMI is 7.74 mS/m.

The observed differences between the drone-GPR and EMI might result from the following reasons: 1) too large spacing

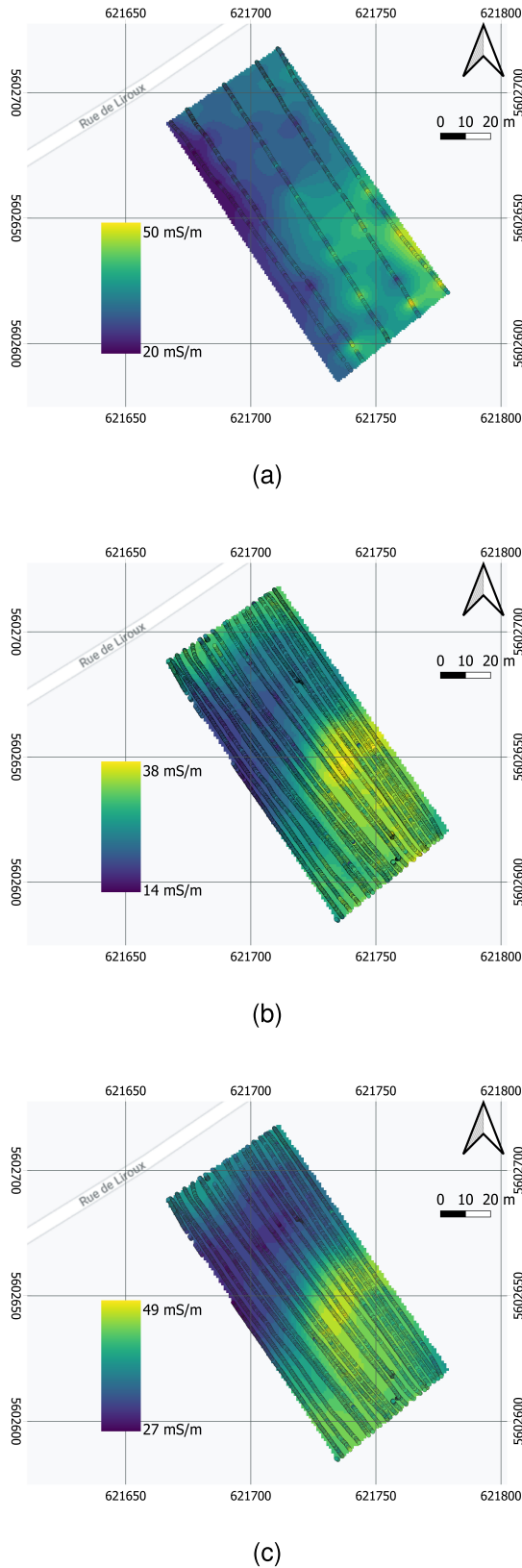


Fig. 9. Agricultural field in Gembloux, Walloon Region, Belgium. Soil electrical conductivity measurement points with corresponding kriging maps as background. The measurements are from (a) low-frequency drone-borne GPR and (b) EM38-MK2 with offset of 0.5 m and (c) offset of 1 m. Coordinates are in WGS84/UTM zone 31N (m).

between the acquisition lines for drone-GPR measurements. Acquisition lines for EMI are much denser, with a distance of 2.5 m on average, but for the drone radar, it is varying from 6 to 16 m. The missing acquisition lines lead to the missing information of the kriging mapping, especially for the high conductivity area; 2) different detection depths. As discussed in the numerical experiments, drone radar characterization depth is around 0.5 to 1 m, depending on the moisture conditions. As for EM38-MK2 in the vertical dipole orientation, the measurement depths for the distance between receiver and transmitter being 0.5 and 1 m are, respectively, 0.75 and 1.5 m (<http://www.geonics.com/html/em38.html>); and 3) different depths of highest sensitivity. For the offset of 1 m, the conductivity of 0.4-m depth under the soil surface contributes the most to the observed apparent electrical conductivity, and for the offset of 0.5 m, it is 0.2 m [52]. However, for the drone GPR, since it focuses on the surface reflexion, the sensitivity is expected to be maximum at the surface and to decrease with depth (although it depends on the properties and their distribution with depth).

VI. CONCLUSION AND PERSPECTIVE

In this study, we analyzed the full-wave inversion method for soil electrical conductivity mapping within the low-frequency GPR range 15–45 MHz. We present the amplitude of the reflexion coefficient at three different frequencies as a function of the relative dielectric permittivity and the electrical conductivity. At the low frequency considered in this study (e.g., 30 MHz), the reflexion coefficient mainly depends on the electrical conductivity, but the relative dielectric permittivity affects it slightly as well.

In order to further investigate the sensitivity of the surface reflexion to permittivity and conductivity, we conducted numerical experiments based on the full-wave inversion method and objective function plots. In the frequency range 15–45 MHz, the soil electrical conductivity is sensitive enough to be retrieved using full-wave inversion with relatively small effects of the permittivity, but still the effects cannot be neglected. The error on the antenna height h , and multi-layered medium produce more error in the estimation of ϵ_r than σ . The depth of sensitivity of the soil conductivity is around 0.5–1 m. For the measurement, the best flying height is considered around 5–6 m above the soil, as a trade-off between high signal-to-noise ratio and more simple modeling in far-field conditions.

The field measurements were conducted over a bare field. To operate in a low-frequency range, we used a 5-m half-wave dipole antenna on a drone. To compare, we performed EMI measurements with the EM38-MK2 instrument for the same field. It provided two datasets of different characterization depths and sensitivities. The agreement in terms of values and variations between the three maps proved the feasibility of soil conductivity characterization using drone-borne GPR and the full-wave inversion method.

The practical benefit of the method is that a GPR with a dipole antenna, still with a reasonable size for drone applications, can be used, thereby providing much longer-range

capabilities compared to the traditional coils used for EMI. It also provides a characterization depth of the same order as the root zone. For classical EMI, to have the same characterization depth, the coils should be very close to the soil (e.g., <20 cm), while for the proposed method, the distance can be as large as 10 m, which is suitable for digital soil mapping using drones. In terms of accuracy, apart from the effects of permittivity which are not fully negligible (but still accounted for), the proposed method presents several important benefits compared to the classical EMI methods. Indeed, it relies on: 1) VNA technology, the calibration of which being an international standard and relatively stable and 2) full-wave inversion using a complete EM model (theoretically exact for wave propagation in 3-D layered media and any antenna). A VNA cannot be used directly for classical coil-based EMI in the kHz frequencies because its sensitivity is not large enough when dealing with soil conductivities [53] and especially long ranges.

This study represents a proof of concept. It is necessary to further validate this technology in the future, and we will focus on conducting soil electrical conductivity measurements and controlling the relevant spatial resolution and detection depth, e.g., by lifting EMI instruments at a certain height or using the ERT method. Importantly, for this topic, there are still scientific challenges. For the drone, stability is needed during flights to avoid effects from the wind. In addition, given the effects of height on the inversion results, it is needed to keep the antenna as parallel as possible to the ground surface [54]. For the radar, a longer dipole antenna could be used to provide lower operating frequencies, hereby to increase the soil conductivity sensitivity.

ACKNOWLEDGMENT

The authors are grateful to Quentin Limbourg from the Walloon Agricultural Research Centre (CRA-W, Belgium) for giving them access to the field.

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