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# Clutter Characterization for Down-Looking Ground Penetrating Radar Imaging

by Traian Dogaru

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# **Clutter Characterization for Down-Looking Ground Penetrating Radar Imaging**

**Traian Dogaru**

*Sensors and Electron Devices Directorate, DEVCOM Army Research Laboratory*

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                             |                                    |                                  | Form Approved<br>OMB No. 0704-0188                          |                                                             |
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| 14. ABSTRACT<br>This report investigates the impact of clutter in down-looking ground penetrating radar (GPR) imaging systems via numeric simulations. The system modeled here is equipped with an antenna array, moves along a synthetic aperture track, and is capable of producing 2- or 3-D images of the underground space. Particular attention is given to the antenna array design to minimize the number of radar channels while maintaining good image quality. A brief phenomenological description of the rough ground surface clutter is presented, followed by a more detailed characterization of the clutter produced by soil permittivity fluctuations modeled as a 3-D random process. The results of large-scale numeric simulations are summarized in terms of clutter mean power and target-to-clutter ratio as a function of image depth. These results show some remarkable similarities between the effects of rough surface and soil inhomogeneity clutter on underground GPR images. Another important outcome is the large improvement in performance of a 3-D imaging system as compared to the 2-D version. |                             |                                    |                                  |                                                             |                                                             |
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## 1. Introduction

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The Signal Processing and Modeling Branch at the US Army Combat Capabilities Development Command Army Research Laboratory is currently developing unmanned aerial vehicle (UAV)-based radar imaging technology for counter-explosive hazard (CEH) applications. The explosive hazards under consideration include landmines, improvised explosive devices, and other close-to-ground-surface targets, which have long posed major detection challenges to any kind of sensors. Since many of these targets are buried underground, ground penetrating radar<sup>1</sup> (GPR) imaging has emerged as one of the technologies holding great promise to solve this problem.

In a series of three previously published DEVCOM Army Research Laboratory technical reports,<sup>2-4</sup> we presented a detailed discussion of the potential performance and issues characteristic to a UAV-based GPR imaging system based on computer simulations of such a system in various operational scenarios. While the first two reports considered a single-channel device operating in synthetic aperture radar (SAR) mode to obtain 2-D images of the underground space, the last installment analyzed a down-looking GPR system equipped with an antenna array capable of creating 3-D images of the same space. The performance analysis in those studies consisted mostly of characterizing the image quality metrics via the point spread function (PSF), as well as simulating the images of several commonly encountered targets in those sensing scenarios. However, those studies gave relatively little consideration to the impact of clutter on the radar images, which is critical to the assessment of these systems' performance.

In this work, we take the GPR imaging system investigation further by carrying out a quantitative evaluation of the clutter characterizing these images as well as the target-to-clutter ratio (TCR), which is the first indicator of detection performance in a clutter-limited radar system.<sup>5</sup> Rough ground surface clutter has received a great deal of attention in the radar literature and its impact on radar detection has been investigated primarily in the context of ground-plane imaging, as most SAR systems operate.<sup>6-8</sup> However, the effect of rough ground surface clutter on underground, vertical-plane GPR images has been rarely analyzed and is probably less well understood. Although the current report does not focus primarily on this type of clutter, we offer a phenomenological explanation of the rough surface clutter presence in underground GPR images and indicate possible mitigation methods.

The main part of this study is dedicated to the clutter produced by inhomogeneities in the soil medium where the targets are buried and the radar sensing and imaging

take place. This topic has received considerably less attention from the radar community as compared to rough ground surface clutter. Several publications have developed statistical models of the soil dielectric property fluctuations based on terrain measurements and demonstrated their impact on GPR-collected data.<sup>9–13</sup> However, to our knowledge, no systematic investigation related to this type of radar clutter has been completed to date. One possible obstacle to such a general study is the fact that soil inhomogeneities may exhibit very large site-to-site variations in terms of model parameters and require a tedious characterization process, making it very difficult to extrapolate the results of a particular investigation to other physical locations.

In this report, we do not attempt to characterize the underground clutter of any specific site. Instead, our approach is to consider computer models based on a range of soil inhomogeneity statistical parameters and try to derive general trends that impact radar system performance. In terms of radar targets, we keep this investigation at the PSF level. A follow-up study will consider GPR imaging of realistic targets encountered in CEH applications in the presence of underground clutter. We think the lessons learned from this exercise can be very useful to the radar system designer and may suggest ways to mitigate the clutter impact on system performance. A particularly important finding is the large clutter-reduction effect that a 3-D GPR imaging system affords when compared to the 2-D version of the same.

This report is organized as follows. In Section 2, we present the down-looking GPR imaging system configuration investigated in this report. This presentation includes a discussion of the optimal antenna array design for this application, as well as phenomenological aspects of rough ground surface clutter in underground images. Section 3 introduces the statistical models of soil inhomogeneities and performs a validation of the electromagnetic (EM) propagation simulation methods using existing analytic models. Section 4 is dedicated to characterizing the clutter induced by soil inhomogeneities in 2- and 3-D GPR images, as well as its impact on target detection performance. We finish with conclusions in Section 5.

## **2. Description and Phenomenology of the Down-Looking GPR Imaging System**

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### **2.1 System Configuration and Simulation Methods for GPR Imaging**

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In previous work investigating GPR imaging systems, we considered various sensing geometries, including down- and side-looking, capable of producing 2- or

3-D images.<sup>2-4</sup> In this report, we focus on down-looking GPR system configurations. Figure 1 shows a schematic representation of a 2- and 3-D down-looking GPR system, respectively. For 2-D imaging, we create a linear synthetic aperture by moving the radar platform along the  $x$ -axis. For 3-D imaging, we need to obtain a 2-D array of aperture samples. The most common way to achieve that is by implementing a physical antenna array along the  $y$ -axis, which in turn is translated along the  $x$ -axis to create a synthetic aperture along that direction.

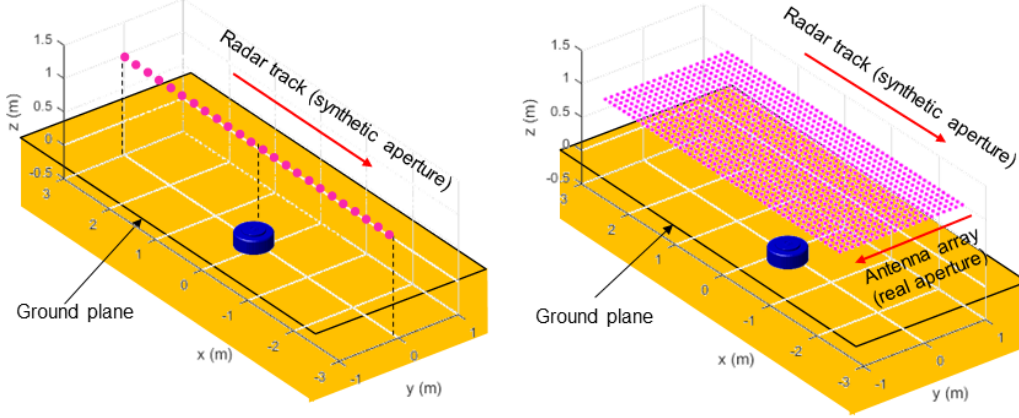


**Fig. 1** Schematic representation of down-looking GPR imaging systems for a) 2-D imaging using a linear 1-D aperture; b) 3-D imaging using a planar 2-D aperture

Our previous analysis of a 3-D UAV-based GPR system<sup>4</sup> assumed an antenna array of 1.2-m length with the platform flying at 1 m above the ground surface. The simulation results showed relatively poor resolution of target images along the array direction. To improve this resolution, in the current study, we increase the antenna array length to 2.4 m and keep the same platform height. While its physical implementation may present practical challenges, this configuration allows us to demonstrate some important near-field effects of antenna arrays, as well as obtain well-focused images of targets buried within a sizable swath across the SAR track. The main reason for keeping the radar platform flying low to the ground is to obtain good image resolution: as is well known, the resolution cell size is proportional to the radar–target range.<sup>5</sup> In practice, this is only possible if the ground surface is free of large obstacles, such as rocks or vegetation (bushes, shrubs, etc.). This condition is usually well satisfied in road clearance operations, where the UAV platform moves along a road.

The complete set of the 3-D imaging radar system parameters is listed:

- Center frequency  $f_0 = 1.25$  GHz
- Bandwidth  $B = 1.5$  GHz, from 0.5 to 2 GHz

- Number of frequency samples  $N = 128$ , spaced 11.7 MHz apart
- Synthetic aperture length ( $x$  direction)  $L_x = 7$  m
- Number of synthetic aperture samples ( $x$  direction)  $M_x = 176$ , spaced 4 cm apart
- Antenna array length ( $y$  direction)  $L_y = 2.4$  m
- Number of receivers in the antenna array ( $y$  direction)  $M_y = 32$ , spaced 7.5 cm apart
- Radar platform height  $h = 1$  m
- Complex dielectric constant of ground  $\epsilon_r = 5 - j0.3$
- 3-D image dimensions:  $D_x = 5$  m;  $D_y = 3.5$  m;  $D_z = 1$  m
- Image resolution:  $\delta x = 8$  cm;  $\delta y = 12 \dots 20$  cm;  $\delta z = 8$  cm
- Image voxel dimensions: 3.33 cm (in  $x$ ); 3.75 cm (in  $y$ ); 3.13 cm (in  $z$ )

The image resolution cell dimensions were evaluated according to the approximate formulas established in our previous work.<sup>3</sup> Note that the synthetic aperture length used for signal integration in the  $x$  direction was extended beyond the image domain limits in that direction by segments long enough to achieve the cross-range resolution limit. By this procedure, one achieves constant  $x$ -direction resolution across the entire image.<sup>3</sup> However, since the antenna array length is fixed, the same procedure could not be implemented in the  $y$  direction. Consequently, the  $y$ -direction resolution is variable, exhibiting degradation as one moves from the center to the edges of the image in that direction. More details related to the antenna array configuration are given in Section 2.2.

As mentioned in the Introduction, this work is primarily concerned with evaluating the radar clutter, more specifically clutter produced by the rough ground surface and the soil dielectric inhomogeneities. These are modeled as random processes describing fluctuations of the air-ground interface height (Section 2.4) and the soil dielectric properties (Section 3), respectively. Point targets are introduced in some simulations to evaluate the imaging system's resolution (Section 2.3) or the TCR (Section 4).

Modeling the radar wave propagation and scattering was performed using the AFDTD software,<sup>14,15</sup> developed at DEVCOM ARL and described in multiple previous publications. Since these represented very large-scale simulations, the computations were carried out on high-performance computing (HPC) platforms

available at the DOD HPC Centers,<sup>16</sup> requiring approximately 3 million central processing unit (CPU) hours to complete the soil inhomogeneity parametric study.

The antennas used in the AFDTD simulations are infinitesimal dipoles, horizontally polarized and oriented in the  $x$  direction, both as transmitters (Tx) and receivers (Rx). Since AFDTD uses soft current sources<sup>17</sup> for field excitation, the antennas are always matched to the current source over the entire frequency range. In practice, this is not possible to implement with dipole antennas. A more realistic low-frequency ultra-wideband (UWB) antenna for GPR applications is the Vivaldi design.<sup>18</sup> However, for the imaging application considered here, the dipole antennas display a pattern in the down-looking direction that is very similar to the Vivaldi counterpart. Moreover, if higher accuracy and realism is required from the numeric simulations, one can use the dipole-generated AFDTD results and the antenna substitution method developed by Dogaru<sup>4</sup> to model imaging by the Vivaldi antenna-equipped GPR system.

One interesting computational aspect of these simulations is the necessity to run the AFDTD code in double precision in order to obtain accurate results. This is due to the requirement to exactly cancel the large coupling response between the Tx and Rx antennas when computing the scattered field. In GPR sensing scenarios, the direct-Tx–Rx field can be many orders of magnitude stronger than the scattered field, with this ratio sometimes exceeding the dynamic range of single precision computer representation of real numbers. In those cases, running the code in double precision is the only way to ensure data accuracy.

The frequency-domain scattered field data obtained from AFDTD simulations are fed into an image formation algorithm, effectively simulating a stepped-frequency UWB radar. The imaging algorithm is based on the matched filter method,<sup>5</sup> which can also be construed as the frequency-domain version of the popular backprojection algorithm.<sup>19</sup> Although the matched filter method is very inefficient from a computational standpoint, we chose it for this study due to its excellent accuracy (no approximations or interpolations are required in the data processing). Formally, the image formation algorithm is described by the following equation:

$$I(\mathbf{r}) = \frac{1}{NM} \sum_{n=1}^N \sum_{m=1}^M P(f_n, \mathbf{r}_{T,m}, \mathbf{r}_{R,m}) \exp\left(j \frac{2\pi f_n}{c} (R_{T,m} + R_{R,m})\right), \quad (1)$$

where  $f_n$  stands for the frequency index  $n$ ;  $\mathbf{r}_{T,m}$  and  $\mathbf{r}_{R,m}$  are the position vectors of the Tx and Rx, respectively, for the Tx–Rx pair index  $m$  in the 2-D sampled aperture;  $R_{T,m}$  and  $R_{R,m}$  are the Tx-voxel and Rx-voxel propagation path lengths, respectively;  $I(\mathbf{r})$  is the complex image voxel amplitude at position vector  $\mathbf{r}$ ;

$P(f_n, \mathbf{r}_{T,m}, \mathbf{r}_{R,m})$  is the radar signal obtained for the Tx–Rx pair index  $m$  at frequency index  $n$ ;  $N$  stands for the number of frequencies and  $M$  stands for the number of Tx–Rx pairs taken into account in the image formation procedure; and  $c$  is the speed of light. Figure 2 describes some of the geometrical elements involved in Eq. 1. Tapered windows were applied to the radar data in the frequency and  $y$  aperture direction, but not in the  $x$  aperture direction. For additional details, such as the calculation of  $R_{T,m}$  and  $R_{R,m}$ , see Dogaru.<sup>2,4</sup>

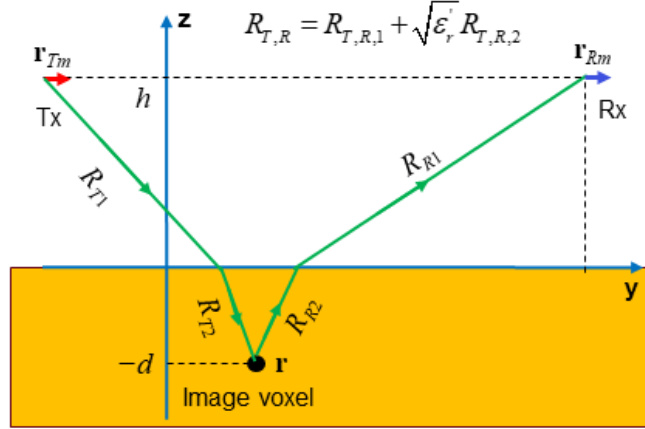


**Fig. 2** Geometric elements involved in the image formation algorithm, showing the propagation path from Tx to the image voxel and back to the Rx in the  $y$ - $z$  plane, consistent with Snell's law

The most significant clutter item in down-looking GPR sensing is the reflection from the air–ground interface (the “ground bounce”). If this interface were perfectly flat over a homogeneous soil, the ground bounce would show as a one-resolution-cell-thick horizontal line of very large magnitude in the radar image. The down-range sidelobes produced by this clutter line can be strong enough to obscure targets buried at shallow depth; consequently, ground bounce cancellation is an important preprocessing step for GPR data.<sup>1</sup> In the ideal case of a flat interface over homogeneous soil, the ground bounce response is relatively easy to predict and subtract from the raw radar signals. The most straightforward method to synthesize this response is via coherently averaging the radar signals across the aperture samples. In all images presented in this report, we used radar data after subtraction of the ground bounce from a flat interface over homogeneous soil.

