ADAPTIVE APPROACHES TO SUBSURFACE SENSING IN THE PRESENCE OF MODERATELY ROUGH AIR-SOIL INTERFACES

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ABSTRACT

An adaptive framework is presented for ultra-wideband ground penetrating radar imaging of low-contrast buried objects embedded in a homogeneous halfspace bounded by a moderately rough interface. The proposed approach relies on recently developed Gabor-based narrow-waisted Gaussian beam algorithms as fast forward scattering predictive models. Preliminary outcomes indicate that the proposed framework is attractive in comparison with standard statistical approaches. Possible applications involve antipersonnel land mine remediation.

INTRODUCTION

In ground penetrating radar (GPR) applications, a major source of variability in the observed signals is due to the distortion introduced by the twice-traversed rough air-ground interface, which the interrogating signal encounters on its way to and from the targets of interest. In some applications such as anti-personnel land mine remediation, where one typically has to deal with shallowly buried small targets having constitutive properties very close to those of the background soil, this *clutter* may introduce severe constraints on target localization and classification. Statistical Monte-Carlo-based approaches for clutter suppression, which work reasonably well in *detection* problems with small roughness [1], turn out to be not completely satisfactory for *localization* and *classification* in the presence moderate roughness [2]. These considerations motivated our recent investigations toward a more robust, physics-based, *adaptive* approach to subsurface imaging in the presence of a moderately (both in height and slope) rough air-soil interface. The proposed approach, so far restricted to two-dimensional (2-D) geometries, is based on the use of physical and statistical modeling techniques to estimate, and compensate for, the related clutter; it works with sparse data, and utilizes recently developed Gabor-based narrow-waisted Gaussian beam (GB) fast forward scattering models [3-5]. Both frequency-stepped [6, 7] and pulsed [8, 9] GPR configurations have been investigated. In this paper, we briefly review the proposed framework and discuss some representative results.

DESCRIPTION OF THE ADAPTIVE APPROACH

The problem strategy is illustrated in Fig. 1. A prior (coarse-scale) interface estimation problem is solved, which, by exploiting the GB fast forward models, is posed as a nonlinear optimization problem [6, 8]. This sets the stage for the actual inverse scattering problem, i.e., the *target imaging* in the presence of a *known* roughness profile. In particular, we focus on the important and challenging case of shallowly-buried low-contrast mine-like targets. An approximate Born-linearized forward model is utilized for the target scattering, wherein the distortion introduced by the twice-traversed roughness profile is accounted for via the Gabor-based quasi-ray fast forward solvers in [3-5]. The resulting reconstructed interface profile is used to correct the raw backscattered field data observed at the receivers so as to compensate for the corresponding clutter; at this stage, statistical models can be invoked to account, in addition, for noise, estimation error and residual unmodeled effects. The forward scattering model is subsequently inverted to retrieve the unknown dielectric permittivity contrast in a suitable test domain. In this connection, use is made of pixel-based and object-based regularization and reconstruction techniques [7, 9] (for algorithmic aspects, accuracy, limitations, and computational issues, see [7, 9]). The various tasks are summarized below.

Forward Scattering Models - The *backbone* of our approach consists of a number of recently developed approximate fast forward solvers for scattering by, and transmission through, moderately rough dielectric interfaces. These forward solvers, which rely on Gabor-based *quasi-ray* Gaussian beam (GB) algorithms in both the frequency (FD) [3] and time domains (TD) [4], have been validated and calibrated over relevant ranges of parameters against rigorous full-wave numerical reference solutions, and have been shown to furnish robust and reliable predictions with computing time and resource requirements considerably cheaper than those of typical full-wave solvers. The above results have so far been restricted to 2-D configurations involving moderate roughness and slightly lossy soils. Generalization to 3-D (vector) configurations is in progress [5].

Interface Profile Reconstruction - In the proposed approach, detailed in [6, 8], a compact low-dimensional spline parameterization of the roughness profile and the GB forward scattering model in [3, 4] are utilized to pose the interface reconstruction problem as a nonlinear optimization involving minimization of a least-square error functional that is based on the GB forward scattering prediction and the available observed data. The optimization strategies and computational issues are discussed in [6, 8]. The outcome was found to provide accurate and robust reconstructions (even with noisy data and imperfect knowledge of soil parameters) with reasonable computing times (~1 min. on a 700 MHz PC) and resources.

Target Reconstruction - The coarse-scale interface profile reconstruction is used to generate predictions of the ground scattering, which is then suppressed so as to leave the late-time observed data primarily representative of the underground target scattering contribution. For the low-contrast targets of interest here, the forward scattering model is linearized via the Born approximation, whereby an approximate GB-parameterized half-space Green's function is used to account for further rough-interface-induced distortion.

Various *pixel-based* and *object-based* regularization techniques have been explored in order to achieve reliable inversion of the forward scattering model and to cope with its inherent *ill-posedness*. Found to be particularly attractive was a *curve-evolution* approach [10], wherein the target homogeneity is enforced explicitly, thereby reducing the imaging problem to estimating the target contour $\vec{C}$ and the relative permittivity contrast $\overline{\Delta\varepsilon_r}$ via minimization of an energy functional. For pulsed excitation, the functional to be minimized has the following form [9]

$$J_{CE}\left(\vec{C},\overline{\Delta\varepsilon_r}\right)=\frac{1}{2}\sum_n\left(e_n^s-\overline{\Delta\varepsilon_r}u_n\right)^2+\beta\int_{\vec{C}}d\ell. \tag{1}$$

The reader is referred to [7] for the frequency-stepped modality. The first term in (1) encourages data fidelity, with e_n^s denoting space-time scattered field observation samples and u_n denoting the corresponding forward model prediction for a given target contour $\vec{C}$ and unitary relative permittivity contrast. The second term serves as regularizer by penalizing the arc-length of the estimated curve, with the regularization parameter β (empirically selected by trial and error in our implementation) affecting its smoothness. Moreover, we minimize the cost functional in (1) via *curve evolution* using the level set method [11].

