Modeling GPR Signal Degradation from Random Rough Ground Surface

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Abstract--**This study attempts to quantify the clutter variation with ground roughness by numerically simulating the wideband scattering of experimentally measured GPR signals by realistic, dispersive soil interfaces. We employ a 2D finite difference time domain (FDTD) method to analyze the delay and amplitude characteristics of ground scattered waves as a function of roughness parameters. Five hundred Monte Carlo simulations of each test case of specified ground root mean square height and correlation length were run with and without a nonmetallic mine target to generate statistics for the clutter and target signal variations. Results indicate that even with moderate roughness, statistics can be generated to enhance the detection of small, shallow, low contrast targets.**

1. INTRODUCTION

The problem of detecting buried dielectric targets -- such as nonmetallic antipersonnel mines -- with ground penetrating radar (GPR) is important and challenging. Because the dielectric constant of the mine target is similar to that of the surrounding soil and its size is comparable to the thickness of soil above it, detection and discrimination are difficult. In addition, the soil dielectric constant may not be well characterized, and the ground surface will usually be rough, often with roughness of the order of the target burial depth.

Impulse ground penetrating radar has been used as a robust and relatively inexpensive means of detecting underground objects. By observing the arrival time of a subsurface scattered pulse and eliminating the reflection from the ground surface by time gating, it is possible to detect deeply-buried anomalies. However, when the target is small, shallow, and of low contrast, special modeling and processing are required to characterize and separate the ground surface clutter from the target signal. A commonly used procedure of background averaging to remove the ground clutter signal can be effective for very smooth ground surfaces, but tends to rapidly degrade for moderate roughness. We simulate the effects of rough ground on the GPR signal using Monte Carlo FDTD modeling of random surface variation. The 2-D TM FDTD code is specifically adapted to frequency-dependent, lossy media, with a lossy Perfectly Matched Layer (PML) ABC [1]. As a baseline, we model the field for a typical bistatic GPR geometry (Fig. 1a), using the measured Geo-Centers TEMR GPR antenna element radiated signal as the excitation (Fig. 1b). The FDTD time and space steps are Δt=20ps and Δ=1.22cm. Simulations are done for 500 surface realizations with and without a mine target at 8.5cm below the nominal surface level for a variety of roughness statistics. Both the probability density function of the height and the surface profile spectrum are assumed Gaussian [2,3].

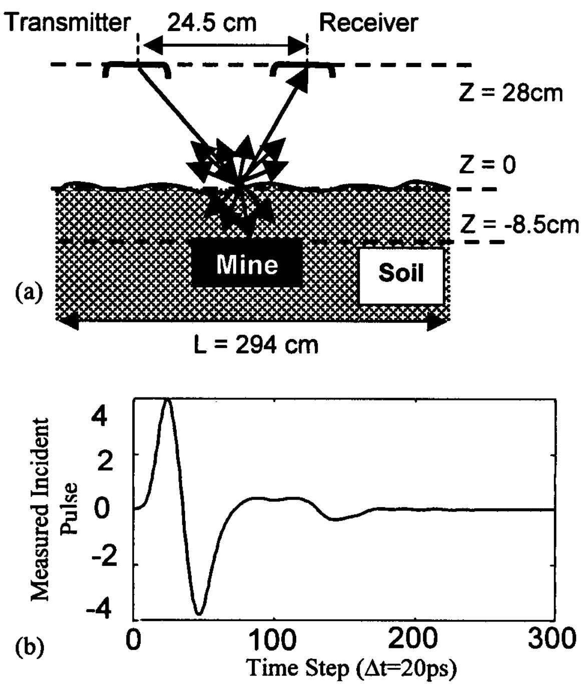

Figure 1: a) Rough surface computational geometry, and b) incident measured waveform

2. FORMULATION

The factors considered as metric measures for the signal statistics are the average time shift and the average scaling of the signal. The Monte Carlo simulations and the cross-correlation function will be used to calculate these statistics. The results will show the effect of the rough surface parameters on these factors.

The cross-correlation function indicates the inter-dependence of the values of two different processes at two different times. Normalizing this function between reference signal '*f*' and any realization signal '*i*' to the energy in the signals gives:

$$C_{fi}(m) = \frac{\sum_{n=1}^{N-|m|} S_f(n) S_i(n+m)}{\sqrt{\sum_{n=1}^{N} |S_f(n)|^2} \sqrt{\sum_{n=1}^{N} |S_i(n)|^2}}, \text{ for m} > 0 \quad (1a)$$

$$C_{fi}(m) = C_{if}(\text{-m}), \qquad \text{for m} < 0 \quad (1b)$$

The relative scaling will be defined as:

$$A_i = \sqrt{\sum_{n=1}^{N} |S_i(n)|^2} / \sqrt{\sum_{n=1}^{N} |S_f(n)|^2} \qquad (1c)$$

where i =1, 2, 3,...M is the rough surface realization index, M is the size of Monte Carlo sample, and N is the total number of time steps.