Nevertheless, the non-ideal nature of the air–ground interface makes the ground bounce removal much more difficult in a realistic scenario. As shown in this report, both the irregular ground surface and the soil dielectric inhomogeneities have additional contributions to the ground bounce impact on the radar image that cannot be simply removed by the mean subtraction method mentioned in the previous

paragraph. Although sophisticated ground bounce removal methods have been proposed in the literature,<sup>20–23</sup> the incoherent and random nature of these clutter sources ensures that some residual contributions are always present in the image. Since this work is not concerned with ground bounce removal techniques, but with the quantitative clutter characterization, we do not attempt to alter the simulated radar data beyond the mean subtraction already described (which in effect cancels only the reflection from a flat interface over a homogeneous soil).

## 2.2 Antenna Array Design

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In this section, we investigate the performance of the multistatic antenna array in various configurations with the goal of finding an optimal solution in terms of resolution, sidelobes, grating lobes, and practical implementation. We assume the entire array length is populated with 33 Rx antenna elements, spaced at regular  $\frac{\lambda_{\min}}{2} = 7.5$  cm intervals, where  $\lambda_{\min}$  is the smallest wavelength in the radar signal spectrum. As is well known in multistatic antenna array theory,<sup>5</sup> this element spacing is required to ensure the absence of grating lobes in the radar images. We also assume each Rx element is equipped with its own independent electronics channel, such that simultaneous reception from all elements is possible for each transmitted signal.

When we use more than one Tx in the multistatic array, the simplest and most usual way of implementing a multiple-input multiple-output (MIMO) configuration is via time multiplexing on transmit.<sup>19</sup> That means the Tx elements are activated sequentially, one at a time, while multiple (or all) Rx elements receive the wave scattered by the scene under interrogation. A major goal of the antenna array design is to minimize the number of Tx elements without sacrificing the image quality metrics, primarily the resolution and sidelobes. The advantages of using a reduced number of Tx elements consist of lower hardware complexity, easier-to-meet timing requirements for a full array scan, as well as lower data throughput and computational load for the image formation algorithm. The reduced Tx element count also decreases the computational complexity of the EM simulations given that each Tx element activation requires a separate AFDTD run to obtain the radar received signals.

In our previous study related to using a multistatic antenna array for GPR imaging,<sup>4</sup> we considered several possible configurations in terms of number of Tx and their placements within the array. However, no clear conclusions were drawn with regard to the optimal array design. In this section, we refine that analysis for the new array

dimensions and indicate what configuration can achieve the best image quality with the minimum number of Tx–Rx pairs.

The analysis consists of creating 2-D images of a point target using radar signals with the same bandwidth as described in Section 2.1 and the antenna array in fixed position (no platform motion along the  $x$  direction). Simulations were performed with the following numbers of Tx elements: 1, 2, 3, 5, 9, and 33. In the 1 Tx configuration, the element is placed in the middle. In the 2 Tx configuration, the elements are placed at the array ends. For the other patterns, the Tx elements were equally spaced along the entire array length. All 33 Rx elements are activated simultaneously for each active Tx. Schematic representations of all the array configurations considered in these simulations are shown in Fig. 3.

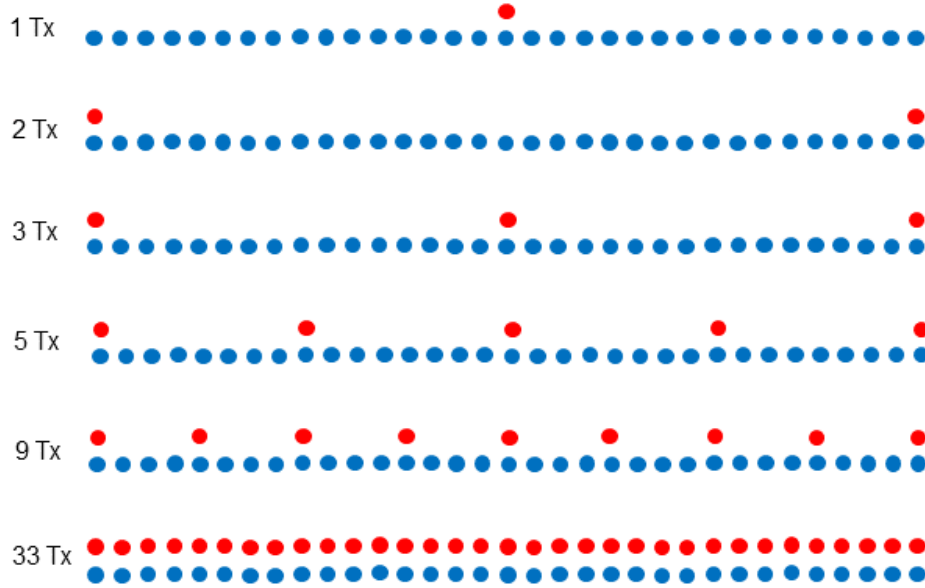


**Fig. 3** Tx and Rx element placements in the multistatic antenna array for various configurations simulated in this section. The red dots represent Tx elements, while the blue dots represent Rx elements.

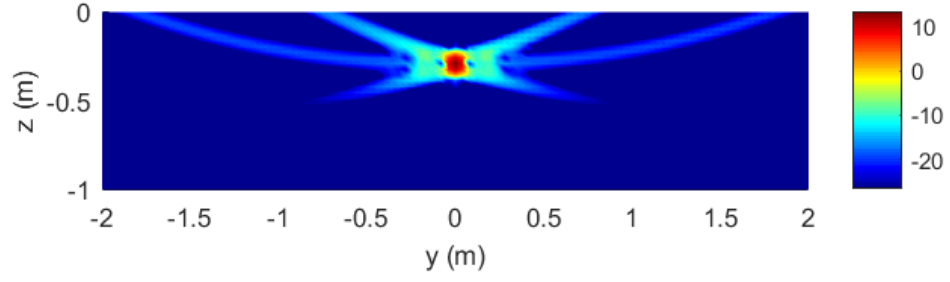
Except for the 1 Tx version, all the other array configurations nominally offer the same image resolution in the  $y$  direction, in the sense that the radar signals cover the same support in the  $k$ -space. However, since the signal magnitudes vary substantially across the array (and as a function of the target position), the configuration has a profound impact on the image quality, both in terms of resolution and sidelobes. The signal magnitude variations encountered in GPR sensing, described in detail in a previous report,<sup>3</sup> are characteristic to the very near-range radar–target geometry and must be taken into account in any analysis of these imaging systems. Additionally, the image metrics obtained with a fixed near-field

array depend considerably on the target position across the image. This is in contrast to radar systems operating at far ranges, where the magnitude of the radar signal illuminating the image domain can be approximated as constant, while the resolution and sidelobes do not change significantly with the target position across the image domain.

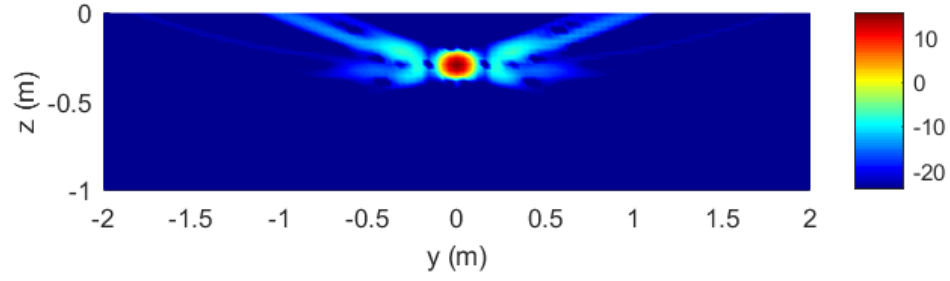
The PSF characterizing each array configuration was obtained for point targets placed either in the center ( $y = 0$ ) or directly below the array end ( $y = 1.2$  m), and buried at 0.3-m depth. We investigated the impact of using a tapered window on the radar data based on the position of the monostatic equivalent coordinate of the Tx–Rx pair along the array. Since there are too many different cases to catalog in this analysis, we only present the graphic results for several select configurations, in Fig. 4 (for targets placed in the center) and Fig. 5 (for targets placed at the edge).

Figures 4 and 5 clearly indicate that two or three Tx elements in the array are not sufficient to create good-quality images, due primarily to the presence of large sidelobes, which are very prominent for targets placed close to the image edges. The explanation for this effect has to do with the highly nonuniform character of the radar signal magnitude across the array, which typically generates elevated image sidelobes. Note that using a tapered window on the radar data can only improve the image quality in some particular cases, but may also lead to serious degradation for targets placed close to the image edges.

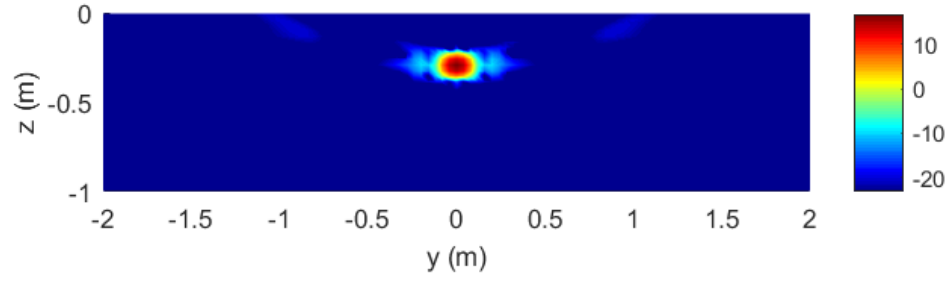
As the number of Tx elements is increased, the sidelobes levels decrease and the image quality improves. We notice that nine Tx elements are sufficient to obtain an image quality comparable to the fully multistatic configuration involving 33 Tx and 33 Rx elements. Interestingly, introducing a tapered data window does not have any significant impact on these latter configurations, since, when we account for all the possible Tx–Rx bistatic pairs, the monostatic equivalent signals<sup>4</sup> across the array naturally display the regular bell-shaped curve required to obtain an image with low sidelobe levels.



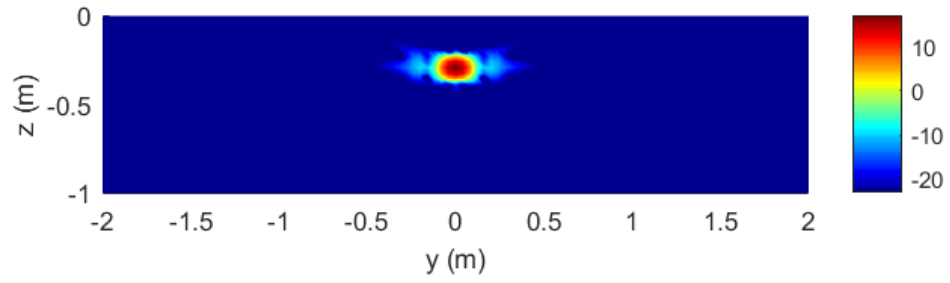
(a)



(b)

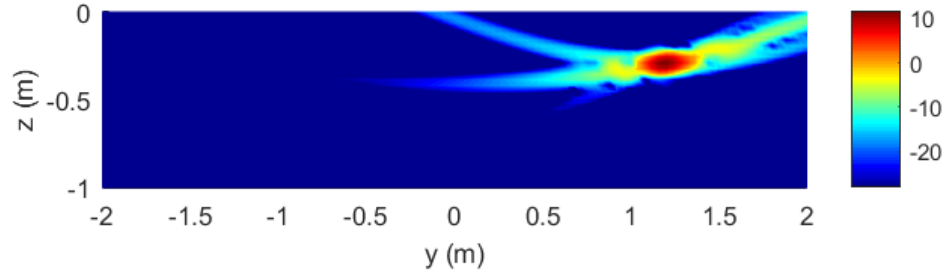


(c)

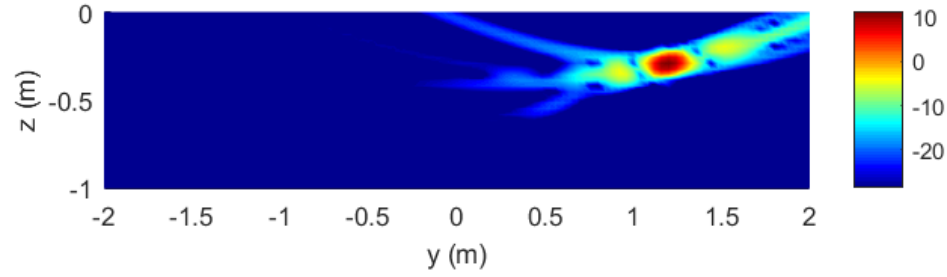


(d)

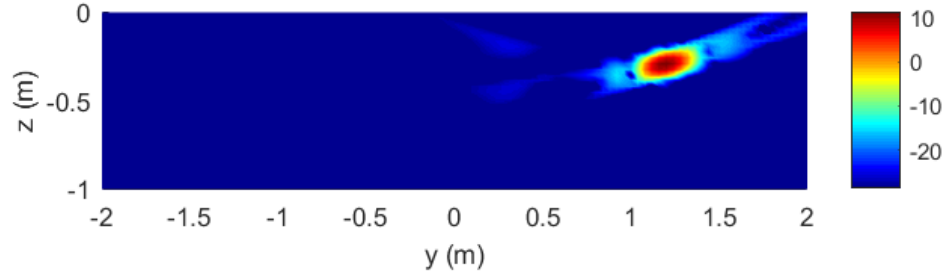
**Fig. 4** PSF obtained in 2-D imaging with the multistatic array for a point target centered in the  $y$  direction and the following array configurations: a) 2 Tx and 33 Rx; b) 3 Tx and 33 Rx; c) 9 Tx and 33 Rx; d) 33 Tx and 33 Rx



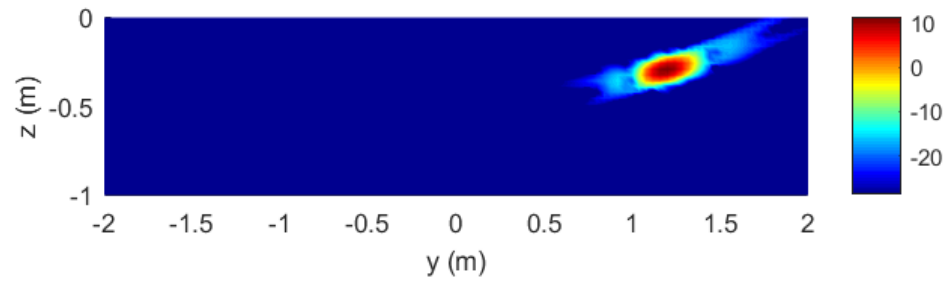
(a)



(b)



(c)



(d)

**Fig. 5** PSF obtained in 2-D imaging with the multistatic array for a point target placed at the array end in the  $y$  direction and the following array configurations: a) 2 Tx and 33 Rx; b) 3 Tx and 33 Rx; c) 9 Tx and 33 Rx; d) 33 Tx and 33 Rx

We can further reduce the number of antenna elements that need to be simultaneously activated during a pulse transmission–reception by associating a limited number of Rx elements (instead of all 33) with each active Tx element. This design idea is based on the fact that only Tx–Rx element pairs placed close to one another in the  $y$  direction can produce a signal strong enough to have a substantial contribution to the target image. The Tx–Rx pairs with large spacing along the array generate very weak signals (due to the relatively large path loss and acute propagation angles) and can therefore be neglected from the image formation process. The advantages of this configuration versus the fully activated Rx array are similar to the ones described in a previous paragraph: lower hardware complexity (since only a limited number of Rx electronics channels need to be simultaneously available), and lower data throughput and computational load for the image formation algorithm.