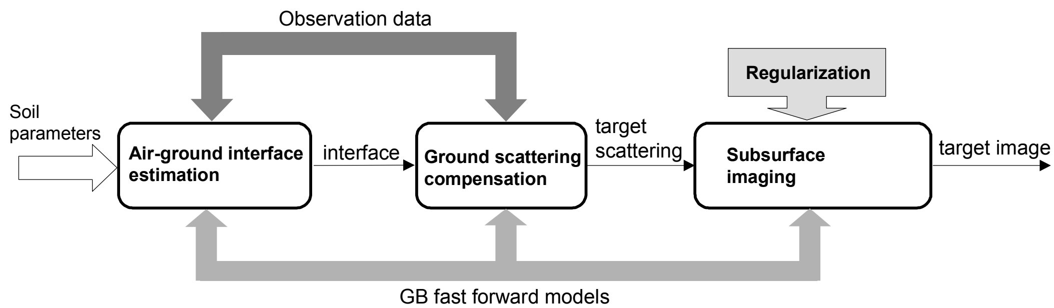

FIGURE 1- Schematic flow-chart of the adaptive approach.

REPRESENTATIVE RESULTS

We consider the simulation geometry and parameters in Fig. 2a, where a plastic mine-like 10cm×6cm elliptic target with relative permittivity $\varepsilon_{r2} = 3.5$ is buried in a homogeneous dielectric half-space with constitutive parameters chosen so as to simulate a class of realistic clay-loam soils (relative permittivity: $\varepsilon_{r1} = 4$, conductivity $\sigma_1 = 0.01$ S/m) with a randomly-selected moderate roughness realization (~3-4 cm peak-to-peak, maximum slope ~30º). We assumed a cosine-tapered quasi-plane-wave pulsed excitation with 80cm aperture width and a fourth-order Rayleigh wide-band time profile (2.45 GHz center frequency, 1.4 GHz bandwidth); the field is observed at 11 receivers located 30cm above ground. Synthetic observation data were generated via a full-wave solution of the forward scattering problem [4] and were corrupted by 10% additive uniform noise. Interface profile reconstruction was achieved via the algorithm in [8] using 100 early-time samples; these results are not shown because of space limitations. Adaptive ground clutter compensation was performed as in [9]. A representative example of curve evolution target reconstruction, using 100 late-time samples, is shown in Fig. 2b, yielding rather accurate target boundary and dielectric contrast estimations. Similar results were obtained for the frequency-stepped configuration [7].

CONCLUSIONS

An adaptive approach for subsurface sensing in the presence of moderately rough interfaces has been presented, which exploits short-pulse Gabor-based narrow-waisted Gaussian beam algorithms as fast forward scattering models. Preliminary 2-D results, restricted to slightly lossy soils and low-contrast targets, show that quite accurate target reconstructions can be obtained with reasonable computing time and resources. Overall computing times are on the order of a few minutes, thus leaving room for optimism that extensions to more realistic 3-D configurations (currently under investigation) will remain computationally feasible.

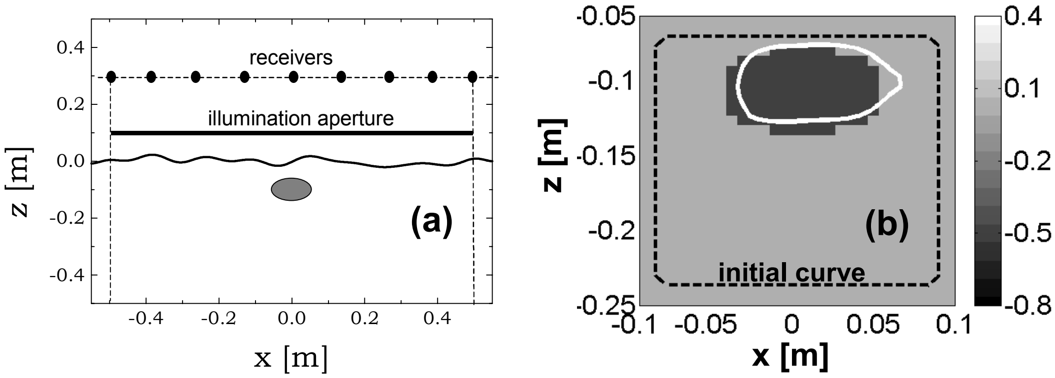

FIGURE 2 - Numerical results. (a): Simulation geometry and parameters. Soil: $\varepsilon_{r1} = 4$, $\sigma_1 = 0.01$ S/m. Target: 10cm×6cm ellipse with center at 10cm below nominal ground, $\varepsilon_{r2} = 3.5$, $\sigma_2 = 0$. Excitation: cosine-tapered quasi-plane-wave with 80cm aperture width, fourth-order Rayleigh wide-band excitation (2.45 GHz center frequency, 1.4 GHz bandwidth). The backscattered field is observed at 11 equispaced receivers located 30cm above nominal ground. (b): Curve evolution target reconstruction (white curve) is superposed on ground truth (relative permittivity contrast gray-scale plot). The estimated target relative permittivity is $\varepsilon_{r2} = 3.56$ (1.7% error).

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