3. NUMERICAL RESULTS

Scatter plots of the shifts of the ground scattered signals $\tau_{gnd(i)}$ and the mine scattered signals $\tau_{mine(i)}$ relative to a nominal perfectly flat ground for different rough surface parameters are shown in Fig. 2. The soil modeled is Puerto Rican clay loam with 10% moisture and 1.4 g/cc density, with average dielectric constant ε'= 6.2. These shifts are obtained by measuring the time delay between the cross correlation function of the scattered field realization C_{fi} and that of the reference signal C_{ff} as given in Eq. 1. For low contrast targets the dominant aspect of each scattered signal is the ground scattering, so the cross-correlation function gives $\tau_{gnd(i)}$. To find $\tau_{mine(i)}$, Eq. 1 is applied to the difference between the signal scattered by the ground and mine and the ground alone. The surface root mean square height is σ_h = 3cm in Fig. 2a and Fig. 2c while it is 2cm in Fig. 2b and Fig. 2d. The correlation length is l_c= 10cm in Fig. 2a and Fig.2c while it is 3cm in Fig. 2b and Fig. 2d. There is a strong correlation between $\tau_{gnd(i)}$ and $\tau_{mine(i)}$. A regression analysis is conducted to fit these simulated data with a straight line. The slope of this line corresponds to the relative delay between the ground and target scattered signals. The slope is negative and for very long correlation lengths would be $(1-\sqrt{\varepsilon'})$. As shown in Fig. 2, the fitting error increases with the root mean square slope σ_s= $1.414(\sigma_h/l_c)$ [4].

The clutter signal can be suppressed and consequently the target signal can be enhanced using physics-based signal processing in two steps. First, the average clutter signal is found by shifting each ground-only signal by $\tau_{gnd(i)}$, then taking the ensemble average [3]. Second, this average signal is shifted by $\tau_{gnd(i)}$, and scaled by factor A_i in Eq.(1c) for each mine-in-ground signal and subtracted from these signals. The 500 signals produced from this subtraction represent the signals scattered just from the target. The obtained shifts τ_i are amplified by the slope values of the straight lines shown in Fig. 2 and then used to align these target-only signals. This procedure can be performed during actual GPR operation in the field, using several mine-free calibration measurements as the average signal. Thus, the average signal for the mine is obtained for the same roughness parameters of Fig. 2 and shown in Fig. 3. Also shown are curves indicating the ±1 standard deviation (STD) range of the target signal as function of the time step. As expected, the standard deviation is much smaller for the target signal than for the clutter signals. Also visible in Fig. 3 is the increase of clutter with the surface mean square slope σ_s. Correlating any trial signal for a given statistical ground roughness and the average signal for that roughness with inverse weighting by the standard deviation provides a strong parameter for estimating the presence of a mine at a given position.

4. CONCLUSIONS

Identifying the time shift and amplitude scaling of the ground surface clutter by correlation with the ideal flat ground provides a means for clutter removal for a given signal. Shifting this clutter-suppressed signal by a time delay roughly proportional to the differential propagation velocity in the effective soil layer (or absence of soil) relative to the nominal soil level realigns the target signal to its expected temporal position. Using this procedure, even shallow buried nonmetallic mines signals can be distinguished from rough ground surface clutter signals using commercially available (nonideal) impulse GPR sources.