The array configuration based on this idea is illustrated in Fig. 6, where we show the step-by-step Tx–Rx activation sequence during a complete array scan. Note each Tx element is associated with the nearest eight Rx elements, except the two Tx elements at the array ends, which are each associated with four Rx elements.

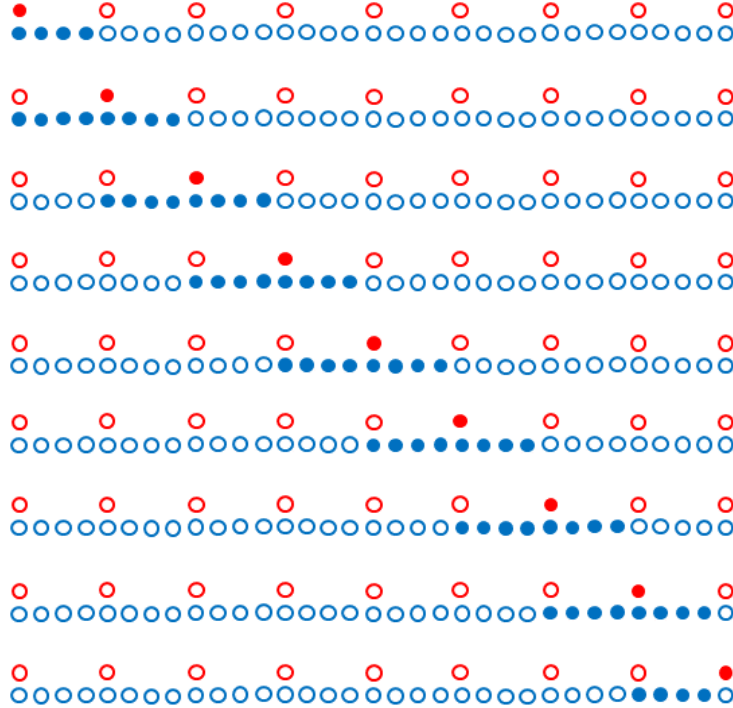


**Fig. 6** Tx and Rx activation pattern using nine sequential Tx elements and eight (or four) simultaneous Rx elements for each active Tx. The filled-in red dots represent active Tx, the filled-in blue dots represent active Rx, while the empty dots represent inactive elements.

The PSF obtained with this array configuration is shown in Fig. 7, where we note some small differences from the images generated by the fully activated Rx array, particularly the larger sidelobes characterizing the target close to the image edge. Nevertheless, after taking into account all the tradeoffs discussed so far in this section, we deemed the quality of the PSF obtained with the array configuration in Fig. 6 satisfactory and decided to employ this Tx–Rx activation scheme for all the simulations in this report. Note that a tapered window was applied to the array data in this case to reduce the sidelobe level.

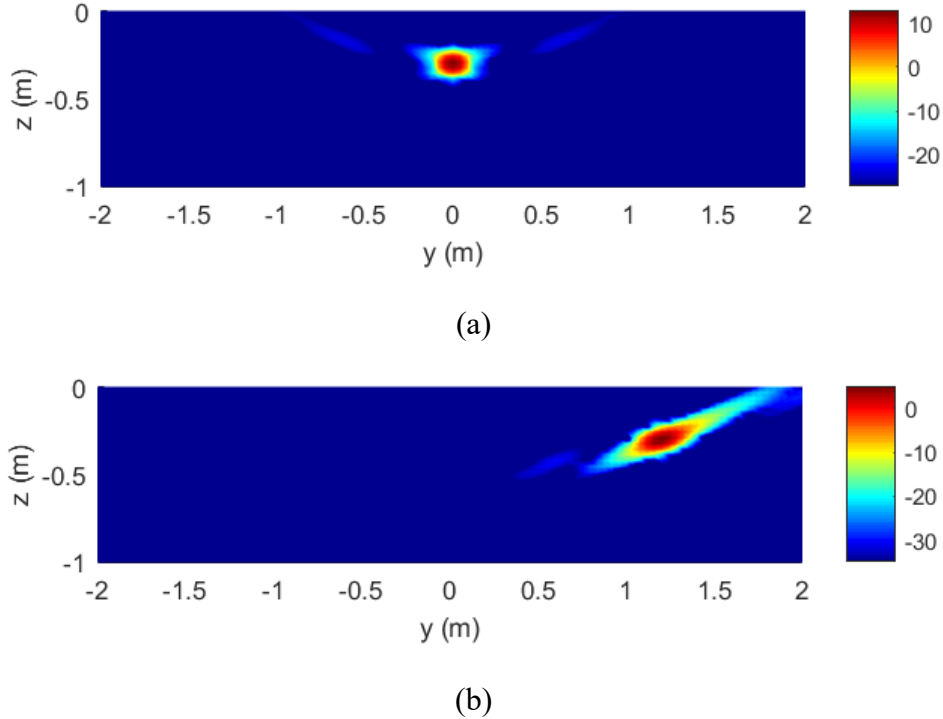


**Fig. 7** PSF obtained in 2-D imaging with the multistatic array in the configuration involving nine Tx and eight Rx elements, with a point target placed a) in the center in the  $y$  direction; b) at the array end in the  $y$  direction

Figure 8 shows a realistic and up-to-scale depiction of the GPR system imaging geometry, including the Tx (red dots) and Rx (blue dots) spatial sample positions. In the actual EM simulations, we assumed the array stays in a fixed position during a full scan before advancing in the  $x$  direction to the next sample along the SAR track. Our previous investigation of 3-D imaging with antenna arrays<sup>24</sup> indicates that, as long as the along-track sampling intervals are small enough (less than  $\frac{\lambda_{\min}}{4}$ ), this model produces identical results with the more realistic scenario of a continuously advancing radar platform.

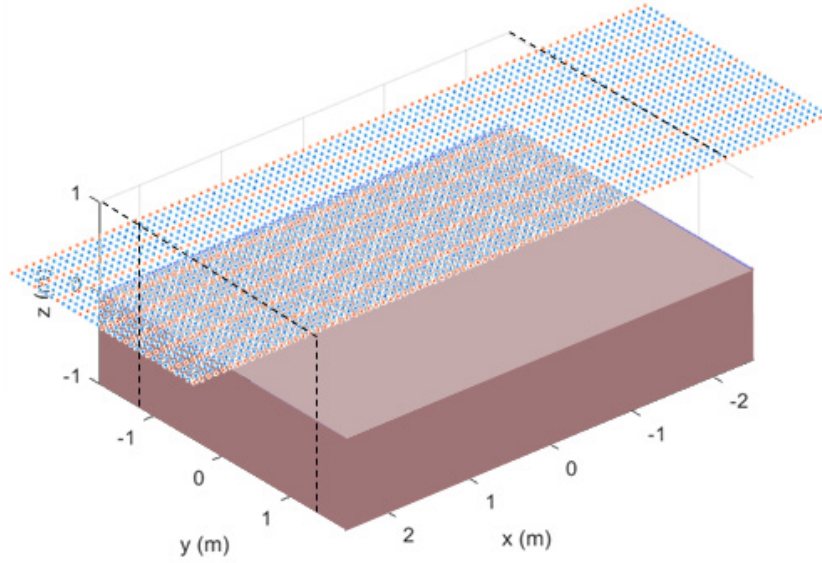


**Fig. 8** Realistic up-to-scale representation of the radar system's 2-D aperture samples (red and blue dots for the Tx and Rx elements, respectively) and the 3-D image volume (brown rectangular box)

To summarize the findings in this section, we note that the very near radar–target range characteristic to GPR sensing produces nonuniform signals (in terms of magnitude) along a multistatic array, which in turn depend strongly on the target's cross-range position within the image domain. Consequently, a relatively large number of Tx elements are required along the array length to ensure uniform illumination of the entire image. The design based on two Tx elements at the array ends, which is very commonly used in MIMO radar applications (see, for example, the forward-looking radar systems developed at DEVCOM ARL<sup>25–26</sup>), is inadequate for close-to-ground, down-looking GPR imaging sensors. The number of simultaneously activated Tx–Rx pairs can be reduced by associating a relatively small number of Rx elements with each active Tx element.

### 2.3 Point Spread Function of the GPR Imaging System

Before investigating the clutter in radar images, we examine the PSF of the GPR system described in the previous sections, assuming propagation in a homogeneous soil medium. For this purpose, we consider nine point targets placed at the same depth (0.3 m) and at various  $x$ - $y$  coordinates throughout the image domain. Here is the complete list of point target coordinates in meters:

- Target #1:  $(-2.0, -1.2, -0.3)$
- Target #2:  $(0, -1.2, -0.3)$

- Target #3:  $(2.0, -1.2, -0.3)$
- Target #4:  $(-2.0, 0, -0.3)$
- Target #5:  $(0, 0, -0.3)$
- Target #6:  $(2.0, 0, -0.3)$
- Target #7:  $(-2.0, 1.2, -0.3)$
- Target #8:  $(0, 1.2, -0.3)$
- Target #9:  $(2.0, 1.2, -0.3)$

Each point target response (PTR) is computed analytically by the formulas established in one of our previous reports.<sup>2</sup> The PTR data are then used to create the 3-D image according to Eq. 1. The 3-D PSF magnitude is calibrated such that it approximately matches the peak image magnitude of a buried TM62P2 plastic landmine. Based on the results of a previous study,<sup>3</sup> the expected image magnitude at 0.15-m depth is  $-20$  dB, whereas at 0.3-m depth, it is  $-25$  dB.

Two-dimensional planar cuts through the 3-D image are shown in Fig. 9, such that each plane goes through as many target images as possible. Only one 2-D image cut is required to represent the PSF in either of the  $x$ - $z$  or  $y$ - $z$  planes due to the obvious symmetry. Note that the resolution in the  $x$  and  $z$  directions is constant throughout the image, whereas the resolution in the  $y$  direction degrades from the image center toward the edges (consistent with the findings in Section 2.2).

When we compare the target return with the clutter level to obtain the TCR (in Sections 2.4 and 4), we are interested in simulating both 2- and 3-D imaging systems. The 2-D images are obtained by moving a single Tx–Rx pair along a linear synthetic aperture, as in Fig. 1a, while the 3-D images are obtained with a moving antenna array, as in Fig. 1b. The PSF of a point target placed at  $x = 0$ ,  $y = 0$ , characterizing the 2-D imaging system, is identical to that obtained in Fig. 9b (target in the center), except its magnitude is larger by about 7 dB. This discrepancy can be explained by the nonuniform radar signal magnitude variation of the target obtained along the antenna array. To enable a fair comparison with the clutter levels generated by the same 2- and 3-D imaging system configurations, the 2-D PSF is recalibrated such that its magnitude exceeds the 3-D PSF by 7 dB (that gives  $-18$  dB at 0.3-m depth for the 2-D PSF).

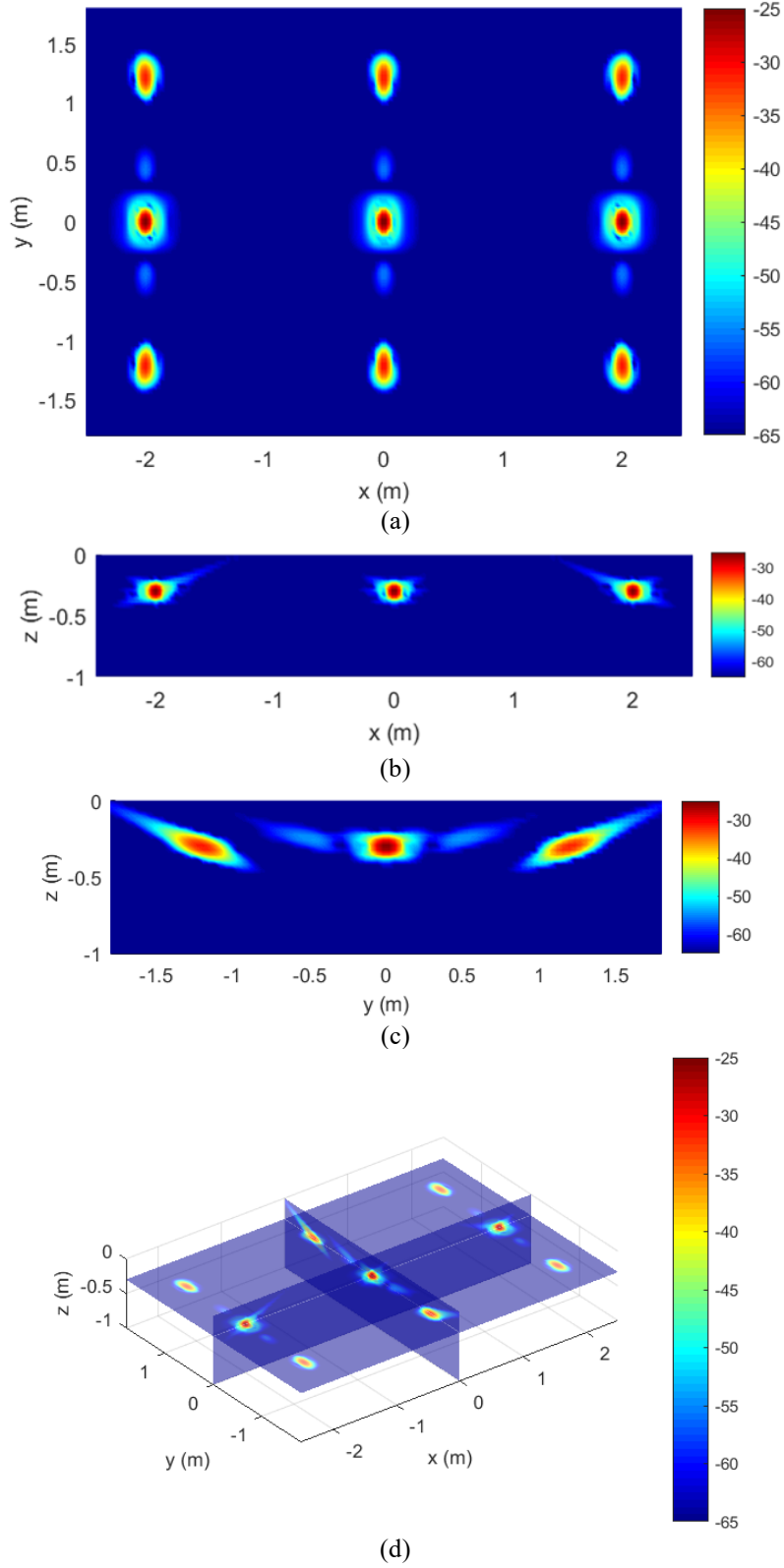


**Fig. 9** PSF of the 3-D GPR imaging system for nine point targets placed at various location throughout the image, showing 2-D cuts in the: a)  $z = -0.3$  m plane; b)  $y = 0$  plane; c)  $x = 0$  plane; d) perspective view of those three planes

Since the soil propagation medium is lossy, it is interesting to examine the variation of the PSF magnitude (more exactly, its peak) with the target burial depth. This variation, obtained by both the 2- and 3-D imaging systems, is shown in Fig. 10, for point targets placed at  $x = 0, y = 0$  (below the antenna array center). In the same figure, we plotted the two-way attenuation of a plane wave propagating in an identical soil medium over a distance equal to the burial depth and normalized to the PSF magnitude at the ground surface. Separate attenuation curves were drawn for the 2- and 3-D systems; although they have identical slopes, the absolute magnitudes are off by 7 dB, as discussed in the previous paragraph. The attenuation formula as a function of depth  $d$  (assuming of a small loss tangent) is<sup>27</sup>

$$A = \exp\left(-2\frac{Z_0\sigma}{\sqrt{\epsilon_r}}d\right), \quad (2)$$

where  $Z_0$  is the free-space impedance, and  $\sigma$  and  $\epsilon_r$  are the conductivity and (real part of) the dielectric constant of the soil, respectively. Since the target response and attenuation curve are almost identical, we infer that the reduction in the target image magnitude with increasing depth can be entirely attributed to the radar wave attenuation in the lossy propagation medium. This aspect is further discussed in Section 4, where we compare the target and clutter responses as a function of image depth.

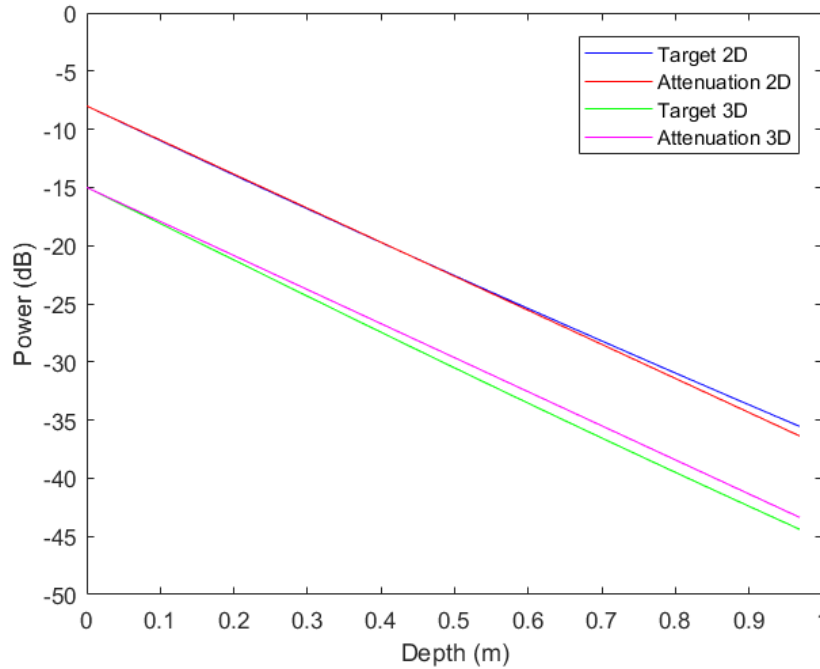


**Fig. 10** Variation of the point target power in the 2- and 3-D GPR images (PSF peak) as a function of burial depth, plotted together with the two-way wave attenuation in the ground medium

## 2.4 Rough Ground Surface Clutter in Down-Looking GPR Imaging

The clutter produced by the rough ground surface is a major performance-limiting factor in GPR imaging and has consequently received a great deal of attention in the radar community, particularly in the context of ground-plane imaging geometries. Both analytical and numerical evaluation methods are available for this type of clutter, mostly relevant to far-field, airborne SAR imaging systems.<sup>14</sup> In this section, we briefly discuss the impact of rough ground clutter on close-to-ground, near-field, down-looking GPR imaging systems, which is qualitatively different from that characterizing the far-field, ground-plane imaging systems counterpart. Although this study stops short of a detailed quantitative rough surface clutter evaluation as a function of various parameters, the phenomenological discussion in this section turns out to be very relevant to other types of clutter in GPR imaging, including that induced by soil dielectric inhomogeneities.

For this investigation, we simulated the imaging system described in Section 2.1 in the presence of a rough ground surface with root mean square (RMS) height  $h_{RMS} = 5$  mm and correlation length  $L_c = 5$  cm. The 2-D surface height  $z(x, y)$  is modeled as a random process with exponential covariance function (power-law spectrum) given by the following expression:

$$C_z(x, y) = h_{RMS}^2 \exp\left(-\frac{\sqrt{x^2 + y^2}}{L_c}\right). \quad (3)$$

Note, when expressed in polar coordinates of the  $x$ - $y$  plane, the covariance function in this model does not depend on the azimuth angle, but only on the horizontal displacement  $\rho = \sqrt{x^2 + y^2}$ .

Figure 11 shows the 2-D images obtained in the vertical  $y = 0$  plane when the imaging system uses a *linear aperture* along the  $x$  direction, corresponding to the middle row from the 2-D aperture shown in Fig. 8 (or the diagram in Fig. 1a). To increase the image sensitivity at large depths (where the wave attenuation is very strong), all clutter images in this report use a dynamic range of 80 dB. Clearly, some amount of clutter cleanup is achieved by the mean subtraction procedure outlined in Section 2.1 in a thin layer located at the ground surface. However, we notice that a large amount of clutter is still present in the image even after the mean subtraction.

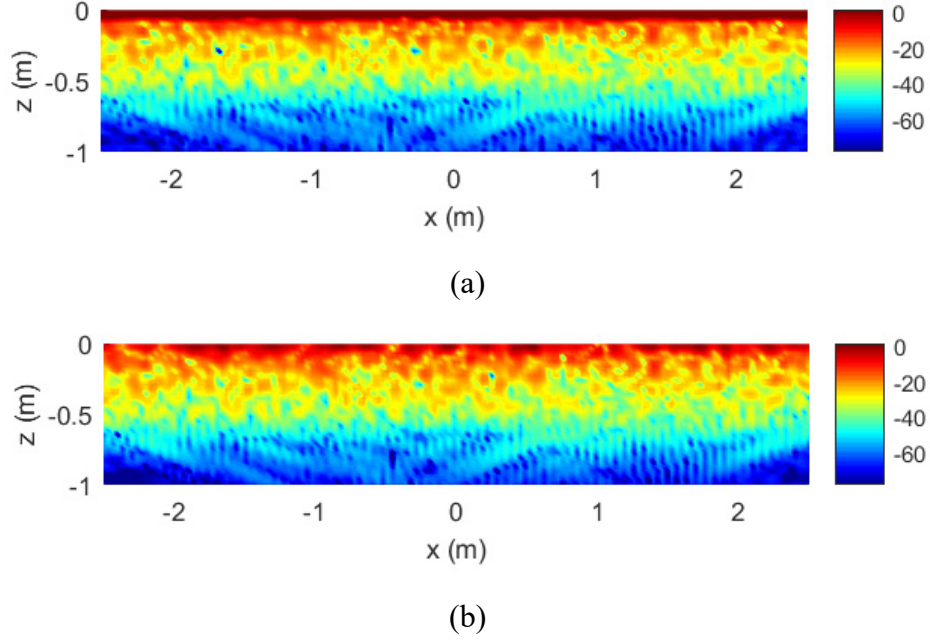


**Fig. 11** 2-D images in the  $y = 0$  plane obtained with a linear aperture in the  $x$  direction, in the presence of rough ground surface, obtained a) from raw radar data (no mean subtraction); b) after subtracting the along-track coherent-mean signal

The phenomenon that requires a detailed explanation in this simulation is the fact that the rough surface-induced clutter extends down to a relatively large depth in the image, clearly well beyond the geometrical height fluctuations of the interface or the extent of the sidelobes created by this interface's image. This effect may seem surprising at first, since one major tenet of radar imaging is that scattering centers should be isolated and placed at their physical location in the image. This is clearly not the case with the rough surface, whose vertical geometrical fluctuations are confined to no more than a few centimeters (less than one resolution cell size) about a horizontal baseline at the interface, while the clutter induced in the Fig. 11 image still appears strong at about 0.5-m depth. The outcome described here is troublesome for the detection performance of the GPR system, since weak targets buried at shallow depth inside the “clutter zone” would most likely go undetected.

To explain this effect, we need to consider the full 3-D geometry of the sensing problem. Since the imaging system considered in Fig. 11 is only capable of resolving scattering centers in 2-D ( $x$  and  $z$  directions), ambiguity curves are created in the  $y$ - $z$  plane by any such scattering centers, including those outside the image plane ( $y = 0$ ). Such ambiguity curves are produced by any point on the rough surface, outside the image plane, as long as the point is illuminated by the antenna beam. These ambiguity curves project onto the image plane at various depths

(depending on the  $y$  coordinate of the scattering center), creating the appearance of the clutter extending deep into the image.

A simple simulation illustrates the explanation in the previous paragraph. In Fig. 12, we consider the same 2-D imaging system as in Fig. 11, but instead of a rough surface, we place three isolated point targets at the interface ( $z = 0$ ) with various offsets along the  $y$  axis (0, 1.5, and 3 m, respectively). The image is created in the  $y = 0$  vertical plane and displayed in Fig. 12a. Although the target placed in the image plane ( $y = 0$ ) shows up at the correct location, the other two targets placed outside the image plane appear at various depths below the interface. The  $x = 0$  plane image displayed in Fig. 12b, obtained by applying the image formation procedure described by Eq. 1 to the entire 3-D space, clearly shows the ambiguity curves generated by each target and their projections onto the image plane  $y = 0$ .

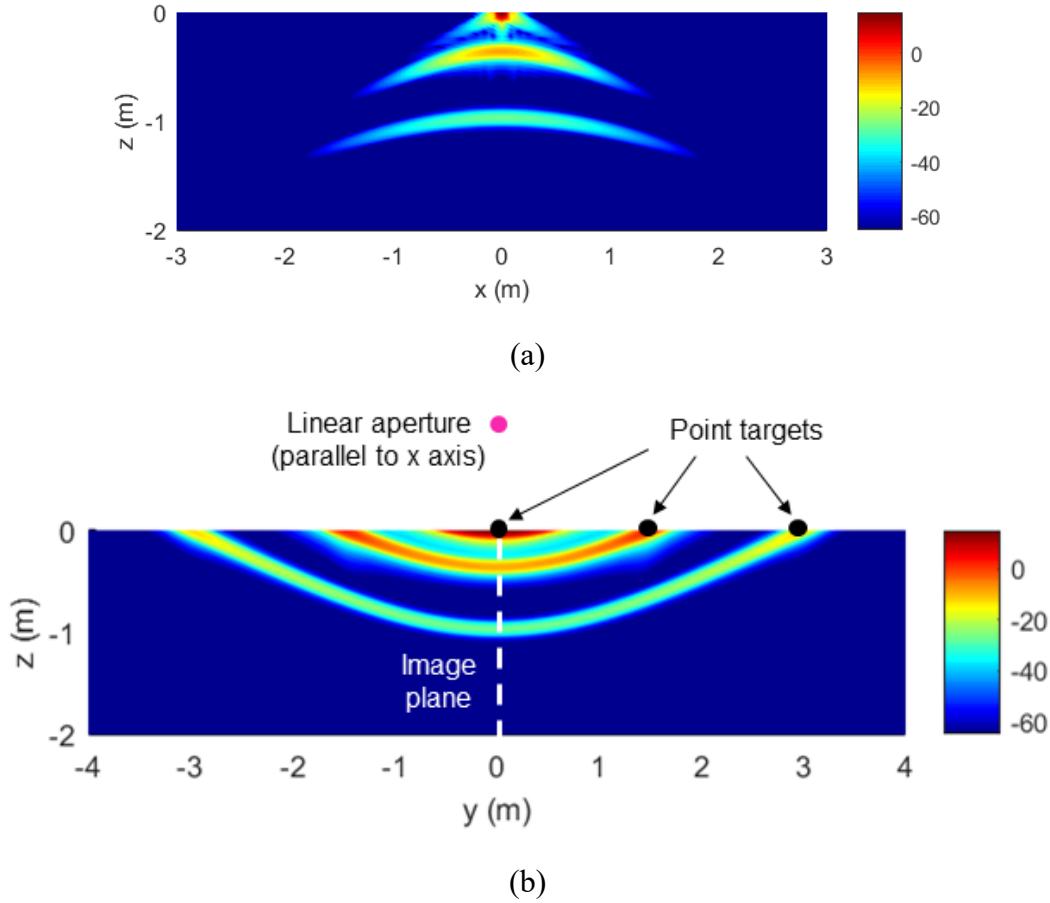


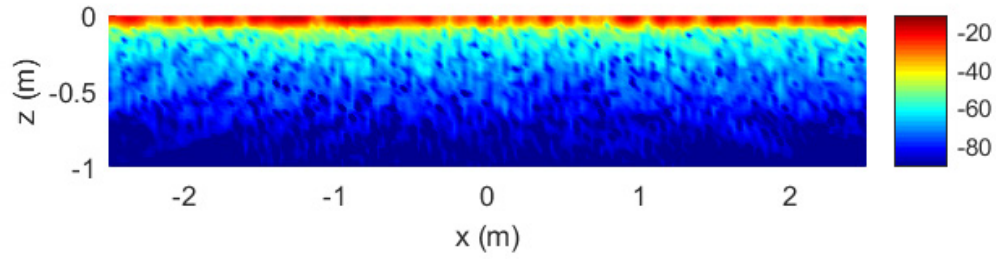
**Fig. 12** 2-D images of three point targets obtained with an GPR imaging system involving a linear synthetic aperture along the  $x$  direction, shown in the a)  $y = 0$  plane; b)  $x = 0$  plane

The same principle applies to clutter produced by scattering centers along a rough air-ground interface. Each point on this surface illuminated by the antenna beam produces a contribution to the image clutter whose depth and magnitude depend on

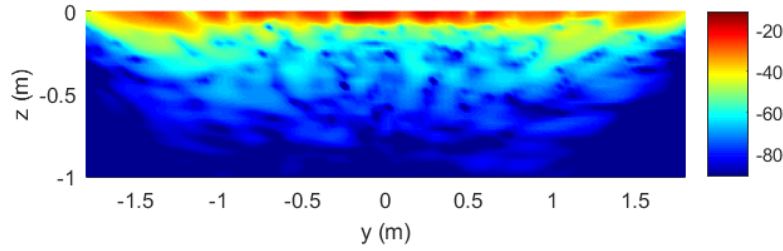
the  $y$ -directed offset of the scattering center. Thus, larger  $y$  offset is associated to lower magnitude (due to the longer propagation path) and larger depth of the ambiguity curve—this explains why the clutter magnitude eventually tapers down with image depth (incidentally, note that this tapering is not directly related to the radar wave attenuation through the soil).