ACKNOWLEDGMENTS

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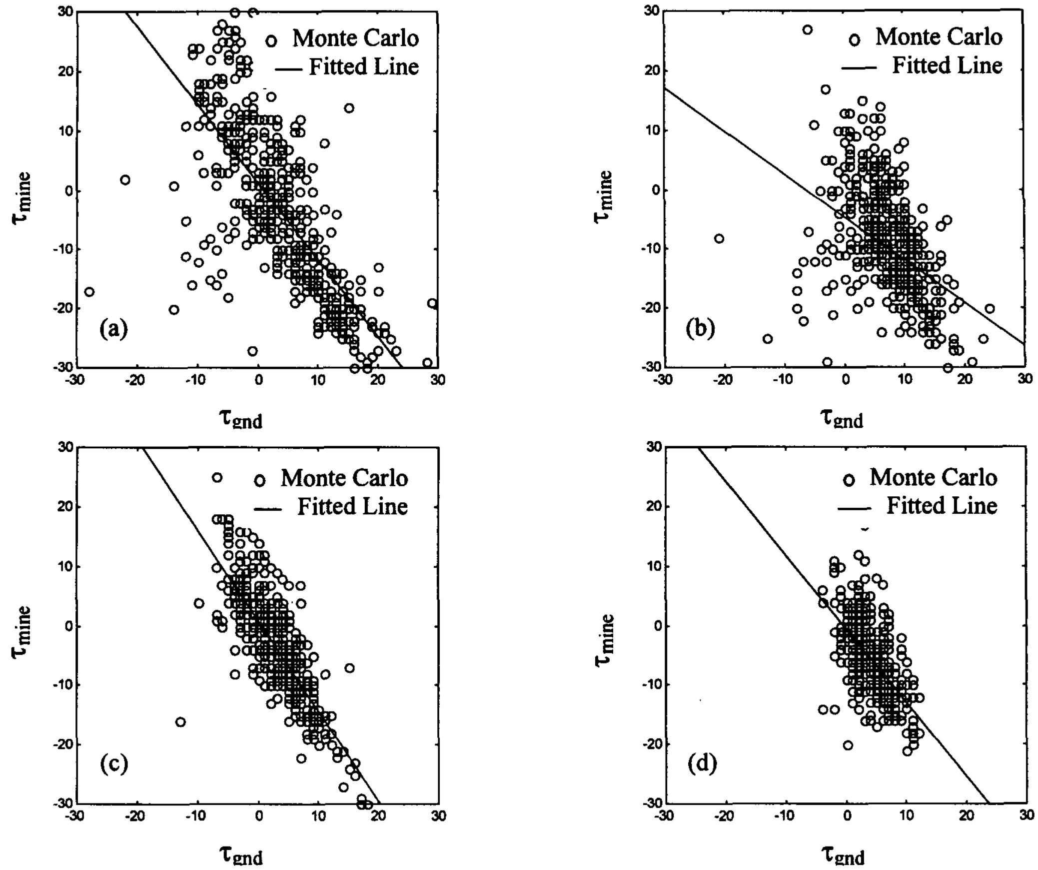

Figure 2: Shift of mine scattered signal versus shift of ground scattered signal for roughness: a) (σ_h, l_c) = (3cm,10cm), b) (σ_h, l_c) = (2cm,10cm), c) (σ_h, l_c) = (3cm,3cm), and d) (σ_h, l_c) = (2cm,3cm).

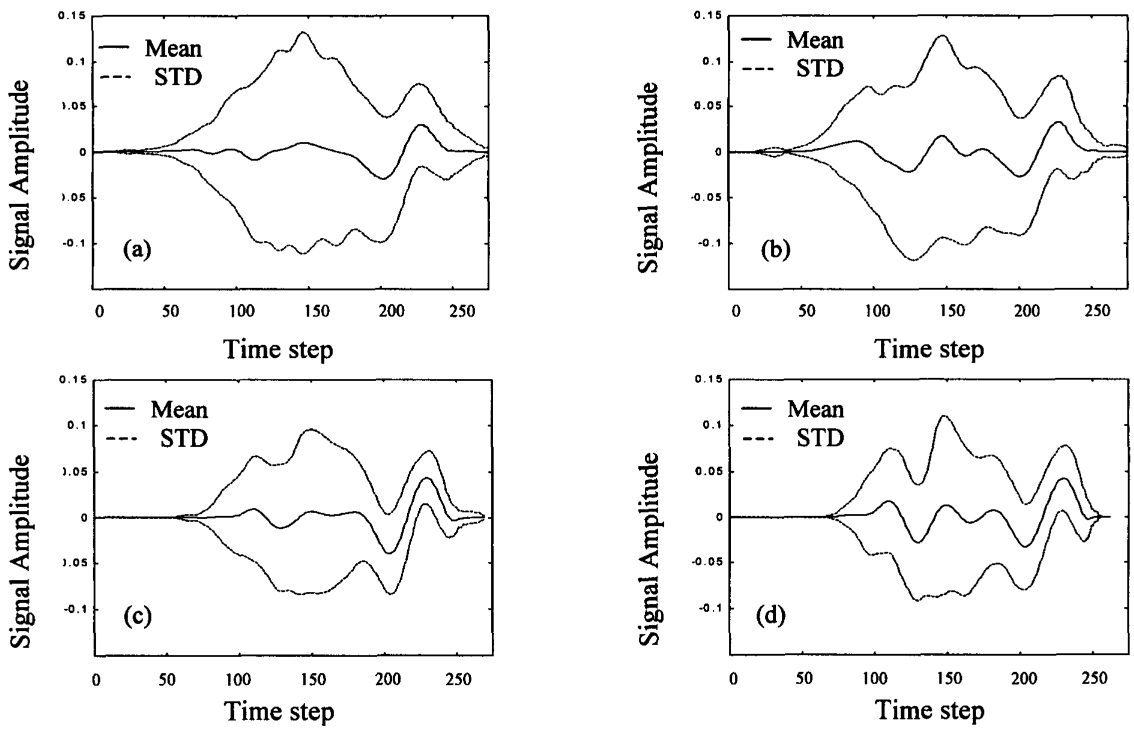

Figure 3: Average mine scatter signal with standard deviation ranges versus time step (Δt=20ps) for roughness parameters of Fig. 2