One obvious way to mitigate this effect is by narrowing down the antenna beam ground footprint in the  $y$  direction. This can be achieved by either lowering the platform height or increasing the antenna aperture in that direction. Even for UAV platforms flying as low as physically possible, GPR antennas operating at low microwave frequencies typically have wide beams, casting a large footprint on the ground surface. The only effective solution to narrow down this footprint is to create a large aperture by means of an antenna array. This essentially brings us to the GPR system configuration depicted in Fig. 1b, equipped with an antenna array in the  $y$  direction and capable of 3-D image formation. Note that the 3-D image formation process effectively narrows down the beam footprint to the size of a resolution cell (via “digital beamforming”,<sup>19</sup> which is part of the imaging algorithm) and confines the rough surface clutter to an image region corresponding more or less to the location of its physical source, the air–ground interface.

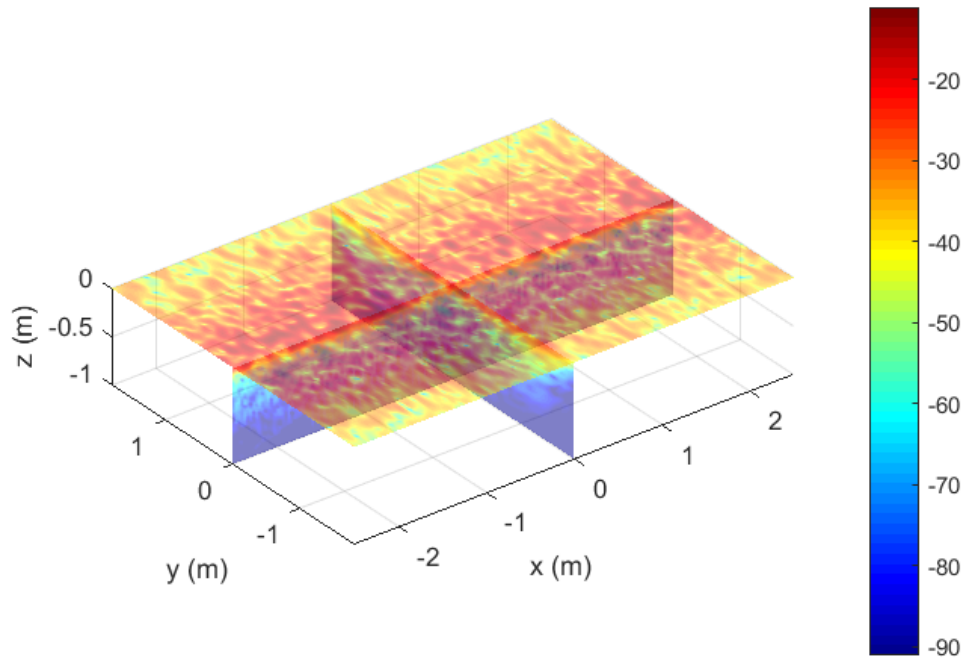
The reduction in the image clutter with depth is clearly visible in the images shown in Fig. 13, obtained with the full 2-D aperture configuration described in Section 2.1 in the presence of a rough surface with the parameters described earlier in this section after mean signal subtraction. In particular, one could directly compare the images in Figs. 11b and 13a, which were created in the same plane ( $y = 0$ ). In contrast to Fig. 11b, the image clutter in Fig. 13a is mostly confined to a thin layer about the air–ground interface and its magnitude drops very rapidly with depth. This effect is clearly beneficial in terms of detection performance, since it allows good spatial separation between the buried target and the rough surface clutter in the radar image. Another noteworthy feature visible in Figs. 13b and 13c is the nonuniform mean clutter magnitude along the  $y$ -axis, due to the variable image resolution in that direction.



(a)



(b)



(c)

**Fig. 13** 3-D image of the rough ground surface in the following representations: a) 2-D cut in the vertical  $y = 0$  plane; b) 2-D cut in the vertical  $x = 0$  plane; c) perspective view showing cuts through the planes  $x = 0$ ,  $y = 0$ , and  $z = 0$

Figure 14 looks at the mean rough surface clutter power versus image depth, for the 2- and 3-D images obtained in this section. The mean clutter power at a certain

depth is computed by averaging the power of all pixels/voxels located at the same  $z$  coordinate, in the  $y = 0$  vertical plane. Note that, in the 3-D images, the voxel resolution varies along the  $y$  direction, and so does the mean voxel power. Consequently, we should not consider 3-D image voxels outside the  $y = 0$  plane in the comparison with the 2-D images, to avoid generating misleading conclusions.

The graphs in Fig. 14, which compare the point target and mean clutter power in the radar images, clearly suggest that large improvement in TCR can be obtained by going from a 2-D to a 3-D imaging system, particularly at depths exceeding one resolution cell (0.1 m). This effect is due to the sharp drop in the mean clutter power in the 3-D image beyond that threshold. As shown in Section 4, this behavior is very similar to that displayed by clutter induced by soil inhomogeneities with large correlation lengths.

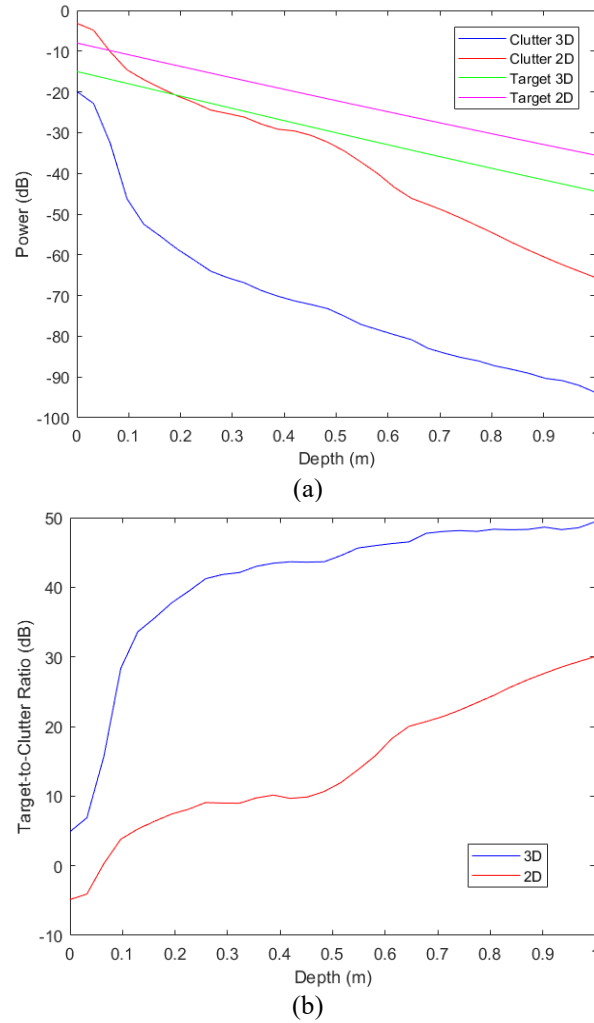


**Fig. 14 Comparison between the target and mean rough surface clutter power as a function of depth in 2- and 3-D images: a) target and mean clutter power; b) TCRs for the same scenarios**

The rough surface clutter analysis carried out in this section is relevant to other types of clutter in 2-D vertical-plane GPR imaging as well. For instance, one can consider the effect of discrete or distributed clutter objects placed above or below the air-ground interface outside the image plane. Since the system cannot resolve those scattering centers in the third dimension, the resulting ambiguity curves may project to unexpected locations in the actual radar image, even though no physical object is present at those locations. Although this report focuses on down-looking GPR systems, we should mention in passing that side-looking GPR systems meant to create 2-D vertical plane images may fare even worse in terms of clutter, since they typically cast a much wider antenna beam footprint on the ground than the low-flying, down-looking system counterparts. The most-effective clutter mitigation solution for all these sensing scenarios consists of implementing a 3-D imaging system, as explained in previous paragraphs.

### **3. Statistical Models of Soil Dielectric Inhomogeneities**

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Besides the rough air-ground interface, dielectric permittivity fluctuations in the underground propagation medium constitute another major clutter source in GPR sensing and imaging. While the rough surface itself is confined to a small physical region about the interface between the two media, dielectric inhomogeneities may extend deep into the ground. Consequently, we expect them to generate significant levels of radar clutter at larger depths than the rough surface and have a stronger negative impact on deep-buried target detection.

The soil dielectric properties have been well investigated and documented in the GPR and remote sensing literature. Sophisticated empirical models of the soil complex permittivity as a function of water content and mineral composition exist,<sup>28–31</sup> allowing investigators to derive the dielectric properties based on soil moisture content maps in cases where direct dielectric measurements are not available. Note the main electromagnetic material parameters relevant to GPR systems (operating at frequencies of 100 MHz and above) are conductivity and permittivity, whereas magnetic permeability has no significant impact on GPR operation.<sup>9</sup>

The spatial variability of soil dielectrics has received a systematic treatment in several papers by Takahashi, Igel, and Preetz,<sup>9–13</sup> who fitted statistical models of the permittivity fluctuations in topsoil onto direct field measurements. Our current clutter study is largely based on implementing these models within the AFDTD EM solver framework. One conclusion of their research is that the permittivity fluctuations are mostly confined to a relatively thin layer of about 0.5 m below the surface; beyond that depth, the soil can be considered homogeneous. Other

investigators<sup>32–33</sup> have measured the variation of mean soil dielectrics properties with depth without necessarily considering their fluctuations in the horizontal direction. Needless to say, these models are characterized by parameters highly dependent on the type of terrain and geographical location.

In this report, we model the soil dielectric constant (or real part of the complex relative permittivity) and conductivity as 3-D stationary random processes with Gaussian probability density function (PDF). Although in the models by Takahashi et al. the dielectric constant and conductivity have somewhat different statistics in terms of PDF and covariance, we consider them perfectly correlated to one another, meaning that if we are given the dielectric constant at a sample point, the conductivity value at that point is uniquely determined. The main reason for this simplification is that the AFDTD software would not be able to accommodate the huge number of sample points with different dielectric properties obtained by independent combinations of permittivity–conductivity pairs. However, another way to make sense of this model is the reasonable assumption that both the dielectric constant and the conductivity are uniquely related to the soil water content.

The spatial correlation of soil dielectric properties has been characterized in terms of the semivariogram,<sup>34</sup> which is a concept used in geophysical engineering to investigate the spatial distribution of general properties in the underground medium, such as mass density or mineral content. It can be shown, for a stationary random process  $f(\mathbf{r})$ , the semivariogram  $\gamma_f(\mathbf{r})$  is related to the covariance function  $C_f(\mathbf{r})$  by

$$\gamma_f(\mathbf{r}) = \sigma_f^2 - C_f(\mathbf{r}), \quad (4)$$

where  $\sigma_f^2$  is the variance of the random process and  $\mathbf{r}$  is the displacement vector between two points in the medium. Since the covariance is a notion more familiar to the radar engineers, we use it to replace the semivariogram for the remainder of this report.

Similarly to statistical models of terrain surface roughness (which is a 2-D random process), the most commonly used covariances for soil dielectric fluctuations are Gaussian and exponential. The analytic expressions for these covariance functions are

$$C_\epsilon(\mathbf{r}) = \sigma_\epsilon^2 \exp\left(-\frac{r^2}{L_\epsilon^2}\right) \text{ (Gaussian)}, \quad (5a)$$

$$C_\varepsilon(\mathbf{r}) = \sigma_\varepsilon^2 \exp\left(-\frac{r}{L_\varepsilon}\right) \text{ (exponential),} \quad (5b)$$

where  $\sigma_\varepsilon^2$  and  $L_\varepsilon$  are the variance and correlation length of the dielectric constant  $\varepsilon_r(\mathbf{r})$ , respectively. Note that although we wrote the covariance function specifically for the dielectric constant, we implicitly assume the same covariance for the conductivity. The expressions in Eq. 5 indicate that the covariance functions in our models depend on the radial displacement  $r = |\mathbf{r}| = \sqrt{x^2 + y^2 + z^2}$  only, but not on the azimuth and elevation angles (in other words, we assume the soil dielectric statistics are isotropic).

The power spectral densities (PSDs) corresponding to these covariance functions are their 3-D Fourier transforms, which turn out to be

$$W_\varepsilon(\mathbf{k}) = \pi^{1.5} \sigma_\varepsilon^2 L_\varepsilon^3 \exp\left(-\frac{k_r^2 L_\varepsilon^2}{4}\right) \text{ (Gaussian),} \quad (6a)$$

$$W_\varepsilon(\mathbf{k}) = 8\pi \frac{\sigma_\varepsilon^2 L_\varepsilon^3}{(1 + k_r^2 L_\varepsilon^2)^2} \text{ (exponential),} \quad (6b)$$

where  $\mathbf{k} = (k_x, k_y, k_z)$  is the Fourier domain counterpart of  $\mathbf{r} = (x, y, z)$  and  $k_r = |\mathbf{k}| = \sqrt{k_x^2 + k_y^2 + k_z^2}$  (note again that the spectra depend only on the radial component of  $\mathbf{k}$ ).

The exponential PSD follows a power-law variation with  $k_r$  ( $\sim k_r^{-4}$ ), which is characteristic to fractal random processes. In this case, the fractal dimension is  $D = 2.5$ . Interestingly, fractal models for soil dielectric inhomogeneities have been proposed by at least one author<sup>35</sup> and are implemented as a feature in the open-source gprMax software<sup>36</sup> developed specifically for EM modeling of GPR sensing scenarios. In this report, we consider both Gaussian and exponential covariances for the soil dielectric fluctuations with various model parameters in terms of standard deviation and correlation length. The correlation lengths in our simulations in Section 4 were set to 0.2 m or shorter, due to limitations in the AFDTD computational domain size (note that when the correlation length becomes comparable to the shortest computational domain dimension, the random process stationarity assumption becomes questionable). These values are comparable to the ones measured by Igel and Preetz in field experiments.<sup>10,12</sup> Note that, due to slightly different definitions of the correlation length, the quantity  $L_\varepsilon$  employed in this report is equivalent to one third of that reported by Igel and Preetz.

To generate the 3-D profiles of the soil dielectrics within the AFDTD software, we start with a homogeneous background of dielectric constant  $\bar{\varepsilon}_r$  and conductivity  $\bar{s}$ , which are the means of the random processes  $\varepsilon_r(\mathbf{r})$  and  $s(\mathbf{r})$ , respectively. Then, we specify the standard deviation of each process, defined as

$$\sigma_{\varepsilon} = \sqrt{\left\langle \left( \varepsilon_r(\mathbf{r}) - \bar{\varepsilon}_r \right)^2 \right\rangle}, \quad (7a)$$

$$\sigma_s = \sqrt{\left\langle \left( s(\mathbf{r}) - \bar{s} \right)^2 \right\rangle}, \quad (7b)$$

where the brackets  $\langle \cdot \rangle$  denote the ensemble mean. (Note: In this report, we use the symbol “ $s$ ” for conductivity instead of the usual “ $\sigma$ ” to avoid confusion with the symbol denoting standard deviation.) The range of variation for  $\varepsilon_r$  and  $s$  is truncated to about three standard deviations on either side of the mean. When performing this truncation, we must ensure that we avoid non-physical values for the random variables  $\varepsilon_r$  and  $s$  (for instance,  $\varepsilon_r$  cannot be less than 1, and  $s$  cannot be negative).

Since the random number generators available in various software library implementations can only create sets of independent (uncorrelated) random numbers, obtaining a 3-D random process with a specific covariance function in a computer program requires a more convoluted procedure that uses the PSD in the spectral domain. This implementation is made possible by the fundamental property that the Fourier transform of a stationary random process is an uncorrelated process; moreover, the variance of the Fourier transform (as a new random process vs. frequency) is the PSD of the original process. While this is a well-known result in the theory of 1-D random processes,<sup>37</sup> it can be extended to the 2- and 3-D cases as well.<sup>38</sup> Then, based on the linear system theory with random inputs and outputs,<sup>37</sup> an uncorrelated (white noise) process is multiplied by a transfer function equal to the square root of the PSD, and the result is inverse-Fourier-transformed to obtain the process with the desired covariance function.

The step-by-step practical implementation of the 3-D dielectric constant profile goes as follows:

- Generate a 3-D real random number array of the desired dimensions, with zero mean and unit variance (3-D “white noise”).
- Take a 3-D fast Fourier transform (FFT) of this array to the spectral domain (or  $k$ -space).

- Multiply the new complex 3-D array element-by-element with a 3-D transfer function  $H(\mathbf{k}) = \sqrt{W_\varepsilon(\mathbf{k})}$ , where  $W_\varepsilon(\mathbf{k})$  is the PSD given by one of Eqs. 6a or 6b. Note that, when implementing the expressions in Eqs. 6a or 6b, the  $k$ -vector components,  $k_x$ ,  $k_y$ , and  $k_z$ , must take on values according to the FFT sampling rules.
- Take a 3-D inverse FFT back to the spatial domain. The new array contains the dielectric constant deviation with respect to the mean.
- Taper the dielectric constant deviation to zero toward the computational domain edges (as explained in a subsequent paragraph).
- Truncate the dielectric constant deviations to  $\pm 3\sigma_\varepsilon$ , ensuring the values obtained at each spatial sample point make physical sense.
- Add the dielectric constant deviation to the mean (background) dielectric constant.

A schematic description of these implementation steps is shown in Fig. 15. Since we assume the conductivity is perfectly correlated to the dielectric constant, the procedure need not be repeated to obtain the 3-D conductivity profile. Instead, we pick the mean conductivity value and the upper and lower truncation limits, establish the linear dependence between the two properties within these limits, and assign the conductivity at each sample point based on the previously determined dielectric constant at the same point.

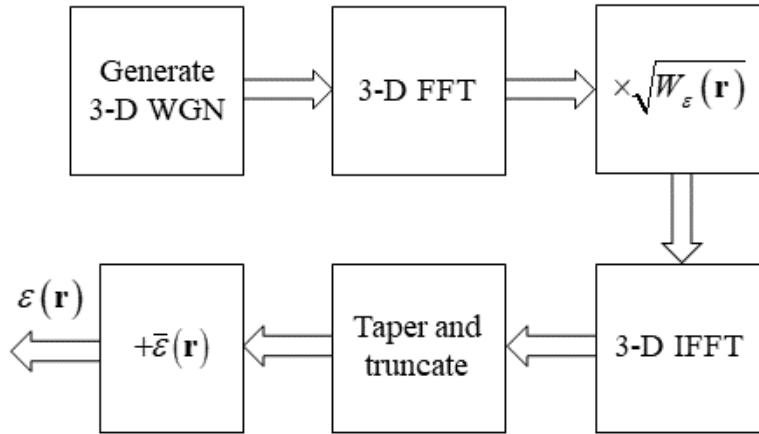
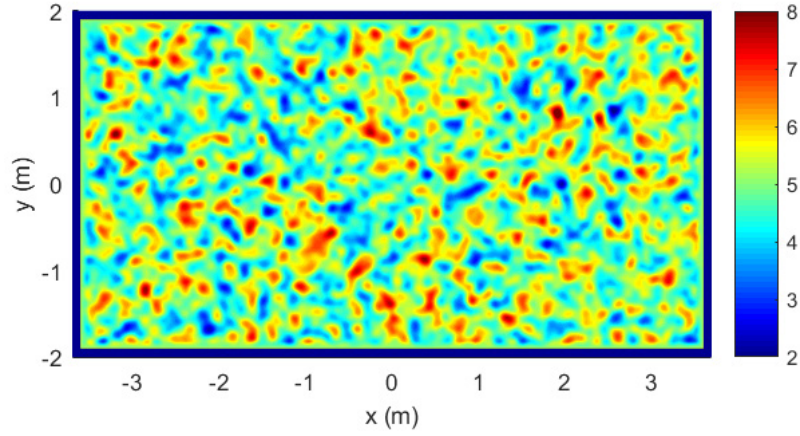
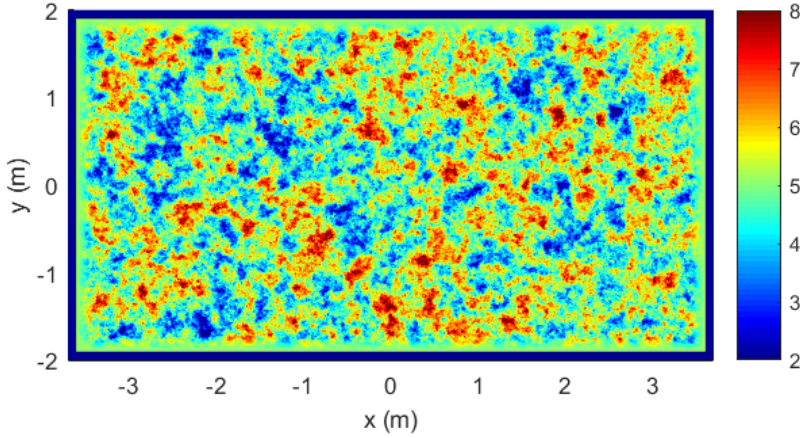


**Fig. 15** Numeric procedure for generating the soil dielectric constant fluctuations as a 3-D random process with a given covariance function.  $W_\varepsilon(\mathbf{r})$  stands for the PSD of the process and WGN for “white Gaussian noise”.

Examples of the dielectric constant maps obtained by this procedure are shown in Fig. 16, using a Gaussian (Fig. 16a) and an exponential (Fig. 16b) covariance function. Only 2-D cuts through the 3-D volume are shown here, since the same statistics are encountered in all three Cartesian directions. One can clearly see that, even though we used the same correlation lengths in both cases, the exponential profile displays permittivity fluctuations with more prominent fine structure (or high-frequency content), whereas the Gaussian profile variation is generally smoother.



(a)



(b)

**Fig. 16** Dielectric constant maps representing soil permittivity fluctuations obtained by the procedure outlined in this section for the a) Gaussian covariance function and b) exponential covariance function. Only horizontal 2-D cuts through the 3-D volume are shown. In both models, the dielectric constant mean is 5, its RMS deviation is 0.8, while the correlation length is 0.1 m. The associated color bars represent dielectric constant values.

The dark-blue outer frame of the maps in Fig. 16 represents the perfectly matched layer (PML) region in the finite-difference, time-domain (FDTD) computational

domain.<sup>17</sup> The PML must be matched to a fixed permittivity value, which is the background (or mean) permittivity of the soil. Therefore, to avoid spurious (non-physical) reflections, the dielectric fluctuations cannot extend into the PML region; moreover, the permittivity must be set to the same background value in the immediately neighborhood of the PML. That explains the tapering of the dielectric constant deviation toward the computational domain edges previously mentioned. In our implementation, we used a half-cosine window with the width of one correlation length for this purpose.

A major limitation of the soil dielectric fluctuation model implemented in this report is the failure to account for variations in the mean dielectric properties with depth. Although these variations have been documented by some investigators as occurring in natural environments,<sup>32–33</sup> our current simulation tools cannot accommodate such models. One possible issue is related to generating such a permittivity profile, which now becomes a nonstationary process (the statistics depend on the  $z$  coordinate). However, if only the mean of the process (not the variance or covariance) depends on depth, then the same generation procedure previously outlined can be used in this case, with the exception that the mean (background) dielectric constant and conductivity added in the last step vary with depth. The more substantial obstacle to implementing this model has to do with the PML in the AFDTD software, whose properties would have to follow the continuous variations of the background permittivity with depth. Although theoretically possible, we are not aware of any existing FDTD implementation that can accommodate such a complex PML structure.

Nevertheless, we believe that the soil dielectric fluctuation models introduced in this work are useful in understanding the radar clutter phenomenology induced by these fluctuations. One important conclusion of the numerical simulations in Section 4 is that the largest impact of the soil inhomogeneities shows up close to the air–ground interface (similarly to the rough surface clutter); therefore, their exact behavior at large depths is most likely of secondary importance in terms of radar clutter. Moreover, the measurements described by Igel and Preetz<sup>10</sup> suggest that the dielectric fluctuations in the soil become muted below a certain depth. Undoubtedly, all these factors in the model are dependent of specific geographical location. Future investigations and improved simulation tools should allow the implementation of more realistic models and shed more light on these important issues related to clutter in GPR sensing.

## 4. Quantitative Evaluation of the Ground Clutter and Target-to-Clutter Ratio

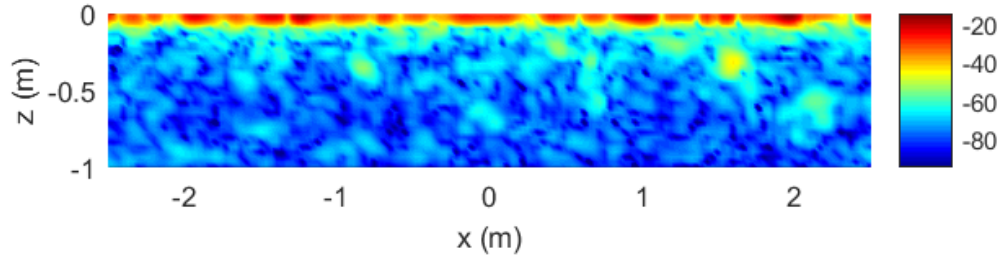
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### 4.1 Clutter Maps Obtained with the GPR Imaging System

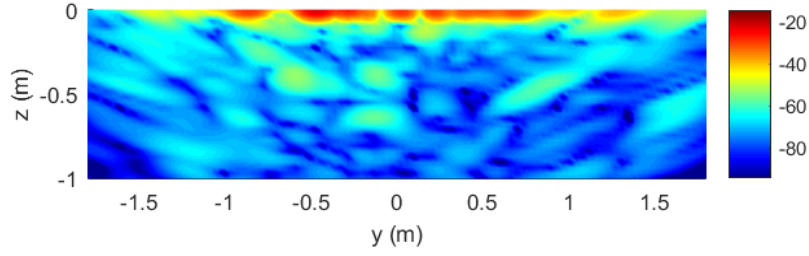
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Large-scale simulations of the GPR imaging system described in Section 2 were performed to obtain a quantitative evaluation of the clutter levels induced by the soil inhomogeneities described in Section 3 for various statistical model parameters. In this section, we present the clutter maps obtained from these simulations in a format similar to those shown in Section 2.4, where we analyzed the rough ground surface clutter.

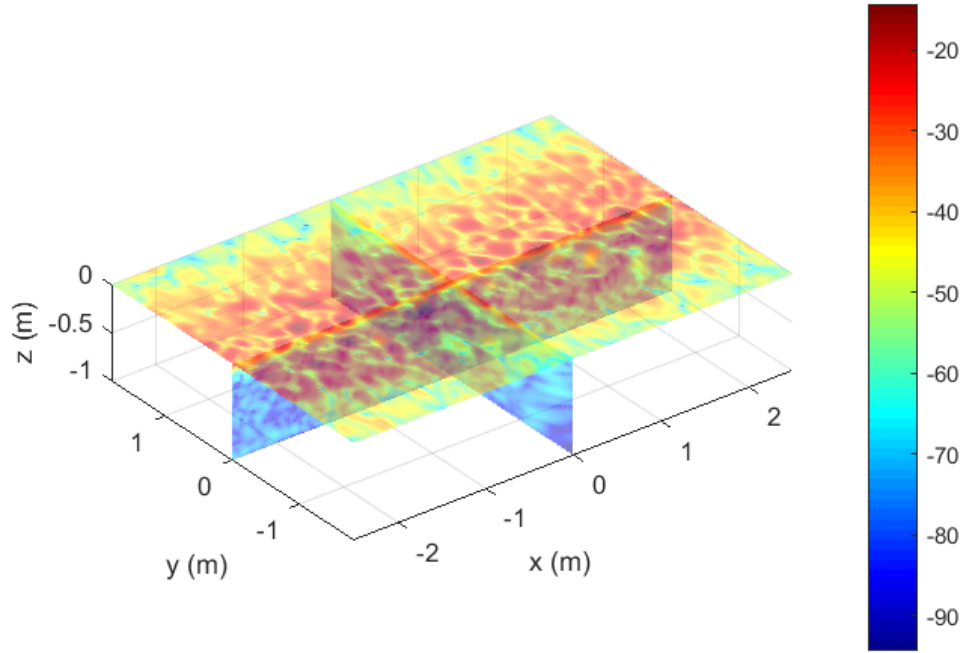
As a prototypical case, we consider a random distribution of soil properties with dielectric constant mean and RMS deviation of  $\bar{\epsilon} = 5$  and  $\sigma_{\epsilon} = 0.8$ , respectively, and Gaussian covariance with correlation length  $L_{\epsilon} = 0.1$  m. The mean and RMS deviation for conductivity are  $\bar{\sigma} = 0.02$  S/m and  $\sigma_{\sigma} = 0.003$  S/m, respectively. The same linear relationship between the dielectric constant and conductivity is preserved through all the other simulations in this section. Planar cuts through the image obtained with the 3-D GPR system are shown in Fig. 17 in the  $y = 0$ ,  $x = 0$ , and  $z = 0$  planes, respectively. The resemblance with the images in Fig. 13, obtained in presence of rough surface clutter, is remarkable: the clutter level is very strong at the air–ground interface level (for a layer with thickness of about one resolution cell), then has a sharp drop and continues to decrease as we advance in depth.



(a)



(b)



(c)

**Fig. 17** 3-D image of inhomogeneous soil with dielectric constant mean of 5, RMS deviation of 0.8, correlation length of 0.1 m, and Gaussian covariance in the following representations: a) 2-D cut in the vertical  $y = 0$  plane; b) 2-D cut in the vertical  $x = 0$  plane; c) perspective view showing cuts through the planes  $x = 0$ ,  $y = 0$ , and  $z = 0$

This behavior has a relatively simple physical explanation. The radar wave reflection is always strong at the air–ground interface, where it transitions from one propagation medium to another. Even after subtracting the coherent average signal, there is still residual scattering due to the soil permittivity fluctuations in the horizontal direction. Again, the dielectric contrast at the transition from air to ground (now measured against the permittivity fluctuations with respect to the mean) produces strong backscattering, visible in the top layer of the radar images. As the incident wave propagates past that layer, it incurs volume scattering due to permittivity fluctuations in the soil medium, but this phenomenon is considerably weaker than the surface scattering previously described. At the same time, the down-propagating incident wave is attenuated along the way, meaning the up-propagating wave scattered back to the radar by deeper layers decreases in magnitude.

Continuing the parallel with the images obtained in the presence of rough surface clutter, we show the clutter maps obtained by the 2-D GPR imaging system (Fig. 1a), before and after coherent mean subtraction, in Fig. 18. These images look very similar to those generated by the rough surface in Fig. 11. Clearly, in the images obtained by the 2-D system (Fig. 18), the high-level clutter extends much deeper inside the ground medium than in their 3-D counterparts (Fig. 17). The explanation is identical to that offered in Section 2.4: strong scattering centers at the air–ground interface placed outside the image plane ( $y = 0$ ) create ambiguity curves that project at various depths onto the image plane. Note that the volume scattering occurring in deep layers of the inhomogeneous ground is not the main source of the differences between the 2- and 3-D imaging scenarios. It is primarily the scattering occurring at the interface that makes the difference between the two, which explains the similarities with the rough ground surface clutter maps. In both clutter scenarios, going from a 2-D to a 3-D imaging capability of the GPR system produces a significant reduction in the clutter level, which in turn has a positive impact on the radar detection performance.

An elegant explanation of the large differences in clutter appearance in the  $y = 0$  plane image between the 2- and 3-D cases can be made by invoking the conservation of energy between the radar measurement and the radar image. In the tomographic interpretation of radar imaging,<sup>39</sup> the image is the multidimensional (2-D or 3-D) Fourier transform of the radar data. (Note: The tomographic interpretation of radar imaging is not rigorously valid for GPR sensing scenarios; however, it offers a good-enough model for the argument made in this paragraph.) By virtue of Parseval’s theorem, the energy (or cumulative power) in the two sets of data should be preserved, up to a constant scaling factor. In the 2-D image, the entire clutter energy must be distributed across the 2-D domain; however, in the

3-D image, the clutter energy has room to spread out over the additional dimension. Thus, most of the underground clutter visible in the  $y = 0$  plane 2-D image is distributed across the  $z = 0$  plane of the 3-D image, significantly reducing the underground ( $z < 0$ ) clutter level in the latter.

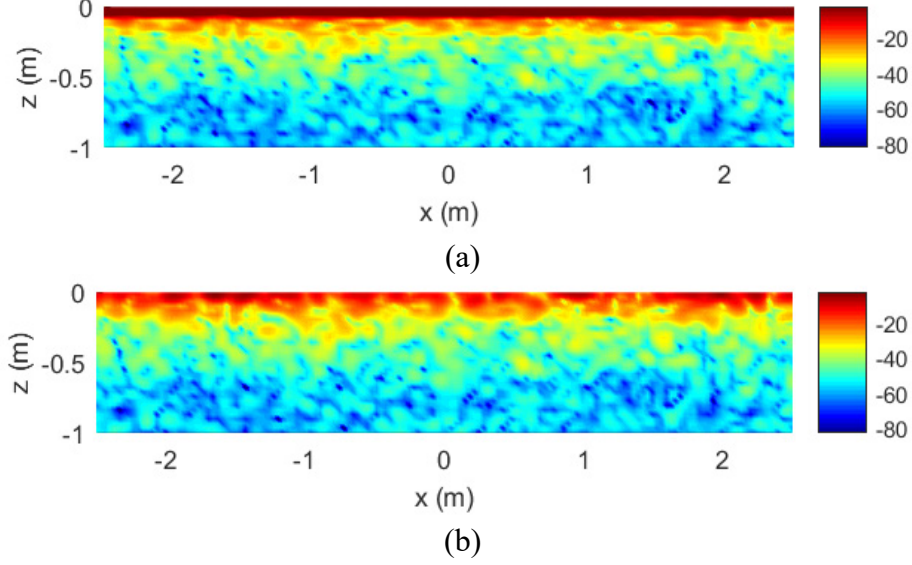


**Fig. 18** 2-D images in the  $y = 0$  plane obtained with a linear aperture in the  $x$  direction, in the presence of inhomogeneous soil clutter with the same parameters as in Fig. 17, obtained a) from raw radar data (no mean subtraction); b) after subtracting the along-track coherent-mean signal

The parametric study of the clutter induced by soil dielectric fluctuations consists of varying the dielectric constant's RMS deviation and correlation length, as well as considering exponential covariance in addition to the Gaussian type. In Fig. 19, we show the planar cut in the  $y = 0$  plane through the images obtained with the 3-D GPR system for all these cases. For a fair comparison, the dynamic ranges of all images were set between the same limits (from  $-20$  down to  $-100$  dB).

Although there are some small differences in the scattering strength of the top layer, the more pronounced differences among the scenarios considered in Fig. 19 occur at larger depths. As expected, increasing the dielectric constant RMS deviation from 0.4 to 0.8 and to 1.2 (Figs. 19b, 19a, and 19c, respectively) produces stronger returns (higher image magnitude) due to enhanced volume scattering at deep levels. Likewise, reducing the correlation length from 0.2 to 0.1 to 0.05 m (Figs. 19d, 19a, and 19e, respectively) leads to an increase in deep-clutter magnitude. At the same time, the soil with exponential covariance produces significantly stronger clutter than the soil with Gaussian covariance for equal RMS deviation and correlation length (compare Figs. 19a and 19f).

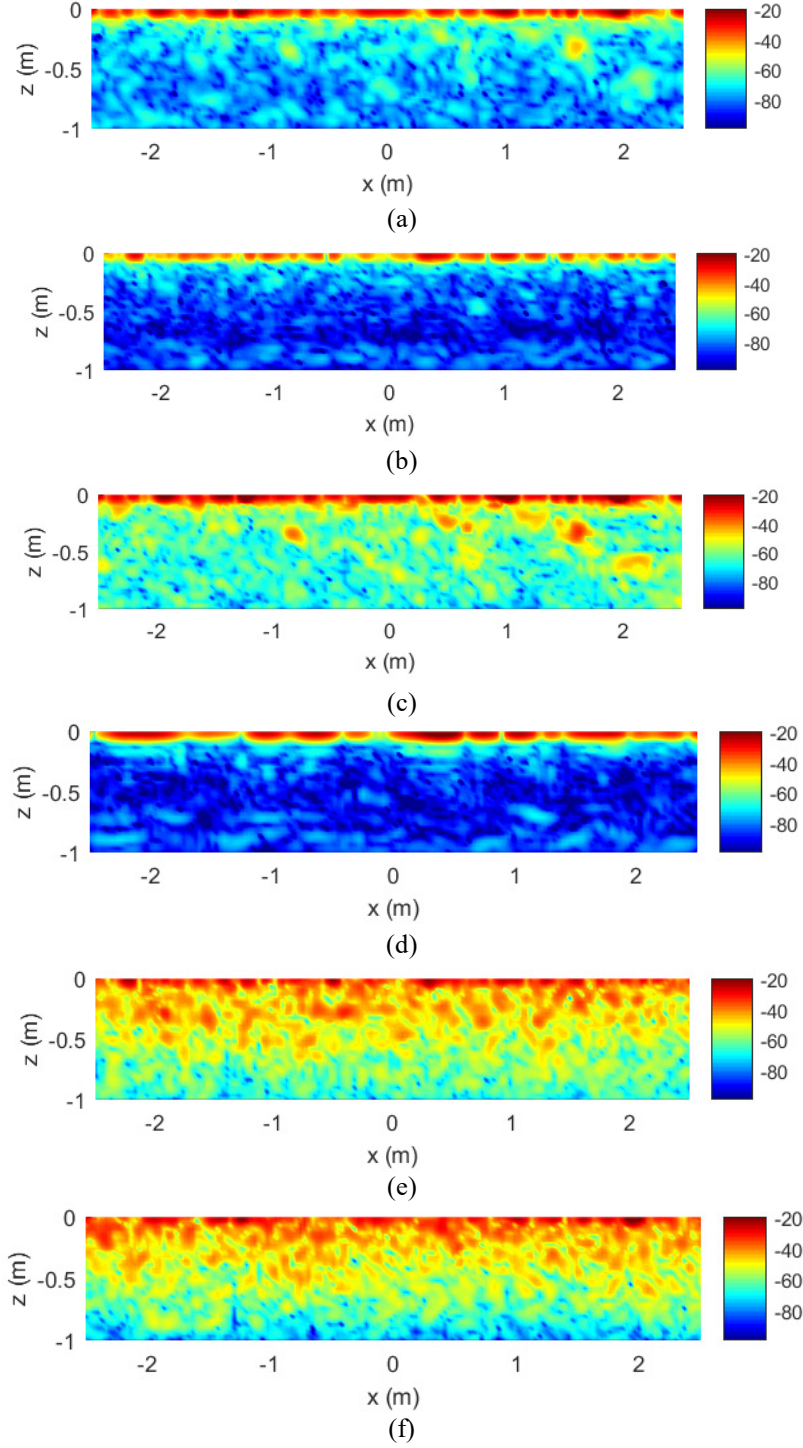


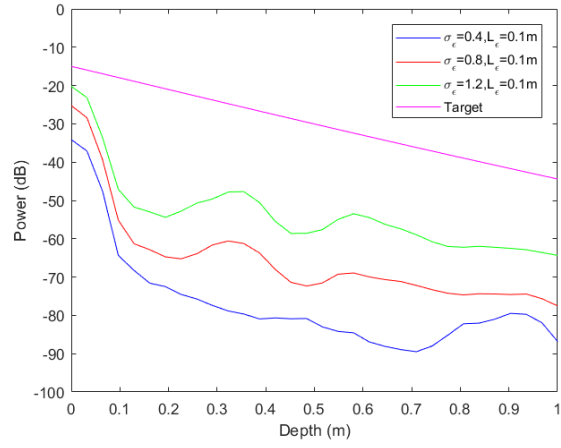
**Fig. 19** Vertical plane ( $y = 0$ ) cuts through the 3-D image of clutter generated by inhomogeneous soil with dielectric constant mean of 5 and the following fluctuation parameters: a)  $\sigma_\epsilon = 0.8$ ,  $L_\epsilon = 0.1$  m; b)  $\sigma_\epsilon = 0.4$ ,  $L_\epsilon = 0.1$  m; c)  $\sigma_\epsilon = 1.2$ ,  $L_\epsilon = 0.1$  m; d)  $\sigma_\epsilon = 0.8$ ,  $L_\epsilon = 0.2$  m; e)  $\sigma_\epsilon = 0.8$ ,  $L_\epsilon = 0.05$  m; f)  $\sigma_\epsilon = 0.8$ ,  $L_\epsilon = 0.1$  m. In all cases, the covariance is Gaussian, except for f), where exponential covariance was considered.

## 4.2 Target and Clutter Power vs. Image Depth

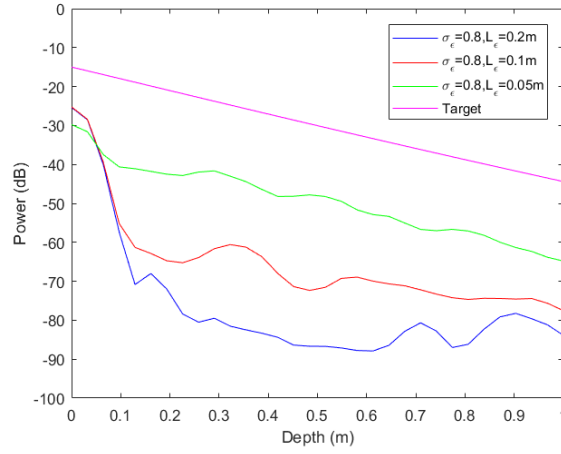
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Although the images displayed in the previous section offer useful visual cues with regard to the impact of various parameters on the inhomogeneous ground clutter, a more precise quantitative assessment can be obtained by computing the mean clutter power at constant image depth. As in the rough surface case (Section 2.4), we only consider the  $y = 0$  plane in the 3-D images created in the presence of soil dielectric fluctuations and evaluate the mean clutter power at a given depth by taking into account all the voxels along the horizontal line at that depth.

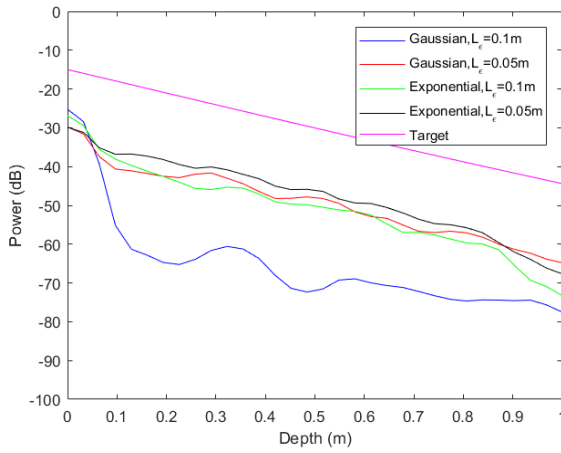
The mean clutter power for all the various sets of parameters considered in Fig. 19, together with the peak voxel power generated by a point target, is plotted as a function of image depth in Fig. 20. The target image magnitude calibration was discussed in Section 2.3. The TCR, which is simply the difference between the decibel values of the target and mean clutter power, is plotted as a function of image depth in Fig. 21 for the same sets of parameters. In Figs. 20c and 21c, we compare the various metrics between soil inhomogeneities with Gaussian and exponential covariance statistics. The graphic results reinforce the conclusions in Section 4.1: at depths beyond one resolution cell (0.1 m), the clutter power becomes larger as the dielectric constant RMS deviation increases and the correlation length decreases. Also, permittivity fluctuations with exponential covariance create stronger clutter than the Gaussian counterpart, all the other parameters being equal.



(a)

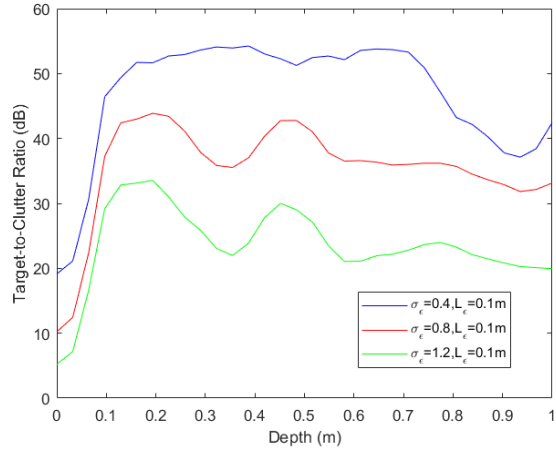


(b)

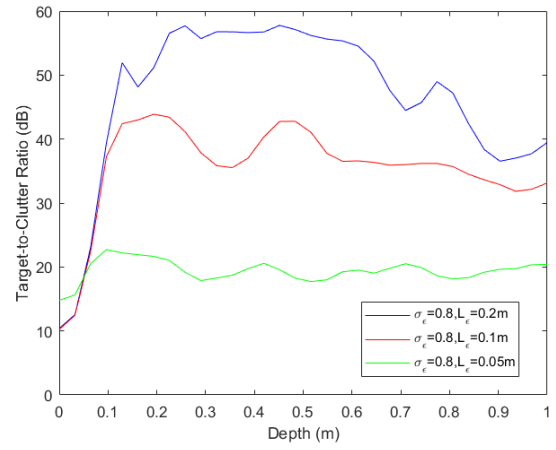


(c)

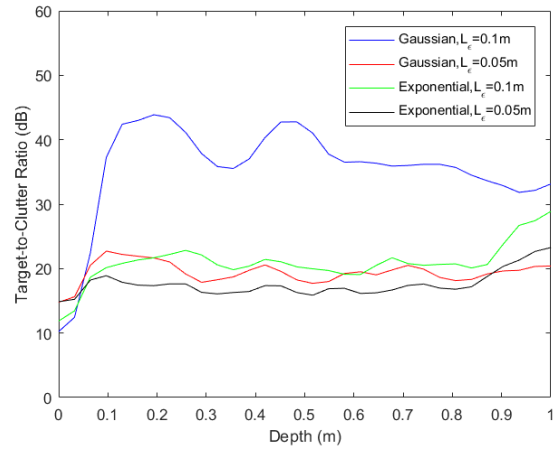
**Fig. 20** Target and mean clutter power vs. depth in the 3-D SAR images for a) various dielectric constant RMS deviations; b) various correlation lengths; c) two different types of covariance function



(a)



(b)



(c)

**Fig. 21 TCR vs. depth in the 3-D SAR images for a) various dielectric constant RMS deviations; b) various correlation lengths; c) two different types of covariance function**

Several additional comments can be made with regard to the graphs in Figs. 20 and 21. The large drop in clutter power around 0.1-m depth seems to occur only for correlation lengths of at least 0.1 m and Gaussian covariance. For  $L_\varepsilon = 0.05$  m (with Gaussian covariance), as well as for exponential covariance, the drop is much smaller, indicating that, when the permittivity fluctuations have strong high-frequency content, they continue to generate strong backscattering at depths beyond the first resolution cell.

At the current stage of this investigation, we cannot offer a rigorous theoretical explanation of the underground image clutter power increase with diminishing correlation length. Several analytical models of EM wave propagation in random media that take into account multiple scattering effects have been developed, such as the strong permittivity fluctuation theory or the quasi-crystalline approximation.<sup>40</sup> Unfortunately, those models have very limited applicability to the scenario investigated in this report.

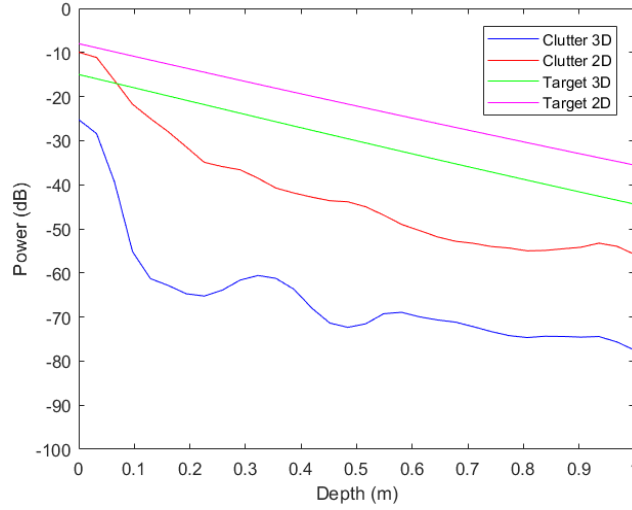
A more useful model in explaining the inhomogeneous ground clutter behavior was developed by Takahashi,<sup>13</sup> by considering single scattering from a dielectric sphere buried in homogeneous soil with dielectric contrast equal to  $\sigma_\varepsilon$  and diameter equal to  $L_\varepsilon$ . (Note: Since Takahashi employs a different definition of the correlation length, we translated the sphere's dimensions to units compatible with the quantities used in this report.) He found that the sphere has maximum radar cross section when  $L_\varepsilon$  equals approximately 0.43 wavelengths (measured in the ground medium), which coincides with the clutter maximum as a function of correlation length in his field GPR measurements. This is also consistent with our numerical models, where the wavelength in the ground at the center frequency of operation (1.25 GHz) is 0.1 m, so the case  $L_\varepsilon = 0.05$  m, which generates very strong clutter in the radar image, corresponds to a correlation length of 0.5 wavelengths. In both models, as well as in the measurements, the clutter power decreases for correlation lengths above this threshold.

Nevertheless, the behavior is less clear for correlation lengths smaller than half a wavelength. Takahashi's model seems inconsistent with the measurements in that regime, whereas our numerical models do not extend into that parameter range. Heuristic reasoning suggests that, when the spacing between distributed scatterers becomes smaller than half a wavelength, the multiple scattering effects should become significant. Therefore, the single scattering model described in the previous paragraph is less likely to be valid, and the clutter power may continue to increase for even smaller correlation length. Future studies should hopefully clarify this dependency for a wider range of parameters.

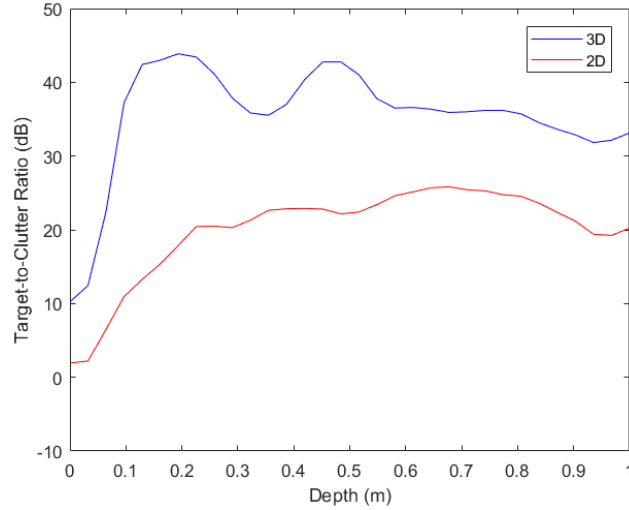
Another observation on the graphs in Figs. 20 and 21 is related to the fact that the mean clutter power curves generally follow the slope of the wave attenuation in the background medium, which is identical to the slope of the target power versus depth (see Fig. 10). However, some of the mean clutter power curves exhibit fairly large fluctuations about the trend lines—these are mostly due to the insufficient number of voxels used in computing the average at each depth. The effect may be exacerbated by the ability of the image focusing process to isolate some inhomogeneity “pockets” into well-defined, bright image features. These are particularly visible in the images obtained for a correlation length comparable to the resolution cell size ( $L_\varepsilon = 0.1$  m).

Nevertheless, we notice that, at depths beyond 0.1 m, the TCR remains largely constant with depth, due to the fact that both target and mean clutter power follow the same trend as the two-way wave attenuation in the medium. In two cases where the clutter power is very low (the sets of parameters  $\sigma_\varepsilon = 0.4$  m,  $L_\varepsilon = 0.1$  m and  $\sigma_\varepsilon = 0.8$ ,  $L_\varepsilon = 0.2$  m), we notice a slight increase in the mean clutter power at very large depth (beyond 0.7 m), which causes the TCR to drop in those regions. We believe those effects are produced by image formation artifacts (or possibly AFDTD modeling artifacts), which start to show up at those extremely low clutter levels of  $-80$  dB.

We can also compare the target, the mean clutter power and the TCR as a function of depth between the 2- and 3-D imaging systems. This is shown in Fig. 22, where we can clearly see the large improvement in TCR (of 15–20 dB) obtained with the 3-D system over the 2-D version once the depth exceeds the size of one resolution cell.



(a)



(b)

**Fig. 22 Comparison between the target and mean clutter power as a function of depth in 2- and 3-D images: a) target and mean clutter power; b) TCRs for the same scenarios**

The reader should be cautioned against drawing over-optimistic conclusions from the simulation results showing TCR numbers in the 40- to 50-dB range (which would virtually ensure perfect detection performance). As a reminder, these results were obtained for a somewhat artificial point target calibration, which is only representative for one type of physical targets. Additionally, the statistical parameters of the permittivity fluctuation models were set in a range that may only characterize soils in certain geographical regions. Note in the simulated cases where the clutter has the largest power, the TCR is limited to about 20 dB. More importantly, when the power of permittivity fluctuation-generated clutter is very low, it is likely that thermal noise or other clutter sources may limit the radar

system's detection performance. Nevertheless, the inhomogeneous ground clutter trends established in this report should be generally valid in a wide variety of scenarios. Additionally, the performance differences between 2- and 3-D imaging are an important result with direct implications on potential design choices for future GPR systems.

## 5. Conclusions

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This report investigated radar clutter properties in down-looking GPR imaging systems and its impact on target detection performance. The main application we had in mind was a UAV-based, UWB, 3-D GPR imaging system capable of detecting buried explosive hazards for road clearing operations. The major emphasis was on clutter produced by volumetric soil permittivity fluctuations, although rough ground surface clutter was also investigated from a phenomenological viewpoint.

After describing the parameters of the GPR imaging system, the modeling methodology, and the imaging algorithm, we presented a detailed discussion of issues involved in developing the antenna array and arrived at a design solution that minimizes the number of simultaneously Tx–Rx active pairs while preserving acceptable image quality. An important conclusion was that a relatively large number of Tx elements are required along the array length to ensure uniform illumination of the entire image. This is a consequence of the near radar–target range characteristic to down-looking GPR systems and stands in contrast with MIMO array designs of far-range radar systems, where two Tx elements are typically sufficient for that purpose.

The clutter produced by rough ground surfaces in down-looking GPR systems was briefly analyzed in Section 2.4, emphasizing the differences between 2- and 3-D imaging systems. A somewhat surprising phenomenon is the clutter's extension deep into the radar image, well beyond the physical location of the air–ground interface height fluctuations. This effect is more pronounced in 2-D images obtained with a linear aperture and can be explained by the ambiguities produced by scattering centers outside the image plane, which project onto the image plane at various depths. The most effective way to mitigate this problem is to create 3-D images by employing a 2-D aperture, thus adding resolution in the third dimension.

To investigate the clutter induced by ground inhomogeneities, we first developed statistical models of the dielectric constant and conductivity fluctuations in the soil medium. These were treated as 3-D stationary random processes with a Gaussian PDF and one of two covariance function types (Gaussian or exponential). The numerical procedure employed in generating these permittivity fluctuations and its

implementation in the AFDTD EM simulation software were described in Section 3 of the report.

The results of GPR imaging simulations in the presence of clutter produced by soil inhomogeneities were summarized in Section 4, where we presented the variation of the mean image clutter power as a function of depth. The most important conclusions for 3-D images are that, for many realistic inhomogeneity distributions, the clutter is very strong in a thin layer close to the air-ground interface and its power drops significantly at larger depths. In general, this means targets buried at very shallow depths may be more difficult to detect without applying additional clutter mitigation procedures. However, as long as the soil permittivity fluctuations conform more or less to the models developed in this study, they should only have a marginal impact on the GPR system detection performance for deep buried targets. The simulations also emphasized the significant improvements in terms of TCR afforded by a 3-D imaging system as compared to its 2-D counterpart.

In terms of clutter power variation with the statistical parameters of the soil dielectric fluctuation model, we found, as expected, that large RMS deviations from the mean permittivity create stronger clutter. At the same time, the image clutter power appears to increase as the correlation length decreases. For the same RMS deviation and correlation length, the exponential covariance model induces larger clutter power than the Gaussian counterpart.

Throughout the report, we discussed various limitations of the clutter models and the simulation methods available for this study. Although the soil dielectric fluctuation parameters were taken within ranges consistent with measurement data available in the literature, they are not necessarily representative of a specific geographic area or terrain type. Instead, we focused on inferring general trends discernable in GPR image clutter, hoping they could assist the radar engineers to design more-performant systems. One striking and somewhat unexpected result is the similar appearance of the rough surface and the volumetric soil inhomogeneity clutter in the underground radar images. Another important conclusion is the large performance improvement that can be achieved by upgrading the GPR system from a 2-D to a 3-D imaging capability. In a follow-up study, we plan to simulate the 3-D GPR imaging system described in this report in the presence of realistic targets encountered in CEH applications.

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## List of Symbols, Abbreviations, and Acronyms

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|        |                                                 |
|--------|-------------------------------------------------|
| 1-D    | one-dimensional                                 |
| 2-D    | two-dimensional                                 |
| 3-D    | three-dimensional                               |
| ARL    | Army Research Laboratory                        |
| CEH    | counter-explosive hazard                        |
| CPU    | central processing unit                         |
| DEVCOM | US Army Combat Capabilities Development Command |
| EM     | electromagnetic                                 |
| FDTD   | finite-difference, time-domain                  |
| FFT    | fast Fourier transform                          |
| GPR    | ground-penetrating radar                        |
| HPC    | high-performance computing                      |
| MIMO   | multiple-input multiple-output                  |
| PDF    | probability density function                    |
| PML    | perfectly matched layer                         |
| PSD    | power spectral density                          |
| PSF    | point spread function                           |
| PTR    | point target response                           |
| RMS    | root mean square                                |
| Rx     | receiver                                        |
| SAR    | synthetic aperture radar                        |
| TCR    | target-to-clutter ratio                         |
| Tx     | transmitter                                     |
| UAV    | unmanned aerial vehicle                         |
| UWB    | ultra-wideband                                  |

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K GALLAGHER  
B PHELAN